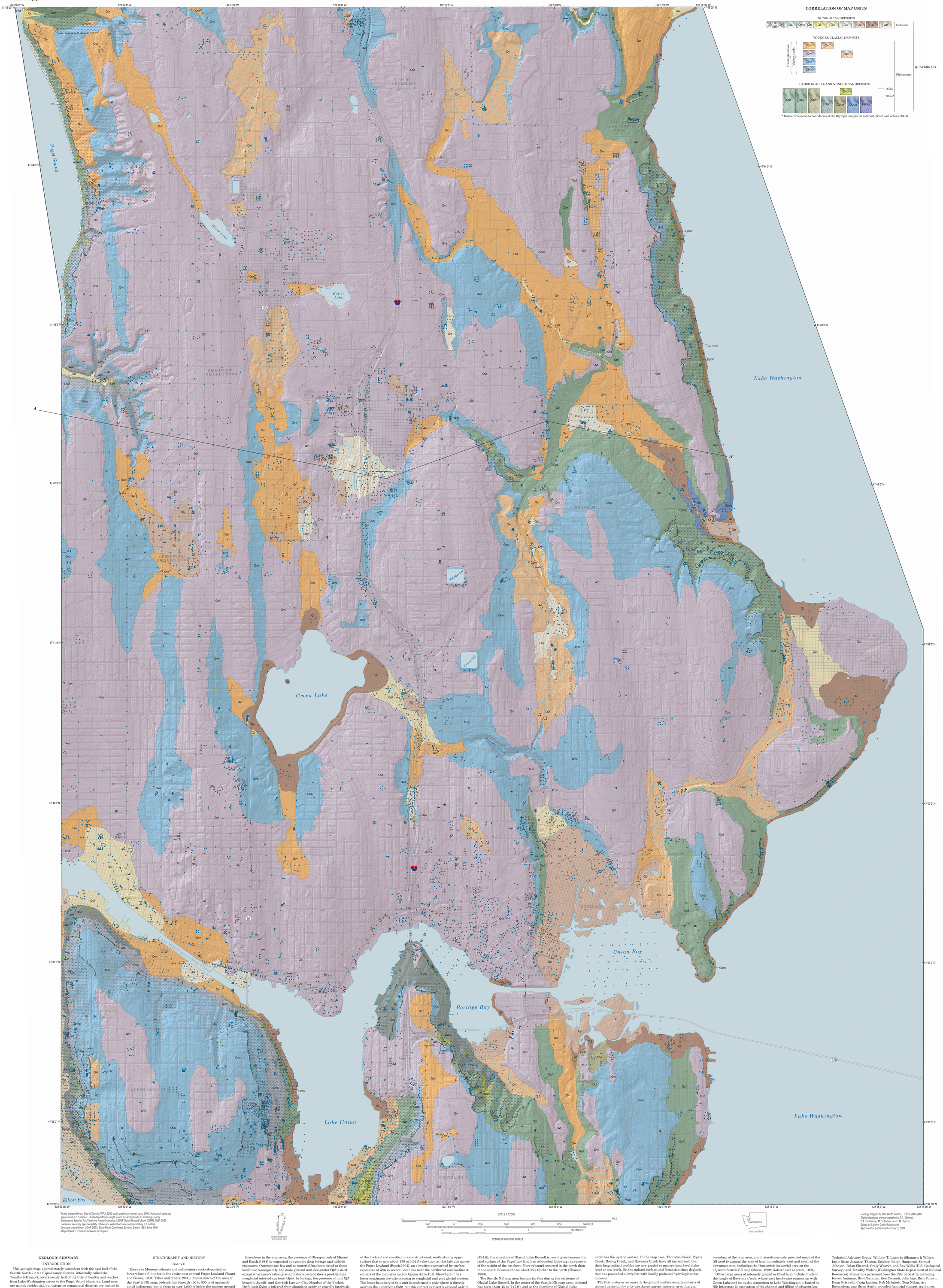
U.S. Department of The Interior
U.S. Geological Survey

Prepared in cooperation with the
City of Seattle and the Pacific Northwest Center for Geologic Mapping Studies at the Department of Earth and Space Sciences, University of Washington

Scientific Investigations Map 3065



Roads extracted from City of Seattle, WA, 1:1200-scale proprietary street data, 2001. Horizontal accuracy approximately 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 approximately 1.8 meters; vertical accuracy approximately 0.3 meters. Contours created from LiDAR DGM. State Plane Coordinate System; Datum 1983, Zone 4601
Map rotated 1.1counterclockwise for display

SCALE 1:12000

CONTOUR INTERVAL 40 FEET

APPROXIMATE MEAN DECLINATION, 2009

Geology mapped by D.B. Booth and K.G. Troost 2000-2005
Digital database and cartography by S.A. Schimel, P.A. Dinterman, M.D. Anders, and J.M. Spritzer
Edited by Carolyn Dornin Manuscript
Approved for publication February 3, 2009

MAP LOCATION

CORRELATION OF MAP UNITS

DESCRIPTION OF MAP UNITS

NONGLACIAL DEPOSITS

m — **Modified land (Holocene)**—Fill of extensively graded natural deposits that obscure or substantially alter original deposit. Labeled as **m** only on Correlation of Map Units. Locally divided into:

gr — **Graded areas**—Extensively graded areas. Some fill likely present. Includes Seattle regrades of 1876-1928 as described by Morse (1989); excludes roadways, parking lots, and landscaped areas. Labeled as **gr** only on Correlation of Map Units. 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 a direct result of human activity. Shown where borehole data provide sufficient information to delineate extent and where greater than about 3 m (9.8 ft) thick over at least tens of meters in lateral extent. 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. Shown on Correlation of Map Units; labeled (as **af**) only on cross section.

afl — **Landfill debris**—Refuse, and other types of debris materials, locally inter-mixed with concrete, bricks, coal, and wood, placed over the exposed lake bottom of Lake Washington at the Montlake landfill and in several other smaller locations across map area, mainly during first half of 20th century. Maximum depths of refuse exceed 20 m (66 ft). Labeled as **afl** only on Correlation of Map Units. Deposits are shown by overprint pattern; underlying unit is shown beneath pattern

Qb — **Beach deposits (Holocene)**—Loose sand and gravel deposited or reworked by modern wave action. Shown on map area only along Puget Sound shoreline, where it is overlain by fill. Unit is commonly present, but generally not mapped, along shoreline below 2.7 m (9 ft; City of Seattle datum). Loose to 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. Numerous unmapped areas of mass-wastage deposits occur elsewhere in quadrangle along ravines and sidewalls of Lake Washington trough. Thickness typically about 3m (9.8 ft) but locally may exceed 10 m (33 ft). On map, deposits are shown by over-print 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 (Holocene)**—Diamict of broken to internally coherent surficial deposits that have been transported downslope en masse by gravity, particularly where coarse deposits (especially unit **Qva**) overlies fine deposits (units **Qvlc** and **Qpf**). Also common within units **Qpf** and **Qpo** where coarse and fine deposits interstratify. Discriminated from other mass-wastage deposits by thickness of identifiable slide deposits, by lateral continuity, and by presence of coherent blocks of geologic materials. 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 in valley of Boeing Creek where stream emerges from confining valleys and reduced gradients cause sediment loads to be deposited. Mapped deposit grades upvalley into alluvium lacking fan morphology.

Qal — **Alluvium (Holocene)**—Sand, silt, gravel, and cobbles; deposited in stream valleys by running water. Normally consolidated

Qw — **Wetland deposits (Holocene)**—Peat and alluvium, poorly drained and intermittently wet. Identified from borings and topography, but areas shown are not complete inventory of such deposits. Loose

Qp — **Peat deposits (Holocene)**—Accumulations of wood and other plant debris forming layers that are greater than about 1 m in thickness and of mappable extent. Deposits are thickest in floors of recessional outwash channels and where lowering of Lake Washington has exposed extensive lake-floor deposits. Gradational with units **Qw** and **Ql**. Loose

Ql — **Lake deposits (Holocene)**—Silt and clay with local peat and other organic sediments, deposited in standing or slow moving water. Most mapped areas are lake bottom sediments exposed by lowering of Lake Washington in 1916. Loose to moderately

Qtf — **Tide-flat deposits (Holocene)**—Silt, sand, and organic sediment and detritus, historically exposed in along Interbay in southwest map corner and now fill-covered. Loose to moderately dense

YOUNGER GLACIAL DEPOSITS

Deposits of Vashon stade of 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 broad outwash channels that carried south-draining glacial meltwater during ice retreat away from the ice margin. Also includes deposits that accumulated in or adjacent to recessional lakes. Deposits less than about 1 m (3.2 ft) thick not shown on map; locally more than 6 m (20 ft) thick. Loose to dense. Locally divided into:

Qvrl — **Lacustrine deposits**—laminated silt and minor clay along southeast shore of Lake Union and above the Washington Park

Qvi — **Ice-contact deposits**—Deposits similar in texture to unit **Qvr** but commonly less well sorted and with silt rich matrix; locally displays hummocky topography suggestive of dead-ice terrain. Contains lenses and pods of till

Qvt — **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 is typically 1 to 10 m (3.2 to 33 ft) thick and generally very dense. 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. Silt lenses are common in lower part but are less abundant upward. Generally unoxidized to slightly oxidized. Locally grades upward into Vashon till and may include overlying areas of Vashon till too small to show at map scale. Locally over 60 m (197 ft) thick; dense to very dense. Includes Esperance Sand Member of the Vashon Drift of 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. Commonly includes widely scattered dropstones; organic material is rare to absent. Marks transition from nonglacial to earliest glacial time, although unequivocal evidence for glacial or nonglacial origin may be absent. Deposits of correlative age and texture may be included in unit **Qpf** where stratigraphic relationships are ambiguous and evidence of age and depositional environment is absent. Conversely, may include fine-grained sediment of unit **Qob** where indistinguishable from **Qvlc**. Absent to over 30 m (98 ft) thick in map area

OLDER GLACIAL AND NONGLACIAL DEPOSITS

Qpf — **Deposits of pre-Fraser glaciation age (Pleistocene)**—Interbedded silt, sand, gravel, and diamicts of indeterminate age and mostly indeterminate 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. Above coastline of Puget Sound, mainly thinly laminated gray silt with neither organics nor drop-stones overlying and interbedded with oxidized sand and sandy gravel; granular layers more common below 60' altitude. Above shoreline of Lake Washington north of Thornton Creek, oxidized sand and gravel common above 50' altitude; laminated silt present throughout but particularly in lower part of unit, with scattered plant debris and local peat beds (all of infinite radiocarbon age). On Capitol Hill, primarily laminated silt overlying finite-dated organic material of unit **Qob**. Some parts of unit as mapped are probably equivalent to dated deposits of unit **Qob** or to overlying **Qvlc** but are mapped as **Qpf** where neither age control nor lithology allow definitive discrimination. Maximum elevation of pre-Fraser deposits as high 65 m (213 ft) on Capitol Hill but more commonly about 40 m (131 ft); base of unit not exposed in map area. Landslides commonly associated with groundwater emergence within and immediately above

Qpfi — **Fine-grained deposits**—Predominantly silt and clay

Qpfn — **Nonglacial sedimentary deposits**—Sediment of inferred nonglacial origin, based on presence of peat or other organic material

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). Absent to 15 m (50 ft) thick in map area. Assigned to Olympia nonglacial interval of Mullineaux and others (1965) on the basis of stratigraphic position and correlation with three radiocarbon dates from north and west flanks of Capitol Hill (see table 1). Elsewhere, unit is distinguished from unit **Qvlc** on the basis of sand and gravel interbedded with silt and locally by presence of organic material.

Qpo — **Deposits of pre-Olympia nonglacial interval age (Pleistocene)**—Interbedded sand, gravel, silt, and diamict of indeterminate age and origin. Very dense. Locally divided into:

Qpon — **Nonglacial deposits of pre-Olympia nonglacial interval age**—Sand, silt (locally organic-rich), gravel, and peat, thinly and discontinuously interbedded. Mapped only along Lake Washington shoreline on the basis of two infinite radiocarbon dates, and may have been deposited in part early during the Olympia nonglacial interval

Qpog — **Glacial deposits of pre-Olympia nonglacial interval age**—Weakly to strongly oxidized silt, sand, gravel, and some till of glacial origin. Underlies Vashon-age deposits and thus must also be of pre-Olympia age. Glacial origin inferred from presence of till and from apparent northern provenance of clasts or mineral grains.

Qpog1 — **Glacial till**—Predominantly till or other diamict where thick enough to show at map scale. Most extensive on west slopes of Queen Anne Hill, where unit is exposed in landslide scars visible from adjacent roadways

Contact—Dashed where approximately

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

Pre-Vashon till—Mapped within unit **Qpf** above Lake Washington shoreline where exposed on valley wall

Peat bed or other organic-rich layer

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

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

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

Exploration Sites
- Field exposure
- Geotechnical boring
- Cone penetrometer test
- Cut
- Geotechnical test pit
- Density probe
- Monitoring or water well

GEOLOGIC SUMMARY

INTRODUCTION

This geologic map, approximately coincident with the east half of the Seattle North 7.5 x 15' quadrangle (herein, informally called the "Seattle NE map"), covers nearly half of the City of Seattle and reaches from Lake Washington across to the Puget Sound shoreline. Land uses are mainly residential, but extensive commercial districts are located in the Northgate neighborhood, adjacent to the University of Washington, and along the corridors of Aurora Avenue North and Lake City Way. Industrial activity is concentrated along the Lake Washington Ship Canal and around Lake Union. One small piece of land outside of the quadrangle boundaries, at the west edge of the Bellevue North quadrangle, is included on this map for geologic continuity. Conversely, a small area in the northeast corner of the Seattle North quadrangle, on the eastside of Lake Washington, is excluded from this map.

Within the boundaries of the map area are two large urban lakes, including the most heavily visited park in the State of Washington (Green Lake Park); a stream (Thornton Creek) that still hosts anadromous salmon despite having its headwaters in a golfcourse and a shopping center; parts of three cities, with a combined residential population of about 300,000 people; and the region's premier research institution, the University of Washington. The north boundary of the map is roughly NE 168th Street in the cities of Shoreline and Lake Forest Park, and the south boundary corresponds to Mercer Street in Seattle. The west boundary is 15th Avenue W (and NW), and the east boundary is formed by Lake Washington. Elevations range from sea level to a maximum of 165 m (541 ft), the latter on a broad till-covered knob in the city of Shoreline near the northwest corner of the map. Previous 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 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 ice sheet reached the central Puget Sound region about 14,500 years ago, as measured by ^{14}C dating, and it had retreated from this area by 13,650 ^{14}C yr B.P. (equivalent calendar years are about 17,600 and 16,600 years ago; 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. Inaddition, they have been deformed by faults and folds, at least as recently as 1,100 years ago, and this deformation further complicates the geologic record.

The landforms and near-surface deposits that cover much of the Seattle NE map area record a relatively brief, recent interval of the region's geologic history. The topography is dominated in the north by a broad, fluted, and south-sloping upland plateau, which gives way to a more complex set of elongated hills in the map's southern half. The valleys of Pipers Creek, Green Lake, and Thornton Creek mark the transition between these two topographic areas. Most of the uplands are mantled by a rolling surface of sand (unit **Qva**) and till (unit **Qvt**) 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 locally exposed where modern erosion and landslides have sliced through the edge of the upland, and where subglacial processes apparently left these older sediments largely free of overlying sediments. Lack of overlying sediments is particularly evident on the hillslopes above Thornton Creek, adjacent to Lake Washington, and on the flanks of Capitol Hill.

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). Across much of the area of the Seattle NE map, bedrock lies beneath 400 to 500 m of unconsolidated sediments, but it drops to over 1,000 m below the modern ground surface in the southern part of the map area (Jones, 1996). The closest outcropping bedrock lies about 8 km (5 mi) to the southwest on Alki Point in the Seattle Southwest map area (Troost and others, 2006).

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, it 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 can resemble its neighbors but infact may be many tens of thousands of years different in age, differentiating them requires laboratory analyses and age determinations (Troost, 1999).

Different depositional environments yielded distinctly different deposits. The following deposits from both the most recent and prior glacial advances are commonly recognized across the Puget Lowland: (1) proglacial lacustrine silt and clay 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 with dropstones) deposited as marine water inundated the isostatically depressed land and floated distal parts of the Puget lobe. All aforementioned deposits, except glaciomarine drift, have been observed in the Seattle NE map area. Nonglacial deposits in the map area include peat and a variety of lake, river, and beach deposits; human-emplaced fill is also common in this urban environment.

Deposits and Landforms Predating the Vashon Stade of the Fraser Glaciation

Nearly all stratigraphic units predating the Vashon stade of the Fraser glaciation are identified on the map as either pre-Fraser deposits (unit **Qpf**) or (more specifically, where possible to differentiate) pre-Olympia deposits (unit **Qpo**). With one exception (Olympia beds of Minard and Booth (1988), unit **Qob**), we have not subdivided pre-Fraser deposits into named units because absolute age control is sparse and therefore the risk of spurious correlation is high. The Olympia nonglacial interval was originally defined 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 70,000 and 15,000 yr B.P. (Troost, 1999); this interval closely approximates the temporal limits for oxygen isotope stage 3 (Winograd and others,1997) and immediately predates the Fraser glaciation (stage 2). Deposits of unequivocal Olympia nonglacial interval age are identified at only two locations in the map area. One is along the northeast face of Capitol Hill overlooking Portage Bay, on the basis of a radiocarbon date obtained from an immediately adjacent borehole drilled for a light-rail transit tunnel (20,500 ± 220 yr B.P.; Beta-119399, table 1); the other is about 1.5 km to the southwest and is based on two radiocarbon dates of about 15,000 yr B.P. (W-1227 and W-1305; table 1).

Elsewhere in the map area, the presence of Olympia beds of Minard and Booth (1988) is suggested by sporadic deep borings and hillside exposures. Outcrops are few and no material has been dated at these localities; consequently, the more general unit designator **Qpf** is used except where pre-Vashon glacial material establishes a pre-Olympia nonglacial interval age (unit **Qpo**). 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 abundant sandy or gravelly interbeds. Although the upper contact of unit **Qpf** in this stratigraphic setting is generally not well exposed at the ground surface because of overlying landslide debris andfor fill, we have constrained its mapped position by determining its elevation in nearby bore holes and projecting it out to the ground surface at constant elevation. Along the Puget Sound coastline on both this and the adjacent Seattle NW map, the maximum elevation of this contact is typically below about 30 m (98 ft) and rises to as high as 50 m (164 ft) only near the north map boundary. On the eastside of the map area along Lake Washington, maximum elevations are modestly higher (75 m [246 ft]), but south of the Lake Washington Ship Canal and just east of Lake Union this contact rises to as much as 105 m (344 ft); this higher elevation reflects a prominent hill in the pre-Vashon-age topography underlain primarily by thick pre-Fraser (and pre-Olympia-age) deposits with a fairly steep north-facing slope.

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 14,500 ^{14}C yr B.P. and retreated back past this area by 13,650 ^{14}C yr B.P.; at maximum ice advance, Seattle was buried by at least 900 m (2,952 ft) of ice (Booth, 1987). The modern landscape is largely the result of deposition and scouring by the Vashon stade glacier, and it has been only slightly modified by more recent activity of stream and wave erosion, 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. Silt and clay were deposited in the impounded lake that subsequently formed. This material has been mapped as Lawton Clay (unit **Qvlc**), of which coastal bluff exposures immediately west of the map area constitute the type section (Mullineaux and others, 1965; Booth and others, 2004). In this map area, we have assigned deposits of silt and rare clay to unit **Qvlc** on the basis of proximity to the type section, stratigraphic position, and the presence of dropstones. Other fine-grained deposits throughout the map area are more conservatively assigned to unit **Qpf**, although some of these probably also correlate with unit **Qvlc**. In particular, fine-grained sediment revealed in boreholes to be overlying unit **Qob** on Capitol Hill is mapped as **Qpf** because data are insufficient to determine if they belong to **Qvlc** or to a fine-grained facies of **Qob**.

Coarser outwash (unit **Qva**) marks direct, active ice sheet deposition by streams flowing from the advancing glacier. The broad uplands of the central part of the map area are underlain by at least a few tens of meters of sandy advance outwash, exposed wherever overlying till and recessional outwash are absent or incised by postglacial erosion. The maximum thickness of **Qva** is determined by both modern and pre-Vashon-age topography; in the northwest corner of the map area, it is about 60 m (197 ft) thick; in the south west corner on Queen Anne Hill, it is over 90 m (295 ft) thick; and on Capitol Hill, it is absent altogether. The outwash inundated the pre-Vashon-age topography of the lowland and resulted in a constructional, south-sloping upper surface that is now about 150 m (492 ft) elevation at this latitude across the Puget Lowland (Booth,1994), an elevation approached by surface exposures of **Qva** in several localities near the northwest and southeast corners of the map area and on Queen Anne Hill. Elsewhere it has lower maximum elevations owing to synglacial and post glacial erosion. The lower boundary of this unit is conformable only where it directly overlies the underlying **Qvlc**, but this contact is directly exposed only in the northwest map area,where the two units show some degree of interfingering of sandy and silty beds over a scale of 1–10 m. The elevation of this contact, as inferred from boring logs and where projected out to the modern ground surface, shows no systematic differences over the map area as a whole and varies between about 45 and 90 m (147 – 295 ft).

As ice covered the region, till (unit **Qvt**) was deposited by the melt-out of debris at the base of the glacier. Throughout the map area, the ground surface where underlain by either advance outwash or till is pervasively fluted and is characterized by elongated hills uniformly oriented north-south (azimuth approximately 170°). The hills are interrupted by the cross cutting valleys of Thornton Creek and Ravenna Creek, and by the broad depression of Green Lake. Glacial fluting is not limited to till-covered areas; this observation suggests that many of the surfaces underlain by advance outwash (unit **Qva**) or older units represent regions where till was never deposited, or where it was deposited and removed while still ice-covered. Till is very common, however, and it blankets almost 60 percent of the land surface of the map area and provides a low-permeability cover to underlying aquifers. This cover not only reduces infiltration and groundwater recharge but also offers protection from surface contaminants. Till thicknesses average about 3 m (9.8 ft) across the map area, with somewhat thicker accumulations in the lee of the major flutes of Queen Anne Hill and the University District that commonly show greater stratification and less induration than till elsewhere in the map area.

The matrix of the till differs from place to place in relative abundance of silt, sand, and sparse clay. The till mostly is gravelly silty sand to gravelly sandy silt, and in many places it is crudely stratified with lenses of sand, gravel, and silt. Cobbles and boulders are scattered throughout the till; boulders more than 3 m (9.8 ft) in diameter are rare. Unoxidized till is light gray and dense to very dense; where weathered, till is light yellowish gray and is generally medium dense. Although a weak brown soil is developed on the till, oxidation rarely extends more than about a meter into the deposit.

Although typical Vashon-age till has low permeability, common structural or stratigraphic discontinuities locally increase its permeability by several orders of magnitude; these increases allow faster transmission of water and contaminants. Depending on subglacial conditions at the time the till was formed and post-depositional strain, hydrologically important discontinuities locally consist of intercalated sand layers, bedding planes, and joints.

Shortly after 14,500 years ago (as measured by radiocarbon dating), the ice margin, which extended more than 50 km south of the map area, began to melt back. Meltwater from the ice sheet and runoff from the Cascade Range drained southward and westward, spilling over divides that were later abandoned as the retreating front of the ice exposed lower divides farther north. By the time that the Seattle NE map area was uncovered by the retreating ice, proglacial drainage was well established across most of the eastern and southern Puget Lowland. Water inundated much of the central and southern lowland, including the map area, because more than one thousand meters of glacial ice still blocked drainage through the Strait of Juande Fuca. The first of the two main recessional lakes occupying the lowland (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 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 (Thorson, 1980).

The Seattle NE map area became ice-free during the existence of Glacial Lake Russell. In the center of the Seattle NE map area, rebound has been about 45 m (147 ft), and so the shoreline of Glacial Lake Russell can be found today at nearly 90 m (295 ft) elevation. Most of the map area, particularly north and northeast of the trough formed by the valleys of Pipers Creek, Green Lake, and Ravenna Creek, lies above this elevation. Outwash channels are prominent at about this altitude, notably the valley occupied by Aurora Avenue North near Northgate and the valley of the northwest branch of Thornton Creek just east of Interstate 5. Lake-bottom topography dating from this interval is suggested by extensive modern peat deposits filling a topographic hollow at an elevation of 78 m (256 ft); this topographic hollow forms the headwaters of the west branch of Thornton Creek. Ice-contact deposits, likely marking an active or stagnant ice front during this recessional interval, lie at the head of these channels at elevations of 105 to 120 m (344 – 394 ft). A third large ice-contact deposit fills a northwest-draining channel near the head of Boeing Creek, in the northwest corner of the map.

The second recessional waterbody, Glacial Lake Bretz, was formed when ice retreated far enough north to uncover a low spillway on the northeast corner of the Olympic Peninsula, about 35 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 NE map area, the calculated elevation of the lake surface ranges from about 37 m (south) to 47 m (north) (approximately 120 – 150 ft). Glacial Lake Bretz likely did not persist for more than a few decades because rapid rates of glacier retreat (Porter and Swanson, 1998) soon opened Puget Sound via the Strait of Juande Fuca, and so thick lake deposits are not likely. Several prominent channels were formed during this lake stage, including a broad trough between Pipers Creek and Green Lake, now infilled with extensive Holocene peat deposits underlying part of the Greenwood neighborhood, and an extensive ice-contact deposit south of NE 95th Street along the valley followed by 25th Avenue NE, which possibly reflects the collapse of a floating ice shelf in Glacial Lake Russell upon the initial formation of Glacial Lake Bretz. A spectacular 8 m glacial-erratic boulder marks the eastern edge of this deposit at an elevation of 89 m (292 ft), at the intersection of NE 72nd Street and 28th Avenue NE. Although thick lake deposits associated with Glacial Lake Bretz are not generally observed, a lacustrine deposit at the south edge of the map area, at the head of a younger outwash channel in the Washington Park Arboretum, almost certainly dates from this time.

Further retreat of the ice sheet reconnected Puget Sound to the open ocean and allowed regional water levels to fall by an additional 40 m (about 130 ft; Thorson, 1989). Thus, the late-glacial marine limit falls near the southedge of the Seattle NE map; 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. Recessional deposits in the map area dating from this interval are probably those mapped at low elevations along the Lake Washington Ship Canal that formed the valley of the Washington Park Arboretum near the southeast corner of the map.

Postglacial Processes and Deposits

Geologic activity since glaciation includes soil formation, wide spread mass failure and cliff retreat, stream channel erosion, and tectonic deformation. As a result of the lowered base level occasioned by drainage of Glacial Lake Bretz, several streams in the map area began to incise through the sequence of glacial and nonglacial deposits that underlies the upland surface. In the map area, Thornton Creek, Pipers Creek, Boeing Creek, and Ravenna Creek have all incised such that their longitudinal profiles are now graded to modern base level (lake level or sea level). On the upland surface, soil formation since deglaciation has proceeded slowly but with locally profound hydrologic consequences.

The first meter or so beneath the ground surface usually consists of top soil underlain by silty weathered parent material or colluvium. Where Vashon-age till (unit **Qvt**) is present, the unweathered 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 more than half of the upland plateau, but its compaction or removal during typical urban development has had dramatic hydrologic effects, particularly increased urban flooding. Several recent projects by the City of Seattle, in the Broadview neighborhood on the till-mantled uplands just east of the valley of Pipers Creek, are seeking to reduce stormwater runoff by amending the remnant soil with compost to increase its water retention capacity.

On areas underlain by Vashon-age advance outwash deposits (unit **Qva**), however, water infiltrates through both the soil and the parent material relatively quickly. It generally continues moving downward until it reaches the top of an underlying fine-grained unit, either the Lawton Clay Member of the Vashon Drift (unit **Qvlc**) or older deposits of pre-Fraser glaciation age (unit **Qpf**). The ground water is then diverted laterally to steep slopes along the coast or in deep ravines, where it emerges as springs. Such slopes, where fine-grained deposits underlie coarse-grained deposits, are particularly susceptible to landslide failure (Tubbs, 1974). This propensity for mass-wasting 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 a silty sand and gravel.

Several zones of landsliding in the Seattle NE map area are quite extensive. The largest of these slide zones follow the Puget Sound coastline north to the edge of the map area and beyond, ring most of Queen Anne Hill, flank the north end of Capitol Hill, and border nearly 3 km of Lake Washington shoreline. Because the slide scarps are relatively steep they have not generally been the site of extensive development, but structures at the base of these areas, particularly along Lake Washington and the east slope of Queen Anne Hill, have suffered from falling debris during wet winters throughout the last century. Mapped slide localities along the Puget Sound coastline from the winter of 1996 – 1997 (Baum and others, 2000) and point localities of all slides on file with the city through 1999 (Shannon and Wilson, Inc., 2000) are included on this map for reference.

Human Modification of the Landscape

To varying degrees, nearly the entire map area has been modified by human activity — either by the addition of fill, by extensive grading, or by the reconstruction of the Lake Washington drainage outlet. Although minor regrading of the land surface is common in almost any urban area, changes to the gross topography of Seattle during the early 20th century were dramatic in their scope. In the area southeast of Queen Anne Hill, "Denny Hill" formerly occupied the land between Lake Union and Elliott Bay (mainly on the adjoining Seattle SE map) and separated the downtown shorelands from the rest of the city to the northeast. Over 4 million cubic meters of sediment were sluiced by hydraulic jets and electric shovels between 1903 and 1928; the sluicing process opened a broad corridor of gently sloping land along the south boundary of the map area, and it simultaneously provided much of the fill used to expand the area of land immediately west and south of the downtown core, including the Duwamish industrial area on the adjacent Seattle SE map (Morse, 1989; Galster and Laprade, 1991).

Other large areas of intensely graded or filled land include much of the length of Ravenna Creek, whose past headwater connection with Green Lake and its outlet connection to Lake Washington is buried by fill; Interstate 5; excavation of the channel and filling of adjacent low areas in the alluvial valley bottom of Salmon Creek (now the Lake Washington Ship Canal west of Lake Union); and the graded corridor of State Highway 99 (Aurora Avenue North) through the landslide complex of east Queen Anne Hill. Delineation of mapped fills is not entirely consistent across the map area, however, because not all such deposits have been identified by subsurface explorations, and because relatively small areas of modified land associated with individual building sites are generally excluded from the mapping. The mapped distribution of the overprint units m, gr, and af, therefore, is intended to show the approximate extent of large-scale human modification and is neither definitive nor complete.

Between 1911 and 1916, Lake Washington was lowered by 3 m (9.8 ft) following the dredging of the now submerged valley of "Salmon Creek," west of Lake Union, and excavation of the Montlake Cutacross a once continuous rib of till extending from the University District south to the north-east flank of Capitol Hill (Chrzastowski, 1983). The lake lowering caused by this grading exposed extensive peat and lake-bottom deposits that have since been largely filled and covered with shoreline development. The largest of the Seattle metropolitan garbage landfills, the one at Montlake in the University District, filled about 200 acres of marsh-land near the mouth of Ravenna Creek between 1926 and 1966 (Seattle-King County, 1984); it is now host to a naturalized wetland area and university athletic fields. Other landfills in the map area include four areas around Green Lake, a site just west of Haller Lake, and a partly filled ravine at the south end of the Washington Park Arboretum.

Regional Structure and Recent Seismicity

The entire Seattle NE map area lies within the "Seattle basin," the deepest of the structural blocks formed in western Washington in Tertiary time as a result of north-south shortening in Oregon and Washington (Pratt and others, 1997; Wells and others, 1998). The east-west-trending Seattle Fault Zone forms the border between the Seattle basin (north) and the Seattle uplift (south) and lies 8-10 km south of the southern boundary of this map area (Troost and others, 2006). During a great earthquake 1,100 years ago, land of the adjacent Seattle NW map area dropped by as much as 1 m (3 ft) relative to sea level, as displayed by sub-sea level deposits exposed by construction excavations at a regional waste water treatment plant (Atwater and Moore, 1992).

Map Summary and Acknowledgements

This map is the second of four geologic maps prepared for the City of Seattle; these maps were developed and plotted at larger scale and greater level of detail than was previously possible. 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 (http://geomapnw.ess.washington.edu), topographic and geomorphic analyses, and the preexisting geologic map of the Seattle area (Waldron and others, 1962). Across most of the area, the locations of geologic contacts and the lithologic descriptions have changed from the previous map as a result of the dramatic increase in data from construction related exposures and the improved understanding of the regional stratigraphic framework of the Puget Lowland.

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 (U.S. Geological Survey); and Timothy Walsh (Washington State Department of Natural Resources). Numerous personnel from the City of Seattle, including Kaveh Aminian, Bob Chandler, Ken Conradi, John Ege, Rich Folsom, Dean Griswold, Craig Ladiser, Rob McIntosh, Tom Nolan, Art Richardson, and Brian Smith provided financial support, guidance, and data for the subsurface data compilation; financial support was provided impart by the City of Seattle. Michael O'Neal (University of Washington) provided ArcView and cross section tools. 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 Rebfuss. The map has greatly benefited from detailed revi