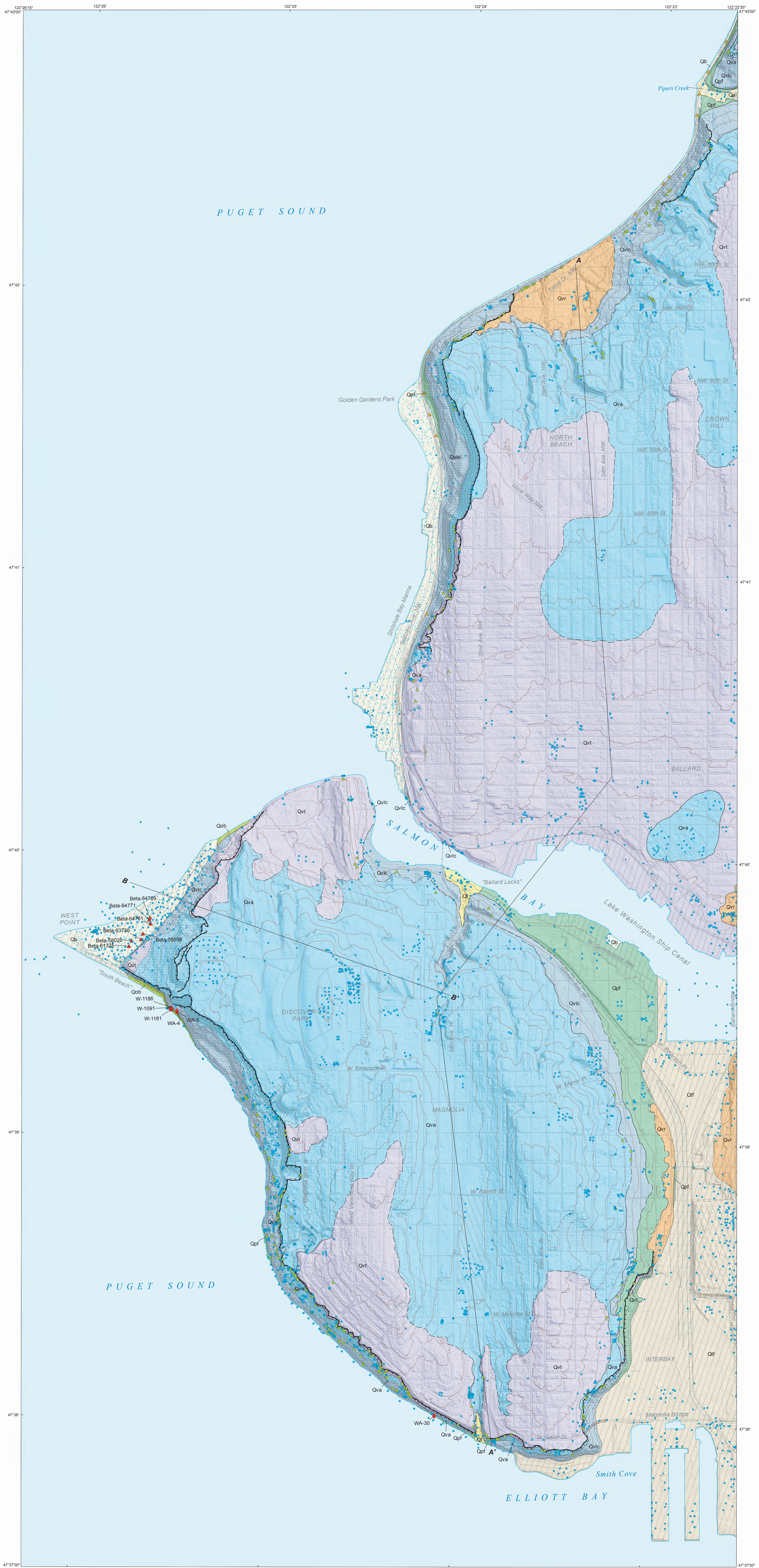
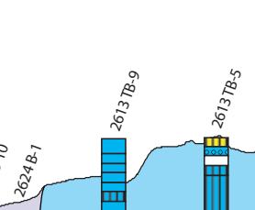
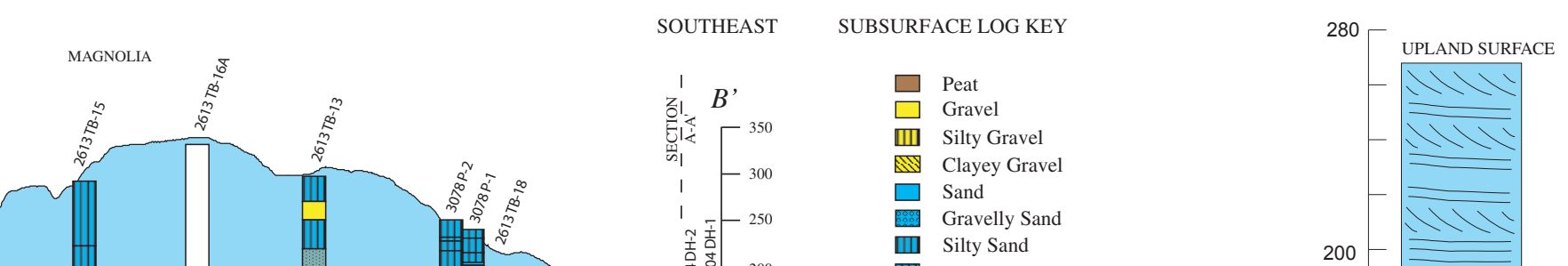
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

SCIENTIFIC INVESTIGATIONS MAP 2903





SCALE 1:12 000



CONTOUR INTERVAL 40 FEET

WASHINGTON

MAP LOCATION

Roads extracted from City of Seattle, WA, 1:1200-scale proprietary street data, 2001. Horizontal accuracy ~1.5 meters

Shaded relief from Puget Sound LiDAR Consortium and King County Endangered Species Act/Sensitive Areas Ordinance, LiDAR Digital Ground Model (DGM), 2001-2003. Horizontal accuracy ~1.8 meters; vertical accuracy ~0.3 meters. Contours created from LiDAR DGM.

State Plane Coordinate System; Datum 1983, Zone 4601

Map rotated 1.1° counterclockwise for display

Geology mapped by D.B. Booth and K.G. Troost, 2000-2003

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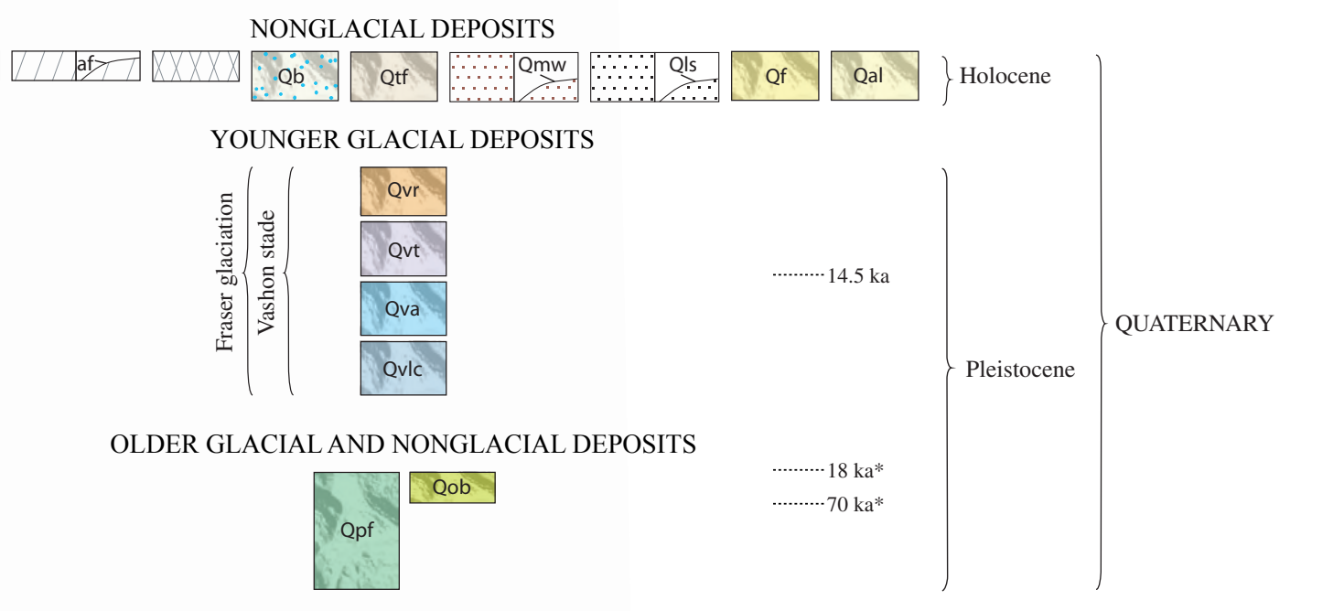
CORRELATION OF MAP UNITS



* Dates correspond to boundaries of the Olympia nonglacial interval (Booth and others, 2004)

DESCRIPTION OF MAP UNITS

NONGLACIAL DEPOSITS

Modified land (Holocene)—Fill or extensively graded natural deposits that obscure or substantially alter original deposit. Consists of:

Graded areas—Extensively graded areas. Some fill likely present. Excludes roadways, parking lots, and landscaped areas. Deposits are shown by overprint pattern; underlying units are shown beneath pattern

af **Artificial fill**—Veneer of gravel, sand, and silt, intermixed with concrete and other materials; placed as direct result of human activity. Shown where borehole data provide sufficient information to delineate extent and where greater than about 3 m (10 ft) thick over at least tens of meters in lateral extent. Thickest fill overlies tideflats of Interbay, where as much as 6 m (20 ft) of fill overlie 15 m (50 ft) of refuse. Thin deposits of fill are present elsewhere throughout map area but are not mapped owing to lack of information. Loose to dense. On map, deposits are shown by overprint pattern; underlying units are shown beneath pattern. Labeled (as af) only on cross section. Locally consists of:

Landfill debris—Gravel, sand, and silt, intermixed with concrete, bricks, coal, wood, refuse, and other types of debris materials; placed over tideflats of Interbay during first half of 20th century. Maximum depths of refuse exceed 20 m (70 ft). Deposits are shown by overprint pattern; underlying unit is shown beneath pattern

Qb **Beach deposits (Holocene)**—Loose sand and gravel; deposited and (or) reworked by modern wave action. Includes organic material accumulated at or near sea level, particularly at West Point. Deposits above 2.7 m (9 ft) elevation (City of Seattle datum) are concealed by fill, except for part of Golden Gardens Park, wherein lies one of very few remnants of unmodified beach in city of Seattle. Unit is commonly present, but generally not mapped, along shoreline below 2.7 m (9 ft). Loose to dense

Qtf **Tideflat deposits (Holocene)**—Silt, sand, and organic sediment and detritus; historically exposed in broad coastal benches at low tide but now fill covered. Loose to moderately dense

Qmw **Mass-wastage deposits (Holocene)**—Colluvium, soil, and landslide debris having indistinct morphology. Mapped on steep slopes, particularly along ravines and coastal bluffs of Puget Sound. Loose to moderately dense and soft to stiff. Thickness typically about 3 m (10 ft) but locally may exceed 10 m (30 ft). On map, deposits are shown by overprint pattern; underlying units are shown, on the basis of subsurface data, beneath pattern. Labeled (as Qmw) only on cross section. Locally consists of:

Qls **Landslide deposits**—Diamict of broken to internally coherent surficial deposits that have been transported downslope en masse by gravity. Discriminated from other mass-wastage deposits by thickness of identifiable slide deposits, by lateral continuity, and by presence of coherent blocks of geologic materials. Located primarily along coastal bluffs of Puget Sound, particularly where coarse-grained deposits (most commonly, unit Qva) overlie fine-grained deposits (either unit Qvlc or Qpf). Slumped blocks hundreds to thousands of meters in lateral extent are prominent above Golden Gardens Park and along south shoreline of Magnolia; a large slide, inferred from topography, likely offsets contacts immediately east of West Point. On map, deposits are shown by overprint pattern; underlying units are shown beneath pattern. Labeled (as Qls) only on cross section

Qf **Alluvial fan deposits (Holocene)**—Sand, silt, gravel, and cobbles; deposited in lobate form where streams emerge from confining valleys onto areas of reduced gradients. Mapped deposit grades upvalley into alluvium lacking fan morphology. Loose to dense

Qal **Alluvium (Holocene)**—Sand, silt, gravel, and cobbles; deposited along Pipers Creek by running water. Loose to dense

YOUNGER GLACIAL DEPOSITS

Deposits of the Vashon stade of the Fraser glaciation of Armstrong and others (1965) (Pleistocene)—Consists of:

Qvr **Recessional outwash deposits**—Stratified sand, moderately sorted to well sorted; less common silty sand, silt, and gravel; locally may include plastic swelling clay. Deposited in outwash channel through Interbay, which carried glacial meltwater southward during ice retreat. Adjacent to Puget Sound, unit also includes broad fan-shaped deposit of silty sand and local sandy gravel that accumulated in or adjacent to recessional lake. Deposits less than about 1 m (3 ft) thick are widespread but are not shown on map; locally, deposits are more than 6 m (20 ft) thick. Loose to dense

Qvt **Vashon till**—Compact diamict of silt, sand, and subrounded to well-rounded gravel; glacially transported and deposited under ice. Commonly is fractured and has intercalated sand lenses. Generally forms undulating, fluted surface; tends to drape topography and is found at both lowest and highest elevations in map area. Unit typically is 1 m (3 ft) thick but can be at least 30 m (100 ft) thick; thickest known deposit in map area is well exposed on northernmost point of hill at Magnolia. Uppermost meter generally is weathered and moderately dense; deeper levels characteristically are unweathered and very dense

Qva **Advance outwash deposits**—Well-sorted sand and gravel; deposited by streams issuing from advancing ice sheet. May grade upward into till. Silt lenses are common in lower part but are less abundant upward. Generally unoxidized to slightly oxidized. May include overlying areas of Vashon till too small to show at map scale. Locally over 60 m (200 ft) thick; dense to very dense. Includes the Esperance Sand Member of the Vashon Drift (Mullineaux and others, 1965). Grades downward into unit Qvlc with increasing silt content

Qvlc **Lawton Clay Member of the Vashon Drift**—Stiff to hard, laminated to massive silt, clayey silt, and silty clay; deposited in lowland or proglacial lakes. Dropstones locally present. Marks transition from nonglacial to earliest glacial time, although unequivocal evidence for glacial or nonglacial origin may be absent. Locally may include fine-grained sediment of unit Qob. Absent in places to over 30 m (100 ft) thick in map area

OLDER GLACIAL AND NONGLACIAL DEPOSITS

Qpf **Deposits of pre-Fraser glaciation age (Pleistocene)**—Interbedded sand, gravel, and silt; of indeterminate age and origin; lightly to heavily oxidized. Discriminated from texturally similar younger deposits, particularly unit Qva, on the basis of stratigraphic position, oxidation, and commonly heterogeneous grain size. On the basis of lithology, elevation, and proximity, some parts of unit probably are equivalent to dated deposits of unit Qob. Maximum elevation inferred to be about 40 m (130 ft); base of unit not exposed in map area. Dense to very dense

Qob **Olympia beds of Minard and Booth (1988) (Pleistocene)**—Sand, silt (locally, organic rich), gravel, and peat; thinly and discontinuously interbedded; deposited during Olympia nonglacial interval (Armstrong and others, 1965). As much as 23 m (85 ft) exposed above sea level in map area. Moderately to heavily oxidized; may contain tephra and (or) diatomaceous layers. Deposits derived from Cascade Range generally are rich in volcanic debris, whereas those recycled from older glacial deposits contain abundant plutonic and metamorphic detritus. Mapped locality on south side of West Point (see fig. 1) constitutes type locality for deposits of Olympia nonglacial interval (Mullineaux and others, 1965). Unit is distinguished from unit Qvlc on the basis of its sand and gravel interbedded with silt and, locally, by presence of organic material. Locally mapped or identified previously as the "sandy phase of the Lawton." Generally very dense and (or) hard

Contact—Dashed where approximately located; dotted where concealed; queried where uncertain (in cross section)

Landslide scarp—Mapped at upper and (or) lateral boundaries of inferred landslides

Beta-53736 ▲ **^{14}C age locality**—See table 1 for ages

WA-4 ♦ **Infrared-stimulated luminescence (IRSL) age locality**—See table 2 for ages

Landslide localities

▲ **Landslides**—From winter of 1996-97 (Baum and others, 2000)

▲ **Landslides**—All slides through 1999 on file with the City of Seattle (Shannon & Wilson, 2000)

Exploration Sites

- ● **Field exposure**
- ▾ **Cone penetrometer test**
- ● **Geotechnical boring**
- ■ **Geotechnical test pit**
- ▲ **Density probe**
- ♦ **Monitoring or water well**

GEOLOGIC SUMMARY

INTRODUCTION

The city of Seattle is located at the center of the intensely developing urban core of the Puget Lowland region. This geologic map (herein known [informally] as "the Seattle NW map") covers much of the northwestern part of the city of Seattle. The map area includes almost all of the west half of the Seattle North 7.5' x 15' quadrangle (in other words, west of longitude 122°22'30"). Not included are small parts of Bainbridge Island and Kitsap Peninsula along the west edge of the quadrangle; also not included is a small piece of the Puget Sound mainland at the north edge of the quadrangle because it is separated by more than 2 km of water from the rest of the Seattle NW map area (note that this area will be added on to the adjacent [informal] Seattle NE map to the east, which is in preparation).

The Seattle NW map area covers the part of the city of Seattle that straddles Salmon Bay and the west end of the Lake Washington Ship Canal, which connects Puget Sound to Lake Washington, about 8 km east of the map area. Land uses are mainly residential; however, associated local commercial centers are present in the neighborhoods of Magnolia, Ballard, Crown Hill, and North Beach, and some industrial activities take place adjacent to the Ship Canal. Within the boundaries of the map area are located a regional wastewater treatment plant at West Point, the Chittenden Locks (also known as the "Ballard Locks") near the west end of the Ship Canal, cargo and fishing-fleet facilities at the port of Seattle, two salt-water marinas, and large municipal parks in Magnolia and at Golden Gardens Park. Elevations range from sea level to a maximum of more than 120 m (400 ft) on a till-covered knob in Magnolia in the southern part of the map area. Previously published geologic maps of this area include those of Waldron and others (1962), Galster and Laprade (1991), and Yount and others (1993).

Seattle lies within the Puget Lowland, an elongate structural and topographic basin between the Cascade Range and the Olympic Mountains. The Seattle area has been glaciated repeatedly during the past two million years by coalescing glaciers that advanced southward from British Columbia. The landscape we see today was molded by cyclic glacial scouring and deposition and later modified by landsliding and stream erosion. The last glacier reached the central Puget Sound region about 17,400 (14,500 radiocarbon) yr B.P., as measured by ^{14}C dating, and it had retreated from this area by 16,400 (13,650 radiocarbon) yr B.P. (Porter and Swanson, 1998). Seattle now sits atop a complex and incomplete succession of interleaved glacial and nonglacial deposits that overlie an irregular bedrock surface. These glacial and nonglacial deposits vary laterally in both texture and thickness, and they contain many local unconformities. In addition, they have been deformed by faults and folds at least as recently as 1,100 years ago, further complicating the geologic record.

The landforms and near-surface deposits that cover much of the Seattle NW map area record a relatively brief, recent period in the geologic history of the region. The topography is dominated by two broad hills that rise from sea level to form part of an extensive upland plain. This plain is mantled by a rolling surface of mainly sand (unit Qva) and till (unit Qvt) that was deposited during the last occupation of the Puget Lowland by a continental ice sheet. Beneath these ice-sheet deposits is a complex succession of older sediments that extends far below sea level across most of the map area. These older sediments are now exposed where modern erosion and landslides have sliced through the edge of the upland, most notably in coastal bluffs along Puget Sound.

STRATIGRAPHY AND HISTORY

Bedrock

Eocene to Miocene volcanic and sedimentary rocks deposited as forearc basin fill underlie the entire east-central Puget Lowland (Yount and Gower, 1991; Tabor and others, 2000). Bedrock throughout the Seattle NW map area is concealed beneath more than 500 m of unconsolidated sediments (Jones, 1996); the closest bedrock crops out about 8 km to the south on Alki Point, in the adjacent [informal] Seattle SW map area (see Troost and others, 2005).

Quaternary Stratigraphic Framework

At least seven invasions of glacial ice and alternating nonglacial intervals have left a discontinuous geologic record in the Puget Lowland (Blunt and others, 1987; Booth and others, 2004). Originating in the mountains of British Columbia, the ice was part of the Cordilleran ice sheet of northwestern North America. During each successive glaciation, the ice advanced into the lowland as a broad tongue, named the Puget lobe by Bretz (1913). In an area where each glacial and interglacial depositional sequence looks alike, differentiating glacial and nonglacial deposits requires laboratory analyses and age determinations (Troost, 1999).

Different depositional environments yielded distinctly different glacial deposits, the following of which are recognized in the region: (1) proglacial lacustrine silts and clays that resulted from the damming of the Strait of Juan de Fuca; (2) advance outwash sand and gravel deposited by streams exiting the front of the advancing glacier; (3) till—a heterogeneous mixture of silt, sand, gravel, and clay—deposited under and along the margin of the glacier; (4) recessional outwash sand and gravel deposited as the ice melted northward; (5) recessional lake deposits of silt and sand; and (6) glaciomarine drift—sandy, clayey silt containing dropstones—deposited as marine water inundated the isostatically depressed land and floated distal parts of the Puget lobe. All of these deposits except glaciomarine drift have been recognized in the Seattle NW map area. Nonglacial deposit types include peat; volcanic ash and volcanogenic mudflows; and lake, river, and beach deposits.

Deposits and Landforms Predating the Vashon Stade of the Fraser Glaciation

Stratigraphic units predating the Vashon stade of the Fraser glaciation are identified on the map as either pre-Fraser-age deposits (unit Qpf) or Olympia beds of Minard and Booth (1988) (unit Qob). We did not subdivide the pre-Olympia-age deposits into named units because absolute age control is sparse, and so the risk of spurious correlation is high.

The Olympia nonglacial interval was defined originally by Armstrong and others (1965) as "the climatic episode immediately preceding the last major glaciation, and represented by nonglacial strata beneath Vashon Drift." The Olympia beds of Minard and Booth (1988) accumulated across the Puget Lowland between about 60,000 and 15,000 yr B.P.; this interval closely approximates the temporal limits for oxygen-isotope stage 3 and immediately predates the Fraser glaciation (oxygen-isotope stage 2) (Winograd and others, 1997).

Deposits of unequivocal Olympia age are exposed at only two locations in the Seattle NW map area: in the wave-cut bench northeast of West Point, and along the bluff in Discovery Park directly south of West Point. The southern locality (see "South Beach" measured section, fig. 1), which is designated as the type locality for Olympia-age deposits in the Puget Lowland (Mullineaux and others, 1965), displays fluvial and nearshore marine sand and gravel interbedded with layers of scattered detrital organic debris. The ^{14}C ages of three samples of wood and peat range from between 23,350 to 19,750 (18,100±700 radiocarbon) yr B.P. and 26,150 to 22,350 (24,000±900 radiocarbon) yr B.P. (Ives and others, 1964; see also, table 1).

Elsewhere in the map area, the presence of Olympia beds is suggested, but not required, by borings along the coastline north of Golden Gardens Park and along the west edge of Interbay. Outcrops are few and no material has been dated at these localities; consequently, the more general unit designator Qpf (pre-Fraser-age deposits) is used. In borings, the presence of unit Qpf beneath the silt- and clay-rich Lawton Clay Member of the Vashon Drift (unit Qvlc) is inferred from the existence of abundant sandy or gravelly interbeds. Although the upper contact of unit Qpf is generally ill-exposed owing to overlying landslide debris and (or) fill, we have constrained its mapped position by determining its elevation in nearby boreholes and projecting it to the ground surface at constant elevation. The maximum elevation of this contact is about 36 m (120 ft), although it generally lies at about one-half this altitude.

Deposits of the Vashon Stade of Fraser Glaciation

The most recent glacial advance, the Vashon stade of the Fraser glaciation (Armstrong and others, 1965), was marked by the advance and retreat of the Puget lobe of the Cordilleran ice sheet in western Washington. The glacier advanced to the central Puget Lowland about 17,400 (14,500 radiocarbon) yr B.P. and retreated back past the map area by 16,400 (13,650 radiocarbon) yr B.P.; at its maximum advance, Seattle was buried by at least 900 m (3,000 ft) of ice (Booth, 1987). The present-day landscape is largely the result of deposition and scouring by the Vashon-age glacier, having been modified only slightly by more recent activities of stream and wave erosion, as well as landsliding, tectonic deformation, and volcanic events.

In contrast to uncertainties in age and stratigraphic assignment of older Pleistocene deposits, the deposits at or near the constructional land surface are readily assigned to the youngest regionally recognized glacial advance, the Vashon stade. These deposits vary in both grain size and topographic expression, owing to rapidly changing depositional environments caused by the advance and retreat of the ice sheet. The leading edge of the advancing ice sheet blocked northward lowland drainage out the Strait of Juan de Fuca, which now connects Puget Sound with the Pacific Ocean. In the impounded lake that subsequently formed, laminated silt and clay were deposited. This material has been mapped as the Lawton Clay Member of the Vashon Drift (unit Qvlc), of which the coastal bluff exposures southeast of West Point constitute the type section (Mullineaux and others, 1965).

Coarser advance outwash deposits (unit Qva) mark direct, active ice-sheet deposition by streams flowing from the advancing glacier. Sandy advance outwash deposits at least a few tens of meters thick (and locally as thick as 90 m) underlie the broad uplands in the central part of the map area. The outwash deposits inundated the pre-Vashon-age topography of the lowland, resulting in a south-sloping surface that is now about 150 m (490 ft) high at this latitude elsewhere across the Puget Lowland (Booth, 1994); this surface only achieves a maximum elevation of 110 m (360 ft) in the Seattle NW map area owing to synglacial and postglacial erosion.

As ice covered the region, till (unit Qvt) was deposited by the melt-out of debris at the base of the glacier. The ground surface underlain by both advance outwash deposits and till locally is fluted with elongated hills that have a weak but uniform north-south orientation (azimuth approx 177°) across the map area. The fluting is expressed more clearly in the southern half of the map area, on the hill at Magnolia. Immediately north of the Ship Canal, ridges and valleys trend in the same orientation but are more subdued than in any other part of the city of Seattle. The till also is much more widespread in this northern area, and its elevation descends to at least as low as modern sea level along the north side of the Ship Canal, as well as across the canal on the extreme north point of the hill at Magnolia. Glacial fluting is not limited to till-covered areas, however, suggesting that surfaces underlain by advance outwash deposits (unit Qva) represent regions where till either was never deposited or was deposited and removed while still covered with ice. Where present, till provides a low-permeability cover to underlying aquifers, which reduces infiltration and groundwater recharge but also offers protection from surface contaminants. Till thicknesses average 2.6 m across the map area and are as great as 27 m in some boreholes. Even thicker till is exposed northeast of West Point and northwest of the "Ballard Locks" in a near-vertical 30-m-high cliff that faces Shilshole Bay Marina.

The matrix of the till differs from place to place in relative proportions of silt, sand, and (usually sparse) clay. The till mostly is gravelly silty sand to gravelly sandy silt; in many places, it is crudely stratified and contains lenses of sand, gravel, and silt. Cobbles and boulders are scattered throughout the till; boulders more than 3 m in diameter are rare. Unoxidized till is light gray and compact; where oxidized, till is light yellowish gray and generally is moderately dense. Although a weak brown soil is developed on the till, oxidation rarely extends more than about a meter into the deposit.

Vashon till typically is very dense and has a fine-grained matrix, but structural or stratigraphic discontinuities locally can increase its permeability by several orders of magnitude, allowing faster transmission of water and contaminants. Depending on subglacial conditions at the time the till was formed, as well as on postdepositional strain, the discontinuities consist of intercalated sand and silt layers, bedding planes, and (or) joints.

Shortly after 17,400 (14,500 radiocarbon) yr B.P., the ice margin, which extended more than 50 km south of the map area, began to melt back. Meltwater from the ice sheet combined with runoff from the Cascade Range and drained southward and westward, spilling over divides that later were abandoned as ice pullback exposed lower divides farther north. By the time that the Seattle NW map area was uncovered by the retreating ice, proglacial drainage was well established across most of the eastern and southern lowland. Water was impounded in a lake that inundated much of the central and southern Puget Lowland, including the map area, because more than 1,000 m of glacial ice still filled the Strait of Juan de Fuca.

The first of two main recessional lakes (Glacial Lake Russell) drained out through the Black Hills into the Chehalis River, many tens of kilometers south of the map area (Thorson, 1980). Although the elevation of the Black Hills spillway was only about 41 m (134 ft), the ancient shoreline of Glacial Lake Russell is now higher because the land surface of the Puget Lowland has rebounded following the removal of the weight of the ice sheet. More rebound occurred in the north than in the south because the ice sheet was thicker to the north. In the center of the Seattle NW map area, rebound has been about 45 m, and so the shoreline of Glacial Lake Russell should have a present-day elevation of nearly 90 m (300 ft). Most of the land in the map area therefore was submerged, and so little or no record of this interval remains here; much clearer expressions are found farther north (see, for example, Booth, 1987). The Seattle NW map area became ice free during the existence of Glacial Lake Russell.

The second water body, Glacial Lake Bretz, was formed when ice retreated far enough north to uncover a lower spillway on the northeast corner of the Olympic Peninsula, about 40 km northwest of the map area (Thorson, 1989). As with Glacial Lake Russell, the ancient shoreline of Glacial Lake Bretz now slopes southward because of differential rebound. In the Seattle NW map area, the calculated elevation of the lake surface ranges from about 37 m (to the south) to 47 m (to the north) (approx 120-150 ft). Glacial Lake Bretz likely did not persist for more than a few decades because of rapid rates of glacier retreat (Porter and Swanson, 1998), and so thick lake deposits are not likely. The single large patch of recessional outwash deposits (unit Qvr) mapped on the north side of North Beach, which has a maximum elevation of 43 m (140 ft), likely is a subaqueous fan containing sediment derived from several upslope gullies incised into advance outwash deposits (unit Qva) along the margin of Glacial Lake Bretz. Although exposures of this deposit (unit Qvr) are very poor, shallow subsurface data show that it consists primarily of medium-density silty sand and at least one local area of gravelly sand and gravel.

Further retreat of the ice sheet reconnected Puget Sound to the open ocean, allowing regional water levels to fall by about an additional 40 m (Thorson, 1989). Thus, the late-glacial marine limit is near the south edge of the Seattle NW map area; farther south, any deposits associated with this recessional stage are now submerged below modern sea level because the amount of isostatic rebound has been exceeded by that of postglacial eustatic sea-level rise. A low terrace 10 to 20 m (35-65 ft) high along the east side of the hill at Magnolia, which has been included in unit Qvr, probably dates from this stage of ice retreat, but its intermediate elevation relative to the specific glacial-lake and marine water levels makes its origin somewhat enigmatic.

Postglacial Processes and Deposits

Geologic activity since glaciation includes soil formation, widespread slope failure and cliff retreat, beach erosion and deposition, stream-channel erosion, and tectonic deformation. As a result of the lowered base level occasioned by the drainage of Glacial Lake Bretz, several streams in the map area began to incise the sequence of glacial and nonglacial deposits that underlies the upland surface. Yet drainage areas are so small, and stream erosion accordingly so feeble, that only the valleys of Pipers Creek (northeast corner of the map area) and of two unnamed channels on the north and south sides of the hill at Magnolia are now graded to modern sea level.

On the upland surface, soil formation since deglaciation has proceeded slowly but locally has had profound hydrologic consequences. The first meter or so beneath the ground surface usually consists of topsoil underlain by silty weathered parent material, colluvium, or fill. Where Vashon till (unit Qvt) is present, the unweathered till deposit absorbs water only very slowly. In contrast, the meter or so of soil that has developed on the till since deglaciation has high infiltration capacities and a large capacity to store and slowly release subsurface runoff. This till-derived "Alderwood" soil (Snyder and others, 1973) once blanketed about one-half of the upland plateau. The compaction or removal of that soil during typical urban or suburban development has had dramatic hydrologic effects.

On areas underlain by Vashon-age advance outwash deposits (unit Qva), however, infiltration through both the soil and the parent material is relatively fast. Water permeates rapidly into the sand and then moves downward to the top of an underlying fine-grained unit, here almost exclusively the Lawton Clay (unit Qvlc). Groundwater then moves laterally to the steep hillsides along the coast and in deep ravines, where it emerges as springs (Tubbs, 1974). In general, steep slopes that contain fine-grained deposits overlain by coarse-grained deposits are particularly susceptible to landslide failure. This mass-wasting condition is found in most of the steeply sloping parts of the map area.

Although colluvium, other mass-wasting deposits, and fill are widespread, they are shown on the map only where they are more than a meter or two thick, a thickness sufficient to alter the ground-surface topography or obscure the underlying deposits. Colluvium a few centimeters to several meters thick, which covers nearly all the valley walls and slopes, consists of a mixture of locally derived materials and is principally a loosely consolidated silt, or silty sand and gravel.

Small landslides, common on steep bluffs and slopes, consist of slumps and earth flows that are chiefly caused by surface erosion or spring sapping. Individual slides generally are small at map scale but can be extremely hazardous in populated areas. Some of the landslides in the Seattle NW map area, however, are quite large. The most extensive landslide complex is found along the southwest-facing bluffs of Magnolia, where winter storm waves driven by prevailing south winds maintain a steep bluff face and spring-sapping by groundwater collected from infiltrating rainwater on the till-free uplands further contributes to continued slope instability. Here, the landslide mechanism primarily is that of a block glide (Varnes, 1978), where mounding of groundwater at the contact between the overlying Vashon-age advance outwash deposits (Qva) and the underlying Lawton Clay (Qvlc) induces lateral slippage near the base of the sandy unit. This process has produced a midslope topographic bench at the elevation of the contact between units Qva and Qvlc, which commonly is about 18 m (60 ft) in this area; this bench has proven to be irresistible for residential development for nearly a century.

In addition to this dominant process of mass slope failures, the area is also subjected to shallow debris slides off the retreating sand face, deep-seated rotational landslides that cut through the Lawton Clay, and failure of jointed and locally stratified Vashon till directly overlying the Lawton Clay. During periods of heavy, continuous rainfall, each of these landslide mechanisms (particularly shallow debris slides) may occur.

Other noteworthy landslide-prone areas are present along the Puget Sound coastline. A large, prehistoric block glide is inferred for the area immediately east and south of West Point on the basis of both topography and offsets in the contacts between units Qob and Qvlc and between units Qvlc and Qva of as much as 15 to 20 m. A smaller slide has severed a park road on the northwest corner of the hill at Magnolia over the last decade. Landslides, both shallow debris flows and deep-seated rotational slides that leave prominent midslope benches, also are abundant north of the Ship Canal. Mapped slide localities from the winter of 1996-97 (Baum and others, 2000), as well as point localities of all slides on file with the City of Seattle through 1999 (Shannon & Wilson, Inc., 2000) are included on this map for reference.

Modern beach deposits (unit Qb) are shown on this map only where extensive: at West Point, along the coastline between Shilshole Bay Marina and Golden Gardens Park, and in the lee of the hill at Magnolia. Except for one small, nearly unique patch of unaltered shoreline at the north end of Golden Gardens Park, these deposits are almost everywhere overlain by fill, which at some localities is over 10 m thick. Fill also overlies tideflat deposits (unit Qtf) east and southeast of Magnolia, where borings typically penetrate 6 m of sand-and-clay fill over as much as 15 m of refuse before encountering organic silt and sand in place.

Human Modification of the Landscape

Several areas within the map area have been modified by the addition of fill, by grading, or by the removal of sand and gravel. The affected areas visible at map scale include the entire Interbay area, a former tidal channel between Magnolia and the rest of Seattle; the regional wastewater treatment plant at West Point; marina complexes at Shilshole Bay and at the south base of the hill at Magnolia; a flat-graded and now-abandoned rifle range in Discovery Park; and several school and community playfields. Near the north tip of the hill at Magnolia, an anomalous flat-topped ridge is the apparent legacy of early development activity, as shown by topographic maps from the early 1900's.

Regional Structure and Recent Seismicity

The entire area of the Seattle NW map lies within the Seattle Basin, the deepest of the structural blocks formed in western Washington in Tertiary time as a result of north-south-directed shortening in Oregon and Washington (Pratt and others, 1997; Wells and others, 1998). The east-west striking Seattle Fault Zone forms the border between the Seattle Basin (to the north) and the Seattle Uplift (to the south), passing through Seattle 8 to 10 km south of the south boundary of the Seattle NW map area (see Troost and others, 2005).

During a large (M ~7.5) earthquake on the Seattle Fault 1,100 years ago, land in the Seattle NW map area dropped by as much as 1 m. The best evidence of this subsidence consists of sub-sea-level deposits on West Point exposed by construction excavations for expansion of the West Point sewage treatment plant (Atwater and Moore, 1992). The plant sits on an archaeological site that shows evidence of fault subsidence and a tsunami. The West Point spit accreted over the past 5,000 years, building outward by longshore drift and upward by sea-level rise. Prior to 1,100 years ago, perimeter beach berms protected a backbeach tidal marsh. Native Americans occupied dry ground around the marsh and used the land as a seasonal shellfish processing area; radiocarbon data (table 1) provide a range of dates (4,237 calibrated yr B.P. through 150 calibrated yr B.P.) for Native American occupation of the spit and backbeach area (Troost and Stein, 1995). The earthquake on the Seattle Fault 1,100 years ago resulted in 1 m of subsidence and deposition of a tsunami sand layer. Beach and shallow-marine sediments concealed the tsunami sand until the early 1990's, when excavation for the treatment plant exposed the layer.

Map Summary and Acknowledgements

This map is the first of four geologic maps prepared for the City of Seattle using a larger scale base map, which allows a more enhanced level of detail than previously was available. Geologic relations shown on this map are based on several sources, including new field mapping of outcrops and excavations, subsurface data compiled in a digital geologic database, topographic and geomorphic analyses, and the preexisting geologic map of the Seattle area (Waldron and others, 1962). Across most of the map area, geologic contacts and lithologic descriptions have changed somewhat from the preexisting map, as a result of both the dramatic increase in data from construction-related exposures and the revised understanding of the regional stratigraphic framework of the Puget Lowland.

The mapping and associated database were completed by the Pacific Northwest Center for Geologic Mapping Studies at the University of Washington, which is a collaborative effort between the University, the City of Seattle, and the U.S. Geological Survey. Particular acknowledgments are due our colleagues who have shared geologic data, insights, and interpretations throughout the current period of mapping: the Seattle Geologic Mapping Project Technical Advisory Group; William T. Laprade (Shannon & Wilson, Inc.); Brian Atwater, Thomas Brocher, Ralph Haugerud, Samuel Johnson, Brian Sherrod, Craig Weaver, and Ray Wells (all USGS); and Timothy Walsh (Washington State Department of Natural Resources). Numerous personnel from the City of Seattle provided financial support, guidance, and data for the subsurface data compilation, including Kaveh Aminian, Bob Chandler, Ken Conradi, John Ege, Rich Folsom, Dean Griswold, Craig Ladiser, Rob McIntosh, Tom Nolan, Art Richardson, and Brian Smith. Michael O'Neal (University of Washington) provided ArcView and cross section tools. The following University of Washington students were invaluable in collecting and entering data: Alyssa Beck, Chris Converse, Sharon Davis, Karen Dubose, Jake Fryer, Lori Greene, Douglas Hathaway, Karin Knudsen, Crystal Mann, Elizabeth Meeks, Suzanne Osborne, and Constance Rehfuss.

Table 1. *Radiocarbon analyses in the Seattle NW map area*

Sample No.	Site Name	Location (lat, long)	Altitude, m [ft]	Sample Type	Conventional ^{14}C age, in yr B.P.[1]	Calibrated ^{14}C age, in yr B.P.[2]	Reference	Map Unit	Pretreatment
W-1091	"South Beach," West Point	47.657° N., 122.425° W.	1 [3]	Wood	20,350±600	20,450 (21,750-19,150)	Ives and others, 1964; Yount and others, 1980	Qob	Not reported
W-1181	"South Beach," West Point	47.657° N., 122.425° W.	1 [3]	Peat	22,400±800	22,550 (24,250-20,850)	Ives and others, 1964; Yount and others, 1980	Qob	Not reported
W-1186	"South Beach," West Point	47.657° N., 122.425° W.	10 [33]	Peat	18,100±700	21,550 (23,350-19,750)	Ives and others, 1964; Yount and others, 1980	Qob	Not reported
Beta-53736	West Point sewage treatment plant	n/a[3]	-3 [-9]	Charcoal/ wood	n/a	3,455 (3,653-3,311)	Sample EPS F1; Larsen and Lewarch, 1995	Qb	Acid-alkali wash
Beta-58026	West Point sewage treatment plant	n/a[3]	-3 [-8.5]	Charcoal/ wood	n/a	4,018 (4,237-3,852)	Sample B2; Larsen and Lewarch, 1995	Qb	Acid-alkali wash
Beta-58038	West Point sewage treatment plant	n/a[3]	-0.3 [-1]	Charcoal/ wood	n/a	1,238 (1,337-1,009)	Sample IM F9; Larsen and Lewarch, 1995	Qb	Acid-alkali wash
Beta-64761	West Point sewage treatment plant	n/a[3]	1 [2.7]	Charcoal/ wood	n/a	776 (926-703)	Sample SG F1; Larsen and Lewarch, 1995	Qb	Acid-alkali wash
Beta-64771	West Point sewage treatment plant	n/a[3]	1 [3.9]	Charcoal/ wood	n/a	470 (510-320)	Sample CL2 F1; Larsen and Lewarch, 1995	Qb	Acid-alkali wash
Beta-61325	West Point sewage treatment plant	n/a[3]	2 [5]	Charcoal/ wood	n/a	280 (310-0)	Sample SB1; Larsen and Lewarch, 1995	Qb	Acid-alkali wash
Beta-64769	West Point sewage treatment plant	n/a[3]	2 [6]	Charcoal/ wood	n/a	43 (150 -10)	Sample CL2 F3; Larsen and Lewarch, 1995	Qb	Acid-alkali wash

[1] Present is considered to be 1950 A.D.
[2] Calibrated radiocarbon age from Stuiver and Reimer (1993). Reported age given with 2-sigma range (in parentheses)
[3] For specific location on West Point, see Larsen and Lewarch (1995)

Table 2. *Infrared-stimulated luminescent (IRSL) ages in the Seattle NW map area*

Lab No.	Location	Elevation, ft	Material	Average IRSL Age, in 1000 yrs	Map Unit
WA-4	"South Beach"	70	Laminated silt/clay	15±1	Qvlc
WA-5	"South Beach"	75	Laminated silt/clay	13±1	Qvlc
WA-30	Southern Magnolia	0	Silt	123±25	Qpf

Dates from S. Mahan, U.S. Geological Survey, Denver, CO, and Mahan and others, 2003. Samples collected in 2000-2003. Ages reflect average of 10-minute bleach (minimum age) and 60-minute bleach (maximum age) with CS-3-67 orange filter

REFERENCES CITED

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., and Moore, A.L., 1992, A tsunami about 1,000 years ago in Puget Sound, Washington: Science, v. 258, p. 1,614-1,617.

Baum, R.L., Harp, E.L., and Hultman, W.A., 2000, Map showing recent and historic landslide activity on coastal bluffs of Puget Sound between Shilshole Bay and Everett, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2346, 1 sheet, scale 1:24,000 [available on World Wide Web at http://pubs.usgs.gov/mf/2000/mf-2346].

Blunt, D.J., Easterbrook, D.J., and Rutter, N.W., 1987, Chronology of Pleistocene sediments in the Puget Lowland, Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 321-353.

Booth, D.B., 1987, Timing and processes of deglaciation along the southern margin of the Cordilleran ice sheet, *in* Ruddimann, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-3, p. 71-90.

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., Troost, K.G., Clague, J.J., and Waitt, R.B., 2004, The Cordilleran ice sheet: Chapter 2, *in* Gillespie, A., Porter, S.C., and Atwater, B., eds., 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 No. 8, 244 p.

Galster, R.W., and Laprade, W.T., 1991, Geology of Seattle, Washington, United States of America: Bulletin of the Association of Engineering Geologists, v. 28, no. 3 (supplement), p. 239-302.

Ives, P.C., Levin, B., Robinson, R.D., and Rubin, M., 1964, U.S. Geological Survey radiocarbon dates VII: Radiocarbon, v. 6, p. 37-76.

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

Larsen, L.L., and Lewarch, D.E., eds., 1995, The archaeology of West Point, Seattle, Washington, 4,000 years of hunter-fisher-gatherer land use in southern Puget Sound: report prepared for King County Department of Metropolitan Services, Seattle, Washington, 942 p.

Mahan, S.A., Troost, K.G., and Booth, D.B., 2003, Dating sediments older than 100 ka in the Seattle-Tacoma urban corridor: A test for infrared stimulated luminescence and thermoluminescence on fine grain deposits [abs.]: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 79.

Minard, J.P., and Booth, D.B., 1988, Geologic map of the Redmond 7.5' quadrangle, King and Snohomish Counties, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2016, scale 1:24,000.

Mullineaux, D.R., Waldron, H.H., and Rubin, M., 1965, Stratigraphy and chronology of late interglacial and early Vashon time in the Seattle area, Washington: U.S. Geological Survey Bulletin 1194-O, 10 p.

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.

Pratt, T.L., Johnson, S.Y., Potter, C.J., Stephenson, W.J., and Finn, C.A., 1997, Seismic reflection images beneath Puget Sound, western Washington State; the Puget Lowland thrust sheet hypothesis: Journal of Geophysical Research, v. 102, no. B12, p. 27,469-27,489.

Shannon & Wilson, Inc., 2000, Seattle Landslide Study: report for Seattle Public Utilities, 164 p., with map folio and Seattle landslide database [available on World Wide Web at http://www.seattle.gov/DPD/Landslide/Study/default.asp].

Snyder, D.E., Gale, P.S., and Pringle, R.F., 1973, Soil survey of King County area, Washington: U.S. Department of Agriculture Soil Conservation Service, 100 p.

Stuiver, M., and Reimer, P.J., 1993, Extended C-14 database and revised CALIB 3.0 C-14 age calibration program: Radiocarbon, v. 35, p. 215-230.

Tabor, R.W., Frizzell, V.A., Jr., Booth, D.B., and Waitt, R.B., 2000, Geologic map of the Snoqualmie Pass 30' x 60' quadrangle, Washington: U.S. Geological Survey Geologic Investigations Series Map I-2538, 1 sheet, scale 1:100,000, 57 p. [available on World Wide Web at http://geopubs.wr.usgs.gov/i-map/i2538/].

Thorson, R.M., 1980, Ice sheet glaciation of the Puget Lowland, Washington, during the Vashon stade (late Pleistocene): 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. 1,163-1,174.

Troost, K.G., 1999, The Olympia nonglacial interval in the southcentral Puget Lowland, Washington: M.S. thesis, Seattle, University of Washington, 123 p.

Troost, K.G., Booth, D.B., Wisher, A., and Shimel, S., 2005, The geologic map of Seattle-a progress report: U.S. Geological Survey Open-File Report 2005-1252, scale 1:24,000 [available on World Wide Web at http://pubs.usgs.gov/of/2005/1252/].

Troost, K.G. and Stein, J.K., 1995, Geology and geoarchaeology of West Point, *in* Larsen, L.L., and Lewarch, D.E., eds., The archaeology of West Point, Seattle, Washington, 4,000 years of hunter-fisher-gatherer land use in southern Puget Sound: report prepared for King County Department of Metropolitan Services, Seattle, Washington, p. 2-1 to 2-78.

Tubbs, D.W., 1974, Landslides in Seattle: Olympia, Washington Division of Geology and Earth Resources Information Circular 52, 15 p.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides; analysis and control: Special Report 176, Transportation Research Board, National Research Council, p. 11-33.

Waldron, H.H., Liesch, B.A., Mullineaux, D.R., and Crandell, D.R., 1962, Preliminary geologic map of Seattle and vicinity, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-354, scale 1:31,680.

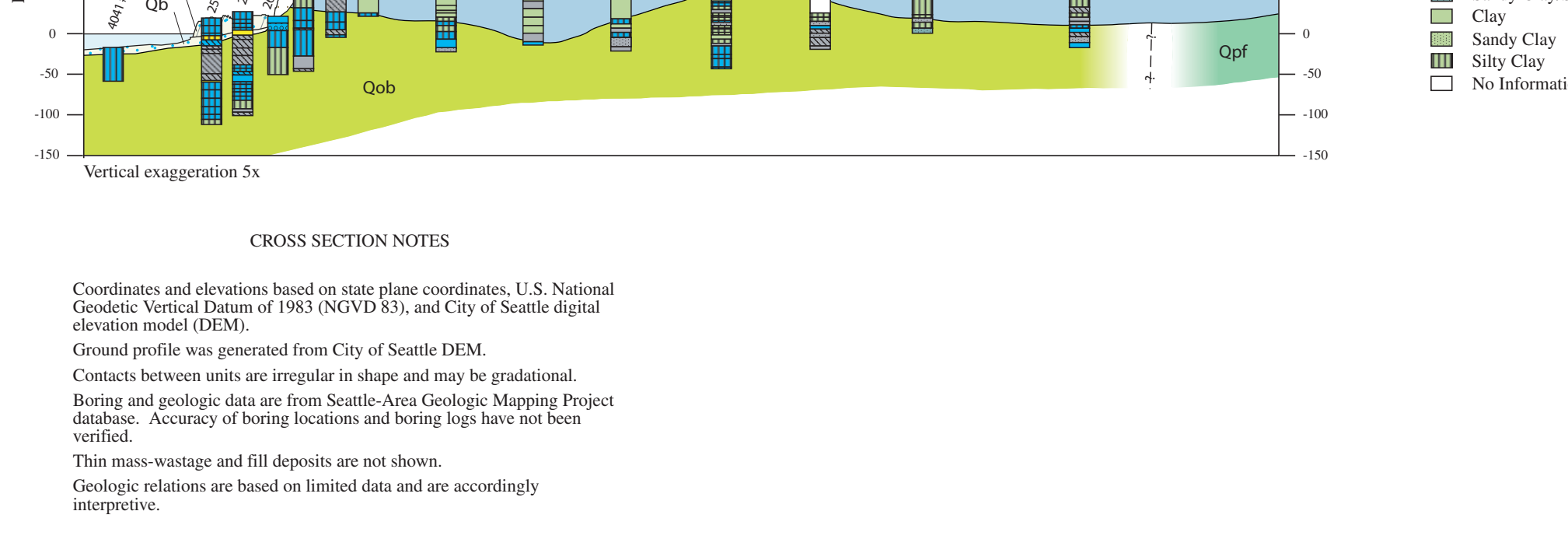
Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Fore-arc migration in Cascadia and its neotectonic significance: Geology, v. 26, no. 8, p. 759-762.

Winograd, I.J., Landwehr, J.M., Ludwig, K.R., Coplen, T.B., and Riggs, A.C., 1997, Duration and structure of the past four interglaciations: Quaternary Research, v. 48, p. 141-154.

Yount, J.C., and Gower, H.D., 1991, Bedrock geologic map of the Seattle 30' by 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 91-147, scale 1:100,000.

Yount, J.C., Marcus, K.L., and Mozley, P.S., 1980, Radiocarbon-dated localities from the Puget Lowland, Washington: U.S. Geological Survey Open-File Report 80-780, 51 p.

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



CROSS SECTION NOTES

Coordinates and elevations based on state plane coordinates, U.S. National Geodetic Vertical Datum of 1983 (NGVD 83), and City of Seattle digital elevation model (DEM).

Ground profile was generated from City of Seattle DEM.

Contacts between units are irregular in shape and may be gradational.

Boring and geologic data are from Seattle-Area Geologic Mapping Project database. Accuracy of boring locations and boring logs have not been verified.

Thin mass-wastage and fill deposits are not shown.

Geologic relations are based on limited data and are accordingly interpretive.

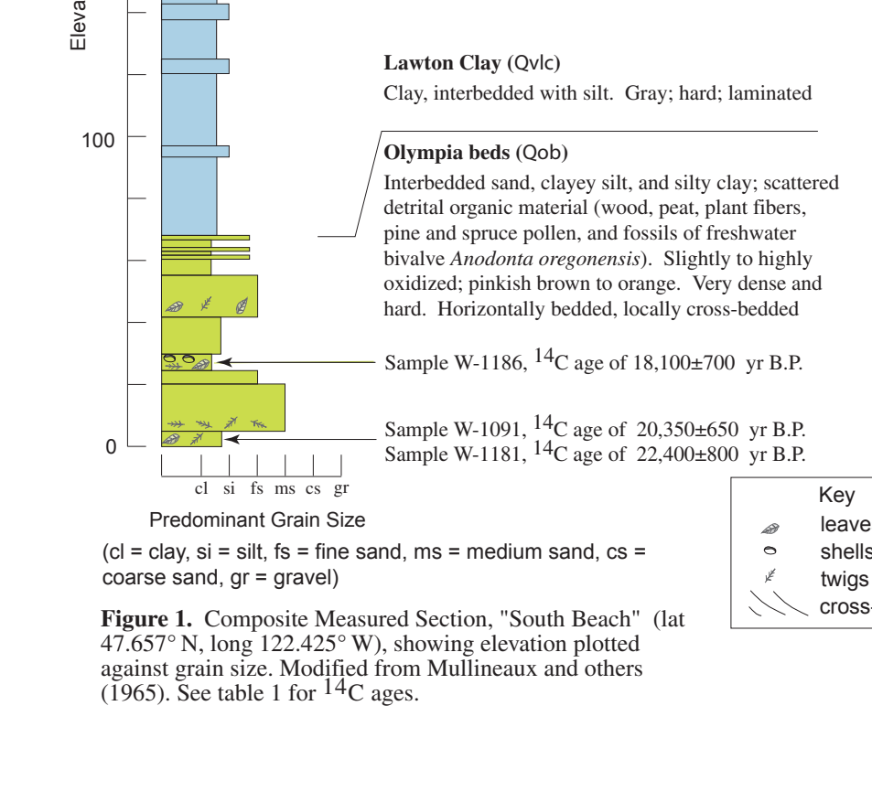
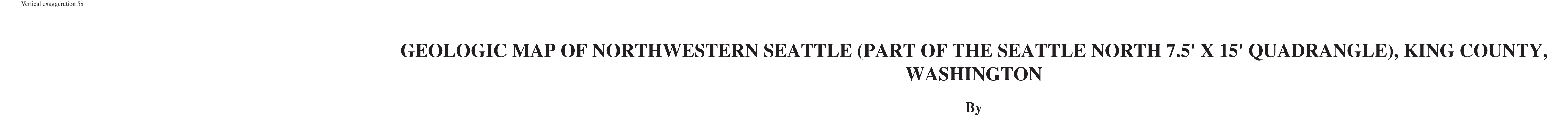


Figure 1. Composite Measured Section, "South Beach" (lat 47.657° N, long 122.425° W), showing elevation plotted against grain size. Modified from Mullineaux and others (1965). See table 1 for ^{14}C ages.



GEOLOGIC MAP OF NORTHWESTERN SEATTLE (PART OF THE SEATTLE NORTH 7.5' X 15' QUADRANGLE), KING COUNTY, WASHINGTON

By

Derek B. Booth, Kathy Goetz Troost, and Scott A. Shimel

2005

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