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Geology of Seattle and the Seattle area, Washington

Kathy Goetz Troost*
Pacific Northwest Center for Geologic Mapping Studies, University of Washington, Box 351310, Seattle, Washington 98195-1310, USA

Derek B. Booth*
Stillwater Sciences, 1314 NE 43rd Street, Suite 210, Seattle, Washington 98105, USA, and *University of Washington, Box 351310, Seattle, Washington 98195-1310, USA*

ABSTRACT

The city of Seattle, Washington State, lies within the Puget Sound Lowland, an elongate structural and topographic basin between the Cascade Range and Olympic Mountains. The area has been impacted by repeated glaciation in the past 2.4 m.y. and crustal deformation related to the Cascadia subduction zone. The present landscape largely results from those repeated cycles of glacial scouring and deposition and tectonic activity, subsequently modified by landsliding, stream erosion and deposition, and human activity. The last glacier to override the area, the Vashon-age glacier of the Fraser glaciation, reached the Seattle area ca. 14,500 ^{14}C yr B.P. (17,400 cal yr B.P.) and had retreated from the area by ca. 13,650 ^{14}C yr B.P. (16,400 cal yr B.P.).

The Seattle area sits atop a complex and incomplete succession of glacial and nonglacial deposits that extends below sea level and overlies an irregular bedrock surface. These subsurface materials show spatial lithologic variability, are truncated by many unconformities, and are deformed by gentle folds and faults. Sediments that predate the last glacial–interglacial cycle are exposed where erosion has sliced into the upland, notably along the shorelines of Puget Sound and Lake Washington, along the Duwamish River valley, and along Holocene streams.

The city of Seattle straddles the Seattle uplift, the Seattle fault zone, and the Seattle basin, three major bedrock structures that reflect north-south crustal shortening in the Puget Lowland. Tertiary bedrock is exposed in isolated locations in south Seattle on the Seattle uplift, and then it drops to 550 m below ground under the north half of the city in the Seattle basin. The 6-km-wide Seattle fault zone runs west to east across the south part of the city. A young strand of the Seattle fault last moved ~1100 yr ago. Seattle has also been shaken by subduction-zone earthquakes on the Cascadia subduction zone and deep earthquakes within the subducting plate. Certain postglacial deposits in Seattle are prone to liquefaction from earthquakes of sufficient size and duration.

The landforms and near-surface deposits that cover much of the Seattle area record a brief period in the geologic history of the region. Upland till plains in many areas are cut by recessional meltwater channels and modern river channels. Till plains display

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*E-mails: Troost: ktroost@u.washington.edu; Booth: dbooth@u.washington.edu.

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north-south drumlins with long axes oriented in the ice-flow direction. Glacially overridden deposits underlie the drumlins and most of the uplands, whereas loosely consolidated postglacial deposits fill deep valleys and recessional meltwater channels. Ice-contact deposits are found in isolated locations across the uplands and along the margins of the uplands, and outwash deposits line upland recessional channels. Soft organic-rich deposits fill former lakes and bogs.

A preliminary geologic map of Seattle was published in 1962 that is only now being replaced by a detailed geologic map. The new map utilizes a data set of 35,000 geotechnical boreholes, geomorphic analyses of light detection and ranging (LIDAR), new field mapping, excavation observations, geochronology, and integration with other geologic and geophysical information. Findings of the new mapping and recent research include recognition of Possession- and Whidbey-age deposits in Seattle, recognition that ~50% of the large drumlins are cored with pre-Vashon deposits and 50% with Vashon deposits, and that numerous unconformities are present in the subsurface. Paleotopographic surfaces display 500 m (1600 feet) of relief. The surficial deposits of Seattle can be grouped into the following categories to exemplify the distribution of geologic materials across the city: postglacial deposits 16%, late glacial deposits 12%, Vashon glacial deposits 60%, pre-Vashon deposits 9%, and bedrock 3%. Of these, 49% are considered fine-grained deposits, 19% are considered intermediate or interbedded deposits, and 32% are considered coarse-grained deposits. These percentages include only the primary geologic units and not the overlying fill and colluvial deposits.

Keywords: Seattle, Washington, Puget Lowland, surficial geology, quaternary geology, geologic map.

INTRODUCTION

The city of Seattle is the largest economic and population center of the Pacific Northwest, hosting ~578,000 residents (2006 estimate). More than 3.5 million people, over half of the population of the state of Washington, live in the surrounding region (http://www.seattle.gov/oir/datasheet/). The city covers 367 km^2, 31% of which is covered by water bodies within the city limits; it ranges in altitude from sea level to 156 m (520 ft) at the highest point, in West Seattle.

Seattle's maritime climate features dry summers and wet winters, although the average number of days with rain during the summer is 7.5 d/mo in June through September. Long-duration, low-to-moderate intensity storms occur frequently from November through April, and annual average precipitation is ~0.9 m. Rainfall intensities are quite low; the 100 yr 1 h rainfall intensity, for example, is less than 25 mm/h, a rate that is exceeded by the 2 yr 1 h rate across more than half of the rest of the United States (U.S. Department of Commerce, 1963). As a counterpoint, the wettest month on record occurred in November 2006, wherein 39.7 cm (15.63 in.) of rain fell in Seattle, with 8.4 cm (3.29 in.) falling on one day; the average rainfall for November is 15 cm (5.9 in).

Glacial Geomorphic Setting

The city of Seattle lies in the center of an elongate structural and topographic basin between the Cascade Range and Olympic Mountains known as the Puget Lowland (Fig. 1). Marine waterways occupy the center of the basin, the main trough of which is Puget Sound. The city occupies land adjacent to Puget Sound and is bounded on the east by another trough, which is occupied by Lake Washington (Fig. 2). The south half of the city is divided by a third trough, the Duwamish valley, which is now filled with alluvial sediment (Fig. 3). The troughs are part of a series of subglacial troughs described by Booth (1994).

The landscape of today was molded by glacial and glaciofluvial scouring and deposition, tectonic folding and faulting, inundation by volcanic mudflow deposits, modern processes such as landsliding and stream erosion, and extensive human modification. Coalescing glaciers advanced southward into the Seattle area from British Columbia repeatedly during the Quaternary period, which represents the past 2.4 m.y. Fluted upland plateaus of till and sand dominate the landscape, interspersed with cross-cutting valleys, deep north-south troughs, and numerous lakes and depressions (Fig. 3). The last ice sheet reached the Seattle region ca. 14,500 ^{14}C yr B.P. and retreated from the area by 13,650 ^{14}C yr B.P. (equivalent to 17,400 cal yr B.P. and 16,400 cal yr B.P.; Porter and Swanson, 1998). The Seattle area sits atop a complex and incomplete succession of interleaved glacial and nonglacial deposits that overlie an irregular bedrock surface.

Tertiary marine and volcaniclastic bedrock is exposed in the southeast part of Seattle and in isolated outcrops at the western tip of West Seattle. Just south of the city

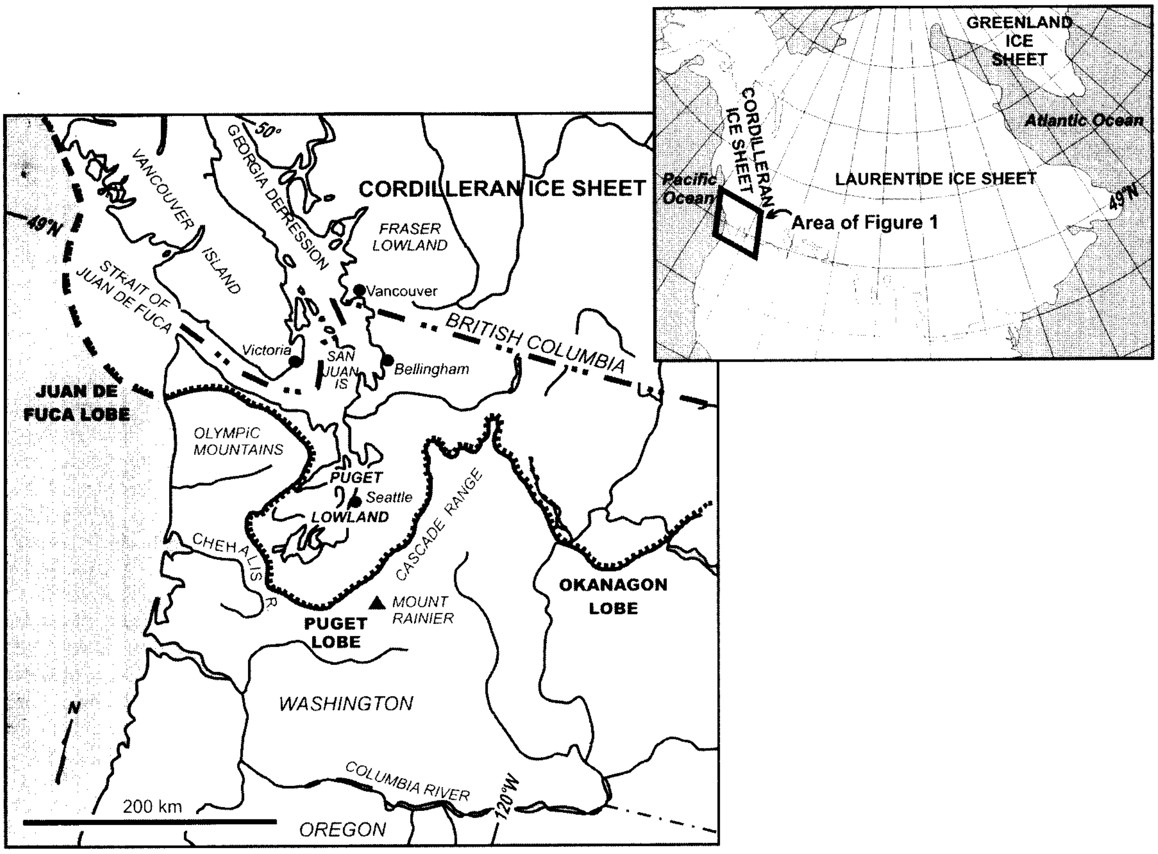

Figure 1. Location of Seattle, Puget Lowland, and most recent ice limit (shown by hachure marks) in Washington State (modified from Booth et al., 2004b).

limits, intrusive rock extends through the alluvium of the Duwamish valley. The surface of the bedrock has been molded into a series of basins and uplifts by faulting and folding with 1.1 km (3600 ft) of relief (Jones, 1996).

Tectonic Setting

The Puget Lowland lies within a forearc basin, which has undergone north-south shortening since late Cenozoic time (Wells et al., 1998). The crustal shortening has produced east-west-trending folds and faults, several bedrock-cored uplifts and basins (Blakely et al., 2002), and Holocene seismicity and surface faulting (Bucknam et al., 1992; Johnson et al., 1999; Blakely et al., 2002; Nelson et al., 2003; Sherrod et al., 2004; Kelsey et al., 2004). Seattle spans part of two of these structures: the Seattle uplift, which extends south from the south-of-downtown area (SODO) for ~30 km into the Tacoma area; and the Seattle basin, which extends north from the SODO area 25 km to the northern city limit (Fig. 4). Dividing these two features is the Seattle fault zone, mapped from Hood Canal east across most of the Puget Lowland. Although discontinuous fault scarps less than 2 km long show movement on the Seattle fault 1100 yr ago (Bucknam et al., 1992), most displacements and truncations of strata seen in outcrops in the Seattle area result from Holocene landsliding, unconformities, or glacial deformation rather than fault movement (Booth et al., 2004a).

Previous Work

Several publications provide excellent information about the geology of the Seattle area. Stark and Mullineaux (1950) wrote about the glacial geology of the city of Seattle as part of a master's thesis. Galster and Laprade (1991) give a thorough description of the engineering and social geologic aspects of the area and provide ample photographs of geologic materials and engineered works. Theirs is the first descriptive manuscript focused on all aspects of the geology of Seattle. Waldron et al. (1962) produced a preliminary geologic map of the Seattle area at a scale of 1:31,680 that persisted until 2005, when it was finally superseded by a more current geologic map of Seattle produced by Troost et al. (2005). Waldron (1967) also produced a final geologic map of the Duwamish Head quadrangle at a scale of 1:24,000. Each of the four U.S. Geological Survey quadrangles that cover the city will be published at scales of 1:12,000, for example, the Seattle Northwest quadrant (Booth et al.,

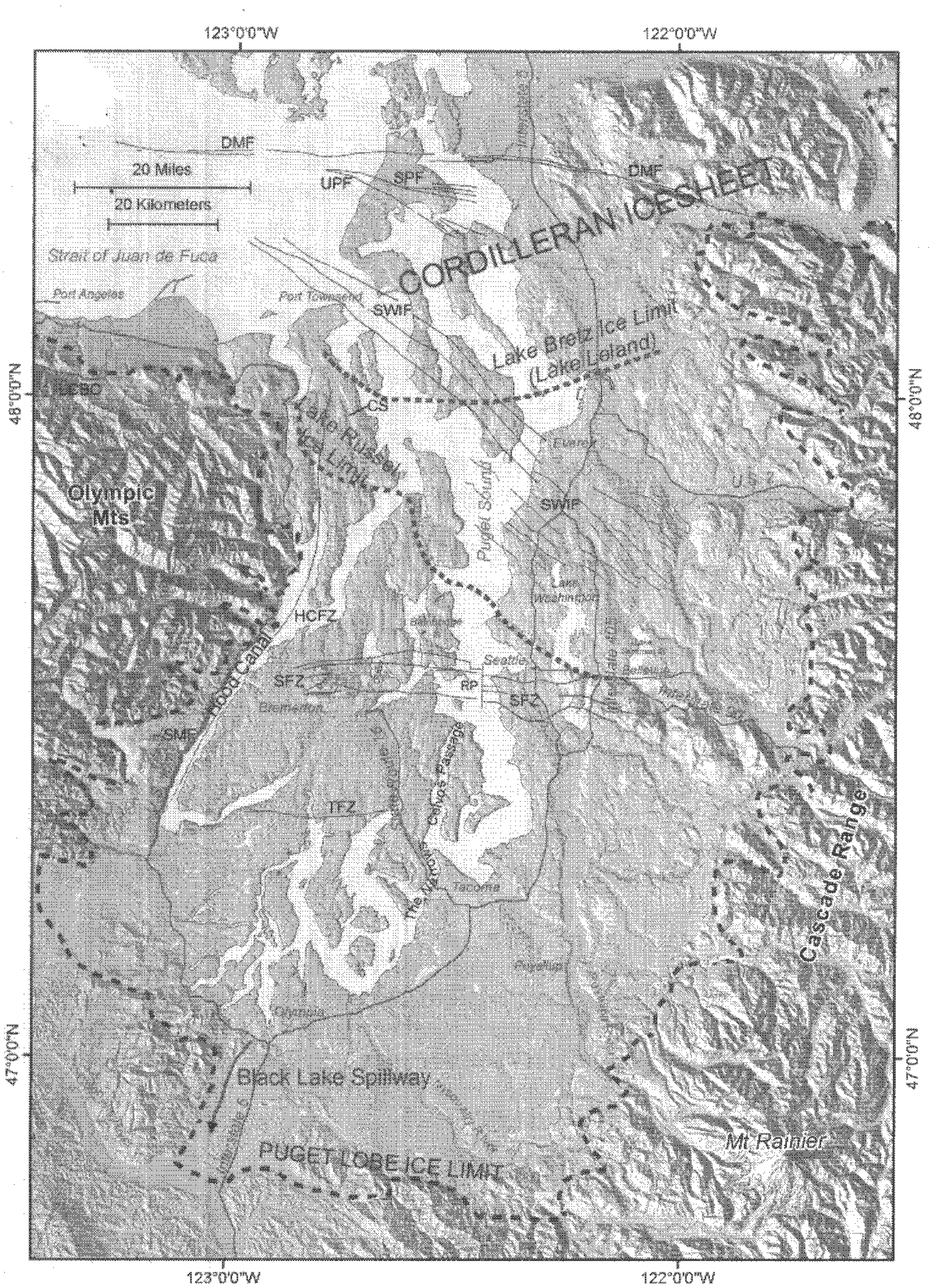

Figure 2. Map showing location of Seattle in the Puget Lowland relative to the area covered by the last ice sheet, Vashon stade of the Puget Lobe, proximity to Mount Rainier, and positions of ice margins during formation of two major recessional lakes. Major active faults shown are from the U.S. Geological Survey Quaternary fault database except for the cluster of faults and lineaments shown for the Southern Whidbey Island fault zone between Lake Washington and Everett (Sherrod et al., 2005a, 2005b, 2008). CS—Chimacum spillway, DMF—Devils Mountain fault zone, HCFZ—Hood Canal fault zone, LCBC—Lake Creek–Boundary Creek fault, RP—Restoration Point, SFZ—Seattle fault zone, SMF—Saddle Mountain fault, SPF—Strawberry Point fault, SWIF—Southern Whidbey Island fault zone, TFZ—Tacoma fault zone, UPF—Utsalady Point fault.

2005). Other geologic maps include the city of Seattle but are at much smaller scales (Yount and Gower, 1991; Yount et al., 1985, 1993).

Development of the Quaternary Framework

Given the predominance of Quaternary deposits, extent of landscape development during the Quaternary period, and influence of the Quaternary period on the geology of Seattle, discussion of the framework is warranted. In the Seattle area, the Quaternary period includes at least seven advances of continental glaciers, multiple incursions of lahars, and tectonic deformation. These events have left a myriad of unconformities, multiple paleotopographic surfaces, extensive channels and channel fills, a variety of lithologies with abundant horizontal and vertical facies changes, and multiple discontinuities. Recognition of unconformities and glacial versus interglacial deposits is

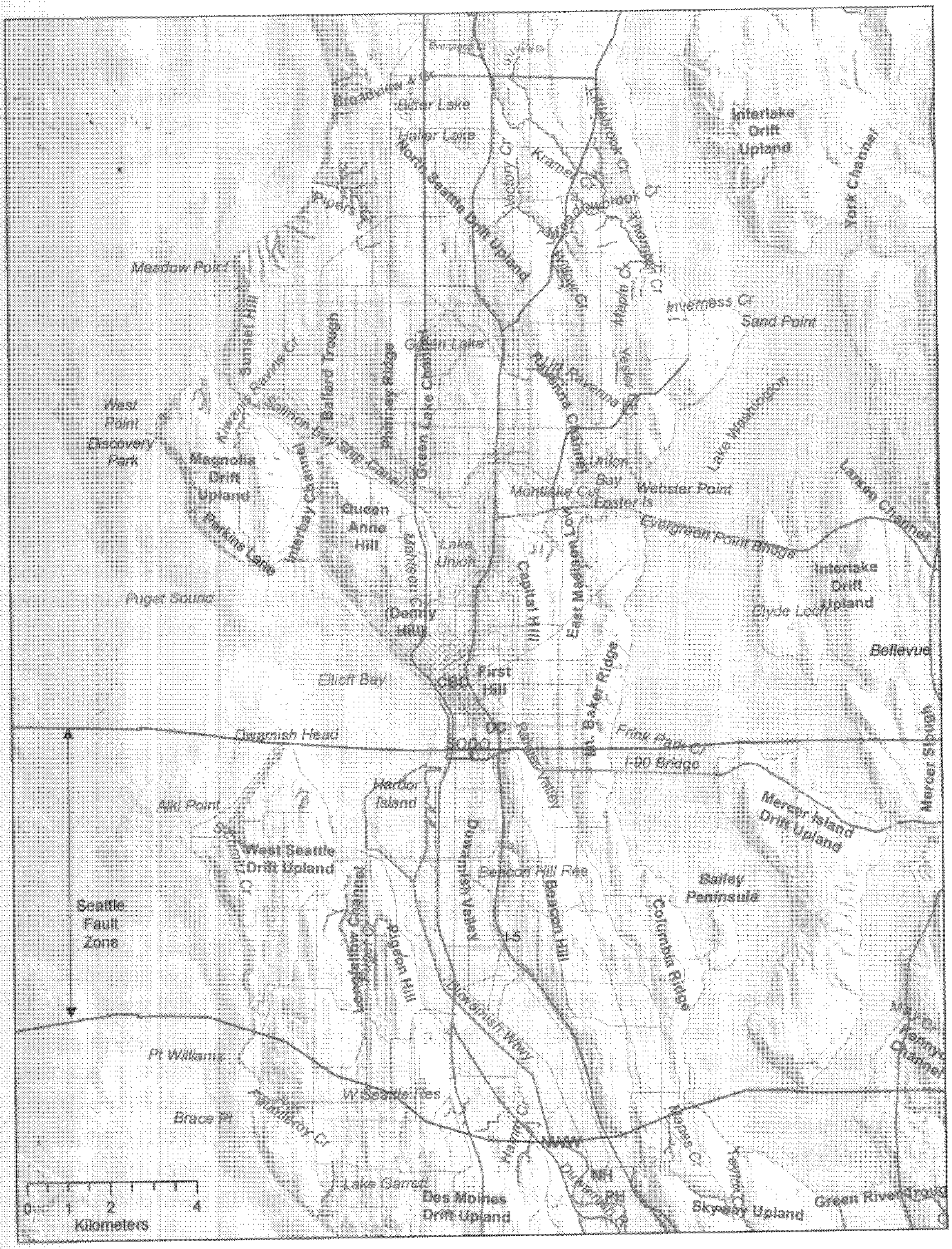

Figure 3. Physiographic map of the Seattle area showing major uplands, hills, and valleys in green typeface (features modified from Galster and Laprade, 1991). Lakes, streams, waterways, marine waters, and reservoirs are shown in blue. CBD—central business district, DC—Dearborn cut, NH—North Hill, NWW—North Wind Weir, PH—Poverty Hill, SODO—south of downtown area. Denny Hill was removed around 1910 to improve transportation in the downtown area. Outline of Seattle fault zone is shown.

important for reconstructing the geologic record, correlating across sites, and trying to project/predict distribution of geologic units.

The modern landscape is an analog for the paleotopography and geomorphic processes active during previous interglacial periods in the Puget Lowland because of demonstrably similar topographic relief prior to the last glaciation (Troost, 2006). Most of the glacial advances into the Puget Lowland probably had equivalent characteristics with respect to thermal regime, amount and distribution of subglacial water, and degree of scouring, which would result in topographic relief similar to present day. Likewise, depositional patterns from the last glaciation provide an analog for previous glaciations, and modern depositional patterns can serve as an analog for previous interglacial periods.

With each glaciation, a new set of unconformities was generated: angular unconformities from deposition against trough walls and on slopes, and disconformities from deposition on weathered surfaces. Glaciers carved deep troughs, like in the modern landscape, but not necessarily in the same places as during previous interglacial periods (Booth, 1994; Booth et al., 2004b). About 50% of modern hills are cored by older hills and 50% are composed of deposits from the last

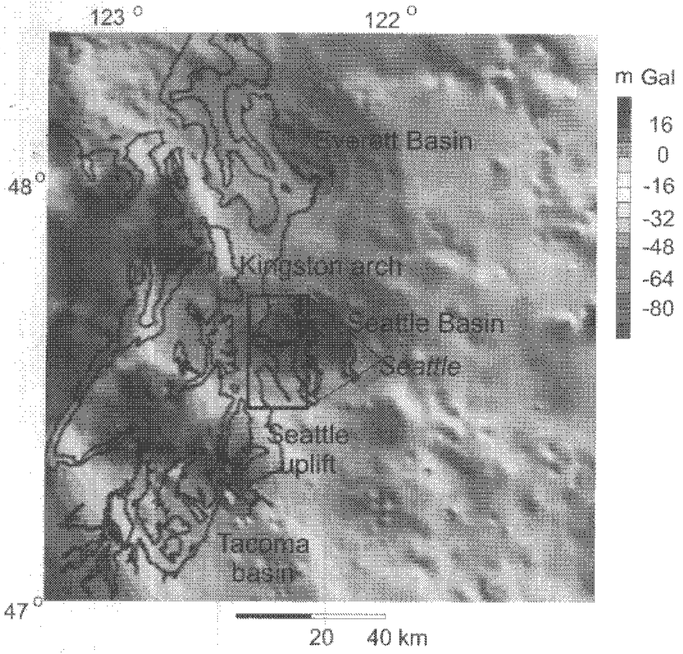

Figure 4. Gravity map modified from Brocher et al. (2004), showing basins and uplifts. Using deep seismic-reflection data and gravity surveys, Pratt et al. (1997) hypothesized a "thrust sheet," with its base ~20 km below the surface, to describe the observed structures in the crust below Puget Sound. They recognize a north-south sequence of basins and uplifts developed on the overriding sheet, separated from the Olympic Mountains on the west by faults and sitting in an uncertain relationship to the adjacent rocks of the Cascade Range on the east. Other models propose deeper thrust sheets or wedge structures bounding the Seattle uplift (Brocher et al., 2001, 2004).

glaciation, suggesting that the geographic distribution of hills also varied between climate cycles (Troost, 2006).

The glacial and interglacial sediment sequences consist of discontinuous stratigraphic units commonly separated by erosional unconformities. Because of the complexity of the resulting depositional record, quantitative techniques, such as chemical analyses and isotopic dating, are necessary to identify and correlate stratigraphic units because each glacial and interglacial depositional sequence looks like its predecessor.

Quantitative and analytical techniques employed include: provenance studies; microfossil studies (pollen and diatom analyses); absolute dating techniques (optically stimulated thermoluminescence, radiocarbon, argon/argon); and paleomagnetic measurements (including secular variation).

Differences in lithology in the sand-size fraction often provide reliable indicators of provenance and, hence, glacial or interglacial origin (Troost, 1999). During glaciation, ice carried clastic material from the mountains of British Columbia (Fig. 1). During interglaciations, Puget Lowland streams reworked the glacial sediments and introduced compositionally distinct clastic materials derived from the bordering Cascade Range and Olympic Mountains.

GEOLOGIC HISTORY AND LANDSCAPE DEVELOPMENT

The rocks and unconsolidated deposits of western Washington record more than 0.25 b.y. of earth history. The foundation of this history is incompletely displayed by rocks now exposed in the foothills and uplands of the North Cascades along the eastern boundary of the Puget Lowland, ~50–100 km northeast of Seattle. They record a history of oceans, volcanic island arcs, and subduction zones, mostly of Mesozoic age, but there are also some late Paleozoic components (which, in western Washington, are as old as 275 Ma) (Frizzell et al., 1987; Tabor and Haugerud, 1999; Tabor et al., 2000). None of these rocks are exposed in the vicinity of Seattle, but their correlatives may lie beneath a thick Tertiary and Quaternary cover.

Tertiary Period

During the Eocene, from ca. 56 to 34 Ma (Gradstein et al., 2004), a wide coastal plain and undersea shelf existed seaward of Washington; the broad deltaic lowlands were called the Weaver Plain by Mackin and Cary (1965). During this time, a volcanic chain sitting on the Kula and Farallon plates merged with the North American plate to form the volcanic underplate of the Olympic Coast range. The Crescent Basalt, made up of submarine lava forming the basement rock beneath Puget Sound, is believed to have formed the core of the Coast Range, having originated farther at sea (Fig. 5).

In the middle to late Eocene, some volcanic eruptions occurred, including in the Seattle area (Orr and Orr, 1996), and the Crescent Formation in the Olympics was initially raised. The submarine volcanic platform subsided, creating a long basin parallel to the margin of western Washington beginning in latest Eocene time.

During the middle and late Eocene (ca. 50–42 Ma), large rivers emptied into the 160–240-km-wide subsiding coastal plain that lay west of the modern Cascade Range and east of the modern Olympic Mountains (and probably east of Puget Sound as well). This ancient river system produced the sandstone and volcanic rocks of the Puget Group on the broad coastal plain. Uplift in the Seattle fault zone is responsible for the prominence of the Newcastle Hills, a few kilometers east of Seattle. Abundant plant debris in the Puget Group provided coal deposits that helped shape the nineteenth-century and first half of the twentieth-century economy and history of the region. Rocks correlative to the Puget Group are now exposed across much of western Washington, particularly along the eastern boundary of the

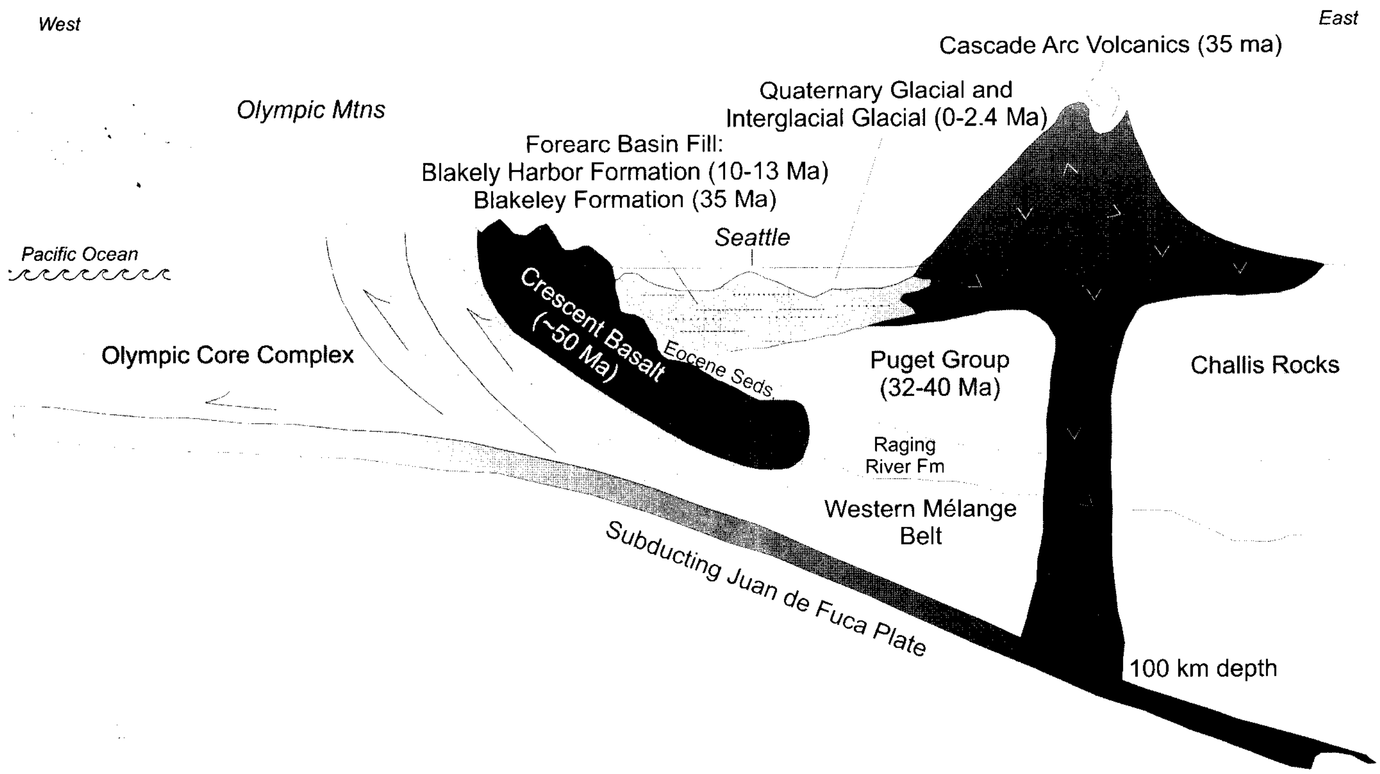

Figure 5. Diagrammatic W–E cross section across western Washington through Seattle, emphasizing the major Tertiary rock units. The Puget Lowland basin is filled with as much as 9 km of young volcaniclastic and sedimentary rocks and Quaternary deposits. Not to scale.

central Puget Lowland and in east and southeast parts of Seattle.

Subsequent reorganization of tectonic plates in the northeastern Pacific Ocean resulted in a more easterly convergence vector, subduction, and volcanism along the Cascade arc in earliest Oligocene time (ca. 33 m.y.), followed by deposition of the marine Blakeley Formation (Fulmer, 1975) across the central Puget Lowland. In the Seattle area, the Blakeley Formation accumulated in a shallow-marine shelf environment (Bourgeois, 1999, written commun.), where it accumulated in deep cold water via turbidity currents (Fulmer, 1975), as on Bainbridge Island, where the rocks are particularly well exposed. Eocene rocks were folded into a series of northwest-trending folds across the state of Washington called the Calkins Range (Mackin and Cary, 1965).

During the Miocene epoch (23–5.3 Ma), uplift of the Olympics and Cascades precipitated terrestrial deposition. Tabor reported reset K-Ar ages in the Crescent Formation of 25–17 Ma (Tabor and Cady, 1978), consistent with uplift of the Olympic Mountains during the Miocene. The Blakely Harbor Formation, ca. 13–10 Ma, was derived from erosion of the surrounding Olympic and Cascade Range highlands (Fulmer, 1975). On Bainbridge Island, the Blakely Harbor Formation has been fission-track dated at 13.3 ± 1.3 Ma (Sherrod et al., 2002).

Uplifting, faulting, and deformation continued during the Miocene and Pliocene, while the Puget Lowland apparently subsided (Orr and Orr, 1996). A major unconformity apparently separates Tertiary bedrock from Quaternary deposits throughout the Puget Lowland. Miocene rocks are discontinuous, and Pliocene rocks have not yet been found anywhere in the Puget Lowland.

Quaternary Period

Seven glacial advances have been documented in the Puget Lowland (Fig. 6), although it is likely that at least a dozen glaciations have occurred here in the last 2.4 m.y., based on the pattern of global marine isotope stages. Little is known about the exact number and extent of previous glaciations and interglacial periods. Of the seven documented glaciations in the Puget Lowland, all have advanced over Seattle. All but the last have left sporadic evidence, and some have left evidence only south of the city. Some general statements can be made about the glaciations and intervening interglacial periods as follows.

Glaciation

During each glaciation, ice advanced into the lowland as a broad tongue, first called the Puget Lobe by Bretz (1913). Originating in the mountains of British Columbia,

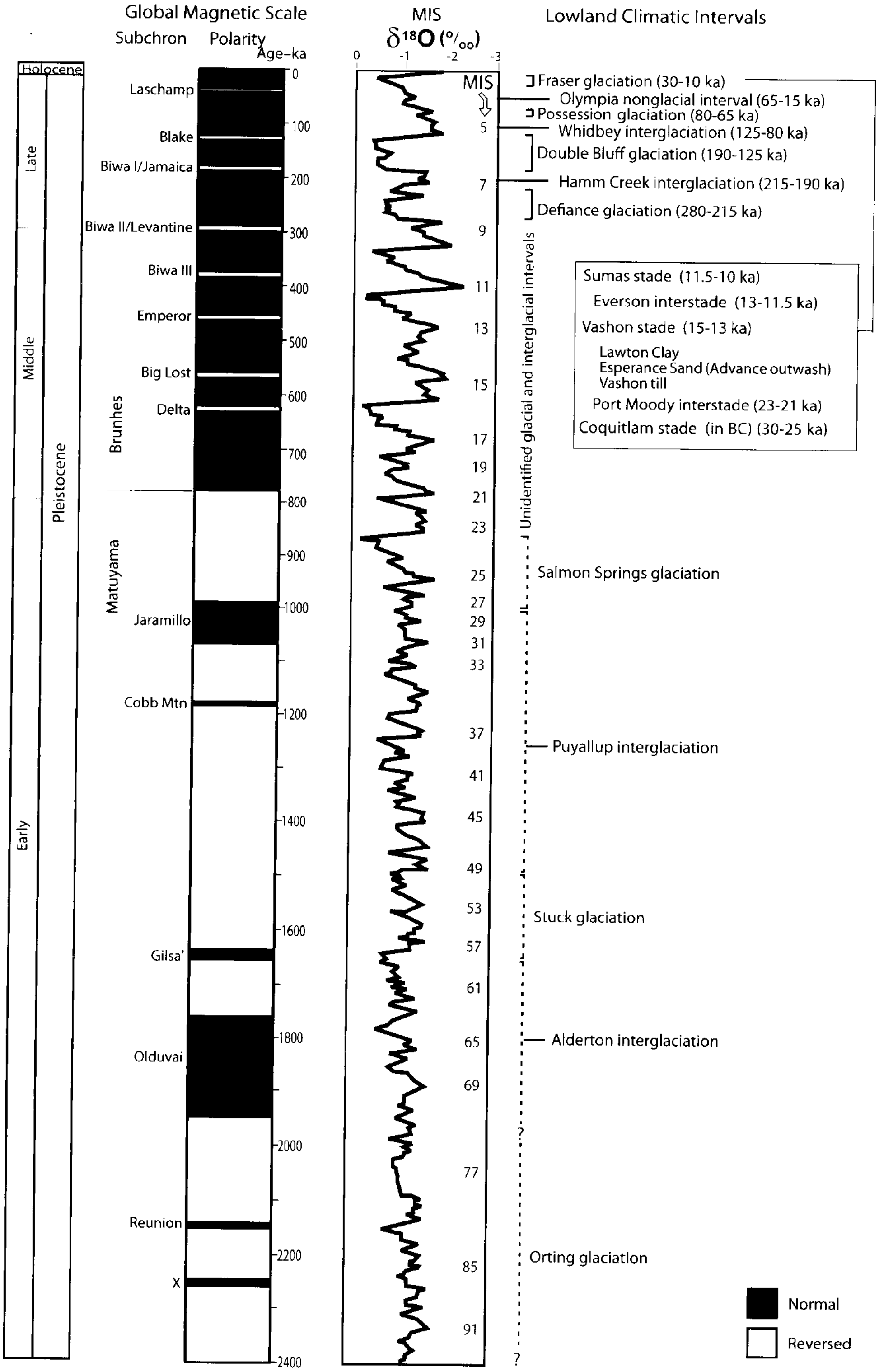

Figure 6. Comparison of marine oxygen isotope curve stages (MIS) using the deep-sea oxygen-isotope data for Ocean Drilling Program (ODP) Site 677 from Shackleton et al. (1990), global magnetic polarity curve (Barendregt, 1995; Cande and Kent, 1995; Mankinnen and Dalrymple, 1979), and ages of climatic intervals in the Puget and Fraser Lowlands. Ages for deposits of the Possession glaciation through Orting glaciation are from Easterbrook et al. (1981), Easterbrook (1986), Blunt et al. (1987), and Easterbrook (1994). Ages for the Defiance glaciation are from Troost et al. (2003). Additional ages from deposits of the Puyallup interglaciation are from R.J. Stewart (1999, personal commun.). Ages for the Olympia nonglacial interval are from Armstrong et al. (1965), Mullineaux et al. (1965), Pessl et al. (1989), and Troost (1999). Ages for the Coquitlam stade are from Hicock and Armstrong (1981). Ages for the Vashon stade are from Armstrong et al. (1965) and Porter and Swanson (1998). Ages for the Everson interstade are from Dethier et al. (1995) and Kovanen and Easterbrook (2001). Ages for the Sumas stade are from Clague et al. (1997), Kovanen and Easterbrook (2001), and Kovanen (2002). Modified from Booth et al. (2004b).

ice coalesced to form the Cordilleran Ice Sheet of northwestern North America, of which the Puget Lobe formed its southwesternmost extent (Fig. 1). Cycles of Cordilleran Ice Sheet advance and retreat into the Puget Lowland were typified by the damming of a proglacial lake in the Puget Sound basin, the spreading of an apron of sandy outwash, deep subglacial scouring, deposition of till, formation of large recessional outwash channels and ice-contact terrain during ice retreat, and (north of the marine limit) deposition of glaciomarine drift. During ice occupation, subglacial drainage carved deep erosional troughs that subsequently filled with postglacial alluvium and, in parts of the eastern and southeastern lowland, volcanic debris flows. Preexisting hills and proglacial outwash deposits were differentially eroded to form drumlin fields on the uplands. Till was deposited extensively but discontinuously over drumlins, on hillsides, and over deposits that accumulated in proglacial and subglacial troughs. The sequence of glacial deposition and erosion is both horizontally and vertically gradational and time-transgressive.

The onset of glacial periods was marked by a change to colder climate, lowering of sea level, and increased deposition and erosion by meltwater. Transitions into and out of glaciations were locally gradual. With the cooling of the climate, sea level dropped as global water transformed from a wet to frozen state and glaciers enlarged. When the ice was present in the lowland, isostatic adjustments of the crust caused the land to subside. When the ice melted and global climate changed, the land rebounded and sea level rose. The amounts of isostatic adjustment and sea-level change varied with each glaciation, depending on the weight of the ice and the degree of climate change.

Interglaciation

Like the glacial record, early to mid-Quaternary interglacial deposits are mostly buried by late Quaternary deposits, so we rely on the modern Puget Lowland as an analog for depositional environments of earlier nonglacial periods. Areas of nondeposition, soil formation, or minor upland erosion dominate most of the present-day Puget Lowland. Significant volumes of sediment are accumulating only in river valleys, lake basins, and Puget Sound, and colluvium is accumulating on slopes. Were the present-day Puget Lowland to be invaded by glacial ice, it would bury a complex and discontinuous nonglacial stratigraphic record. Thick sedimentary sequences would pinch out abruptly against valley walls. Sediment deposited in valleys could be hundreds of meters lower than coeval upland sediment or organic-rich paleosols. Thus, the thickness and lateral continuity of nonglacial sediment of any nonglacial interval should be highly variable owing to the duration of the interval, subsidence and uplift rates, and the altitude and surface topography of fill left by the preceding glacial incursion (Troost, 1999).

Late Quaternary Glacial and Interglacial Cycles

Four named glacial advances passed over Seattle in the last 300,000 yr (Figs. 6 and 7; Table 1): the Defiance glaciation (Troost et al., 2005), named for Point Defiance at Defiance Park in Tacoma, the Double Bluff and Possession glaciations, named for deposits on Whidbey Island (Easterbrook et al., 1967), and the Vashon stade of the Fraser glaciation, named for deposits on Vashon Island (Willis, 1898).

Intervening interglaciations include the Hamm Creek, named for ash-rich deposits found along Hamm Creek in south Seattle (Troost et al., 2005), the Whidbey, named for deltaic deposits on Whidbey Island (Easterbrook et al., 1967), and the Olympia, originally named for the nonglacial deposits typically exposed along the Nisqually River bluffs, but its type section occurs at Discovery Park in Seattle (Armstrong et al., 1965; Noble, 1999, personal commun.).

Evidence for the Double Bluff and Possession glaciations having overridden Seattle includes well-dated measured sections composed of glaciolacustrine deposits and till in the Tacoma area (Troost et al., 2003) and Possession-age glaciolacustrine deposits in Seattle (Mahan et al., 2003). The maximum extent of these glaciers is not known, and it is likely that end moraines of the Possession glaciation were obliterated by the Vashon glacier. Remnant moraines 1.2 km south of the southern Vashon ice margin were attributed to the Double Bluff glaciation by Lea (1984), and based on these moraines, the Double Bluff glacier advanced 2–12 km beyond the extent of the Vashon glacier.

The Whidbey interglaciation lasted from ca. 125 to ca. 80 ka and is correlative with marine oxygen isotope stage (MIS) 5 (Fig. 6). Based on an evaluation of depositional environments from Whidbey-age deposits in Seattle and nearby areas, environments were similar to present day and included peat bogs, river valleys with floodplains, low-lying areas, lakes, estuaries, and uplands with steep slopes. During Whidbey time, reworking and redistribution of Double Bluff glacial deposits occurred, as did mixing of glacial deposits with alluvial deposits from streams from the Washington Cascades. Although there were fluctuations, sea level during part of MIS 5e was nearly as high as modern sea level. Streams in the Seattle area would have been graded to a base level similar to present-day base level—that of Puget Sound. Indeed, Whidbey-age coarse-grained deposits have been identified on the basis of optical dating (Mahan et al., 2003) at the south end of Magnolia Hill near sea level. If more dating techniques were applied to more deposits of unknown age around the city, including in the subsurface, a pattern of paleosurfaces would start to appear, including one of the top of the Whidbey Formation.

The Olympia nonglacial interval spanned ca. 60–15 ka, the time between the Possession glaciation and the Vashon glaciation, and it correlates with MIS 3 (Fig. 6; Table 1). In

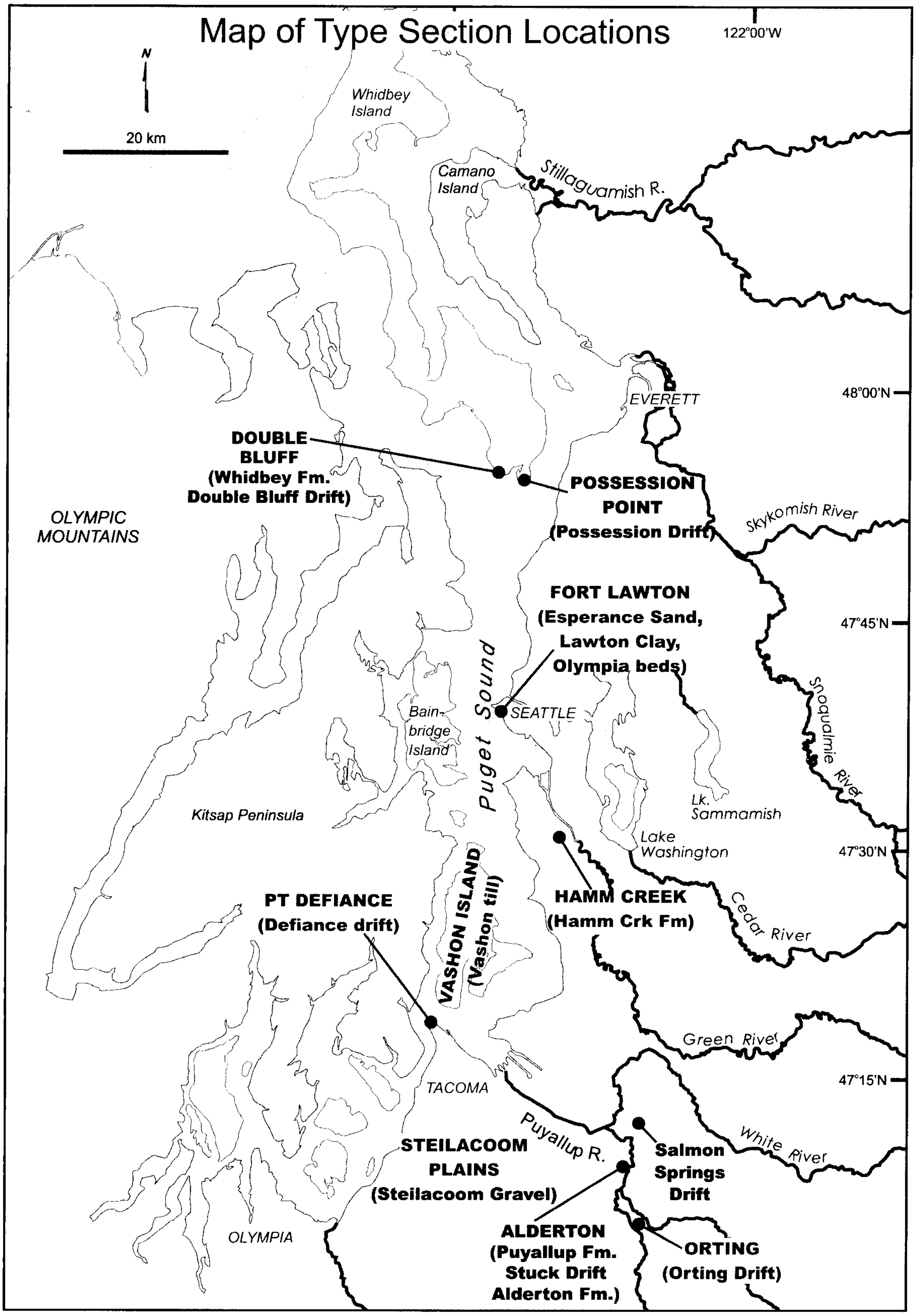

Figure 7. Map showing locations of type and reference sections for named Quaternary geologic units.

TABLE 1. TYPE SECTION DATA FOR QUATERNARY UNITS IN THE SEATTLE AREA

Name (climatic intervals in italics)	Type section location	Reference for nomenclature	Reported age ($\times 10^3$ yr)	Type of date	Location	Reference for age	Comment
Vashon till, *Vashon glaciation*	Vashon Island	Willis (1898)	>13.5	NA	NA	Rigg and Gould (1957)	Youngest limiting age
Vashon Drift, *Vashon stade*		Armstrong et al. (1965)	25.0–13.5	^{14}C yr B.P.	Multiple, Strait of Georgia to Lake Washington	Armstrong et al. (1965)	New dates
			18.0–13.0	^{14}C yr B.P.	Fraser Lowland	Kovanen and Easterbrook (2001)	Compilation
			16.0–13.5	^{14}C yr B.P.	Seattle, Bellevue, Issaquah	Porter and Swanson (1998)	Compilation and new dates
Esperance Sand Member of Vashon Drift	Fort Lawton, Seattle	Mullineaux et al. (1965)	15.0–13.5; 15.0–14.5	^{14}C yr B.P.	Seattle; Issaquah	Mullineaux et al. (1965); Porter and Swanson (1998)	Limiting ages
Lawton Clay Member of Vashon Drift	Fort Lawton, Seattle	Mullineaux et al. (1965)	15.0–13.5; 15.0–14.5	^{14}C yr B.P.	Seattle; Issaquah	Mullineaux et al. (1965); Porter and Swanson (1998)	Limiting ages
Olympia interglaciation	Fort Lawton	Armstrong et al. (1965)	35.0–15.0	^{14}C yr B.P.	Fort Lawton and multiple locations in Washington and British Columbia	Armstrong et al. (1965); Troost (1999)	Compilation and new dates
			24.0–15.0	^{14}C yr B.P.	Fort Lawton and West Seattle	Mullineaux et al. (1965)	New dates
Olympia beds		Minard and Booth (1988)	>45–13.5	^{14}C yr B.P.	Multiple locations around Seattle and Tacoma	Troost (1999); Borden and Troost (2001)	New dates
Possession Drift	Possession Point, Whidbey Island	Easterbrook et al. (1967)	80	Amino acid	Multiple locations	Easterbrook and Rutter (1981)	New dates
Whidbey Formation	Double Bluff, Whidbey Island	Easterbrook et al. (1967)	107–96, avg = 100; 151–102	Amino acid; Thermoluminescence	Multiple locations	Easterbrook and Rutter (1981); Easterbrook (1994)	New dates
Double Bluff Drift	Double Bluff, Whidbey Island	Easterbrook et al. (1967)	250–150;	Amino acid;	Type section	Easterbrook and Rutter (1981);	New dates
Double Bluff glaciation			178–111; 291–177	Amino acid; Thermoluminescence		Blunt et al. (1987); Easterbrook et al. (1992)	NA NA
Hamm Creek interglaciation Hamm Creek Ash	Hamm Creek, Southwest Seattle	Troost et al. (2005)	200 ± 10	Argon/argon	Type section	Troost et al. (2005)	New unit, equivalent to marine oxygen isotope stage (MIS) 7, also found in Snohomish County

many parts of the world, glaciers were still near their maximums, so sea level was still significantly lower than today; however, the Puget Lowland was ice-free (Troost, 1999; Booth et al., 2004b). As during the Whidbey interglaciation, reworking and mixing of glacial deposits and Olympia-age alluvium continued. During the 45,000 yr of the Olympia nonglacial interval, landscape stability was approached, but variations in sea level caused instabilities in base levels.

Vashon Stade

The most recent advance and retreat of the Puget Lobe of the Cordilleran Ice Sheet into the central Puget Lowland is named the Vashon stade of the Fraser glaciation (Armstrong et al., 1965). The glacier reached the central Puget Sound region ca. 14,500 ^{14}C yr B.P. (17,400 cal yr B.P.), and it had retreated from the area by 13,650 ^{14}C yr B.P. (16,400 cal yr B.P.) (Porter and Swanson, 1998); at its maximum, the Seattle area was buried by at least 900 m (3000 ft) of ice (Booth, 1987).

Although age uncertainties preclude assignment of older Pleistocene deposits to named glacial intervals, most near-surface deposits are confidently assigned to the Vashon stade (Fig. 6). Deposits of the Vashon stade have a variety of textural characteristics and landform morphology, owing to rapidly changing depositional environments caused by the advance and retreat of the ice sheet, and, with such evidence, the sequence of events can be reconstructed in detail. It is described in the following sections. In Seattle, the Vashon-age deposits consist of proglacial lacustrine deposits, advance outwash, till, recessional outwash, ice-contact deposits, and recessional lacustrine deposits.

Proglacial Lakes. As the ice first advanced out of British Columbia, it blocked the Strait of Juan de Fuca, which now connects Puget Sound with the Pacific Ocean (Fig. 2). Laminated silt and clay were deposited in the impounded lakes that formed in the course of establishing southerly drainage out of the Puget Lowland; these deposits make up the Lawton Clay (Mullineaux et al., 1965). For the Fraser glaciation, they reached an average maximum elevation near the center of the lowland of ~60 m (200 ft; Thorson, 1989). Other isolated lakes may have formed across the lowland due to increased precipitation, reduced evaporation, or both. The map pattern of this proglacial lake would likely have resembled that of the modern Puget Sound, reflecting a subglacial topography inherited from the previous glacial advance filling troughs to elevation 60 m (200 ft).

Vashon Advance Outwash Deposition. Subsequent glacial outwash deposition followed a broadly predictable pattern. The proglacial lake deposits were covered by sand and gravel of the advance outwash apron (Booth, 1994) to an elevation of 120–180 m (400–600 ft). These outwash sediments completed the filling of the troughs, buried paleohills, and surrounded bedrock promontories. In areas where the Lawton Clay is absent, initiation of the Vashon stade is marked by sandy outwash deposited by streams derived from the advancing ice sheet or subaqueous debris-flow deposition.

Vashon Ice Sheet. As the advancing ice overrode the outwash apron, subglacial troughs were carved, and till was deposited by the melt-out of debris at the base of the glacier. The Vashon glacier deposited till in some areas and eroded the substrate in other areas. Throughout this period, the overriding ice compacted the substrate by applying an effective normal stress equal to the unit-area weight of the ice minus the hydrostatic pressure of the subglacial water (Booth, 1991b). Depending on subglacial water conditions, total ice thickness, and proximity to the ice margin, this effective normal stress probably varied from zero (i.e., near-floating glacier) to nearly the full overburden load (i.e., fully drained conditions, probably attained only close to the glacier snout). The effect of till deposition, loading, and scouring was a sculpted landscape. Even in areas of no till deposition, the land displays megaflutes from the overriding ice (Fig. 8). During the period that the Vashon-age ice sheet covered the region, a tremendous volume of pressurized water was carried by subglacial streams and was responsible for carving the deep troughs of the modern Puget Sound (Booth, 1987). Water discharge reached 5×10^{10} m^3/yr from beneath the glacier near the terminus. The valleys of the Duwamish River, Lake Washington, and Puget Sound are Vashon-age subglacial troughs that have been infilled since deglaciation (Figs. 2 and 3).

Recessional Lakes. Around 13,650 ^{14}C yr B.P., the Vashon glacier began to recede, forming a series of lakes in former subglacial troughs interconnected by recessional streams. Based on delta elevations in proglacial lakes (Thorson, 1980), the main trough of Puget Sound was among the first of the troughs to become ice free. Water was impounded in a series of proglacial lakes that ultimately coalesced and inundated much of the southern Puget Lowland because more than one 1000 m of ice still filled the Strait of Juan de Fuca and prevented northern drainage to the Pacific Ocean. Recession of the ice sheet was accompanied by deposition of sandy outwash along streams, muddy lacustrine deposition into ice-dammed lakes analogous to those formed during the ice advance, and accumulation of ice-contact deposits.

Glacial Lake Russell. The first of these large, Puget Lowland basin–filling, and well-documented recessional lakes, Glacial Lake Russell, formed in the recently abandoned subglacial troughs (Bretz, 1913; Thorson, 1980; Waitt and Thorson, 1983). It began as a small lake occupying

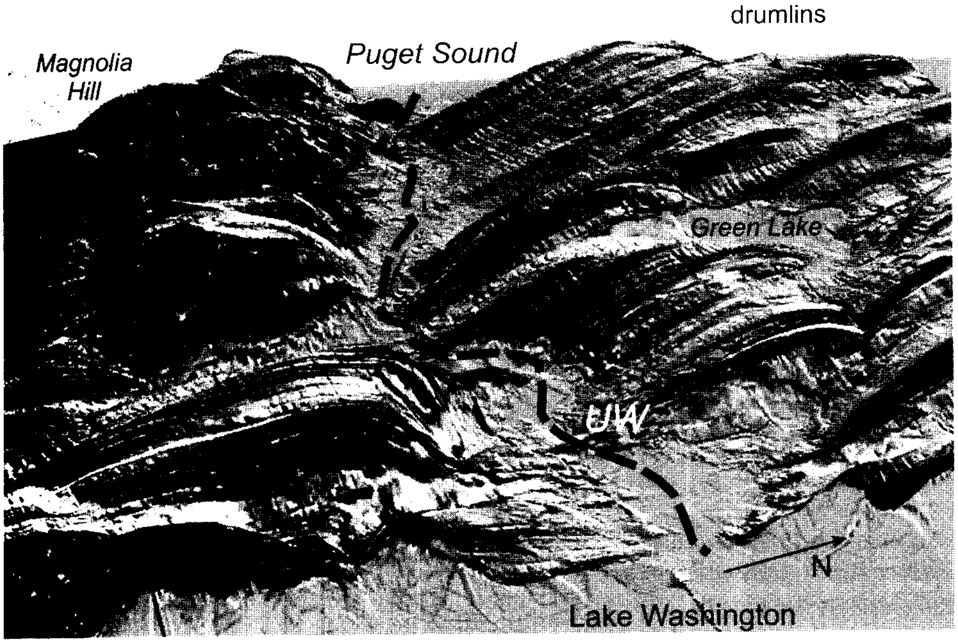

Figure 8. Three-dimensional (3-D) image of shaded-relief digital elevation model from light detection and ranging (LIDAR) data of north Seattle with 8 × vertical exaggeration showing drumlins and scoured topography. View is west-northwest along the ship canal valley (heavy dashed line) from Lake Washington to Puget Sound. Note the north-south glacial striations on the drumlins. UW—University of Washington.

the southern Puget Sound trough, but as more tributary troughs became ice free, the lake enlarged in extent until it reached its maximum when its northern shoreline was located in the north-central lowland (Fig. 2). Water level in Glacial Lake Russell was controlled by its outlet elevation, the Black Lake spillway at 41 m (134 ft) in the Black Hills near Olympia (Fig. 2), and water from the lake drained into the Chehalis River some tens of kilometers to the south (Thorson, 1980). At the latitude of Seattle, the relict shoreline of Glacial Lake Russell now lies at ~100 m (330 ft), higher than the spillway, because of isostatic rebound following retreat of the ice. More rebound occurred in the north than in the south because the ice was thicker to the north, the load heavier, and consequently depression of the crust was greater there.

Glacial Lake Bretz. The second major recessional lake, Glacial Lake Bretz, formed when retreating ice uncovered a lower-elevation spillway, that of the Chimacum valley (Haugerud, 2006), on the northeast coast of the Olympic Peninsula (Fig. 2). This resulted in an abrupt lowering of water level. The shoreline of Glacial Lake Bretz in the Seattle area, for example, now lies at ~30 m (100 ft) in elevation, 70 m below that of Glacial Lake Russell and coincident with breaks in slope along some of the upland edges in the area (Thorson, 1989). Numerous recessional lacustrine deposits and planar surfaces are also present in the Seattle area at the elevation of Glacial Lake Bretz at ~30 m. The tops of some recessional deposits are also coincident with this relict shoreline, suggesting that the deposits may have originated as fan deltas.

Haugerud (2006) determined that other basinwide lakes left shoreline features in Puget Lowland. In Seattle, shoreline features are present at an elevation of 15 m (50 ft).

Postglacial to Holocene

As the Vashon glacier continued to recede well north of Seattle, the ice impounding Glacial Lake Bretz retreated from the Olympic Peninsula and eventually thinned enough to allow the lake to drain into the rising marine waters of the Strait of Juan de Fuca and the Pacific Ocean. Isostatic rebound of ~60 m (200 ft) and marine incursion occurred simultaneously, until rebound was largely complete at around 11,000 ^{14}C yr B.P. (Dethier et al., 1995). The Duwamish River valley, a subglacial valley drained of Glacial Lake Bretz, was inundated with marine water. Isostatic rebound was complete within 1000 yr of ice retreat, while sea level rose at a slower rate, reflecting the transition from MIS 2 to the Holocene (Booth et al., 2004b).

Following drainage of Glacial Lakes Russell and Bretz, streams in the area incised through the Vashon Drift and into the underlying nonglacial and glacial deposits, creating knickpoints in upland streams between ~60 and 75 m (200 and 250 ft) and 30 and 45 m (100 and 150 ft) in elevation, respectively.

Other recent geologic activity includes soil and peat-bog formation, widespread mass failure, beach erosion and deposition, stream-channel erosion, extensive alluvial deposition, accumulation and reworking of volcanic mudflow deposits, sea-level rise, and tectonic deformation.

Duwamish Trough. Significant alluvial deposition has occurred since deglaciation in the south part of Seattle (Plate 1 [on loose insert or in the GSA Data Repository[1]]). Here, the Duwamish River occupies a former subglacial trough that was scoured to as deep as 90 m (300 ft) below modern sea level, much like the other troughs of Puget Sound (Dragovich et al., 1994). Reconstruction of the bottom of the Duwamish trough using boring log data shows many low- to high-amplitude features, including depressions 61 m (200 ft) deep, ridges 30 m (100 ft) high, and bedrock knobs and ridges, some extending above the valley fill (Plate 2L [see footnote 1]).

As sea level rose, the late Pleistocene Duwamish valley rapidly aggraded downstream, and a large delta prograded northward, forming extensive tide flats. As of 7000 yr ago, the Duwamish delta was located near the site of the city of Auburn, ~50 km south of Seattle.

About 5700 yr ago, a massive volcanic mudflow, the Osceola Mudflow, flowed down the White River drainage from the slopes of Mount Rainier, spilling into the Green and Puyallup River drainages. Subsequent reworking of the voluminous, easily eroded deposits on the flanks of Mount Rainier and along the upper river valleys resulted in increased sediment transport and riverine deposition. The Green River rapidly aggraded and prograded its delta downstream north past the south end of Lake Washington, where it joined with that lake's outlet to form the Duwamish River. Post-Osceola deposition brought the river mouth to its modern position at the south edge of Elliott Bay, and extensive tide flats developed on the delta platform (Dragovich et al., 1994; Zehfuss, 2005). At least three lahars contributed to the filling of the Green-Duwamish valley from Auburn to Elliott Bay between 5600 and 1000 cal yr B.P. (Zehfuss, 2005)

Origin of Puget Sound

There are prominent subparallel troughs incised up to 400 m into the topography surrounding the city of Seattle (Fig. 2), which today form one of the world's great estuarine systems. These troughs were once thought to result from ice tongues occupying a preglacial drainage system (Willis, 1898), preserving or enhancing a topography of fluvial origin. This scenario is improbable, however, because impounded proglacial lakes would have floated the ice tongues and precluded any bed contact or ice erosion. Incision by subaerial channels is highly unlikely because the deepest trough bottoms are almost 300 m *below* the southern outlet of the Puget Lowland basin, and Holmes et al. (1988) reported seismic-reflection data that suggest the troughs were excavated during ice occupation to more than twice their current depth. Thus, the troughs must have been gouged out after deposition of the surrounding lowland (Booth, 1994).

However, the troughs must predate subaerial exposure of the glacier bed during the ice recession because many of the eroded troughs are still mantled on their flanks with basal till (see, for example, Booth, 1991a) and filled with deposits of recessional-age lakes (Thorson, 1989). Thus, the troughs were formed primarily (or exclusively) by subglacial processes and probably throughout the period of ice occupation. They were carved primarily by subglacial meltwater (Booth and Hallet, 1993), an inference consistent with many other Pleistocene glacier-occupied troughs and tunnel valleys of similar dimensions and relief elsewhere in the Northern Hemisphere.

Tectonic Setting and Other Geologic Hazards

The Seattle area is subject to many geologic hazards: earthquakes, fault rupture, landslides, volcanic events, compressible soil, flooding, tsunamis, and seiches. Each hazard carries variable levels of occurrence and probability of occurrence as well as degree of risk.

Active Tectonic Processes

Throughout the Tertiary and through the present, Seattle and the Puget Lowland have been affected by major tectonic stresses related to subduction of the Juan de Fuca plate, a fragment of the Pacific plate, beneath the North American plate (Fig. 5). These stresses lead to three earthquakes sources that impact the Seattle area: subduction-zone earthquakes offshore, deep earthquakes within the Benioff zone, and shallow earthquakes along crustal faults like the Seattle fault zone.

Seattle Fault Zone. The east-west Seattle fault zone is one of several active (with a history of Holocene movement) tectonic structures beneath the Puget Lowland. It separates the Seattle basin (north) and the Seattle uplift (south), two of the many structural blocks involved in N-S shortening in western Washington (Pratt et al., 1997; Wells et al., 1998).

The Seattle fault zone passes through Seattle, where its leading edge is roughly along the Interstate 90 (I-90) corridor, and it consists of multiple, mostly north-verging fault strands (Johnson et al., 1999). During a large earthquake 1100 yr ago, land north of the fault subsided by as much as 1 m (3 ft), and land south of the fault was uplifted as much as 7 m (20 ft) (Bucknam et al., 1992), generating a tsunami in Puget Sound (Atwater and Moore, 1992). West and east of Seattle, deposits beneath fault scarps date the most recent fault rupture to ca. A.D. 900–930 (Nelson et al., 2003;

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[1] GSA Data Repository Item 2008217 (Plate 1) and DR Item 2008233 (Plate 2) are available at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

Sherrod et al., 2001, 2004). Trenches excavated on these scarps revealed south-verging faults in all but one location, that of Vasa Park (Sherrod, 2002).

In Seattle, other evidence for offset along strands of the Seattle fault include uplifted beach deposits, offset strata, and deformed strata. Individual strands of the Seattle fault are not shown on the accompanying large-scale map (Plate 1), but they are shown on Figure 2. The precise locations of most of the strands are under investigation. Results from recent mapping suggest landfall of several strands of the Seattle fault in West Seattle; however these are yet to be evaluated in depth (Booth et al., 2003). The leading edge, or deformation front, of the Seattle fault zone is still under investigation as of the time of this manuscript preparation.

Earthquakes. Earthquakes are one of the most significant geologic hazards the Seattle region faces because of the degree of damage and different effects. According to the Federal Emergency Management Agency (FEMA), Washington is ranked second to California in its degree of risk from damaging earthquakes. Earthquake shaking in the Seattle area has been known to trigger ground failures, including: liquefaction, settlement, lateral spreading, delta-front failures, and subaerial and subaqueous landslides (Frankel et al., 2002; Malone et al., 2001; Troost et al., 2001). Bucknam et al. (1992) and Atwater and Moore (1992) documented that the Seattle fault is capable of producing large earthquakes and ground-surface rupture—a magnitude 7.0 or greater earthquake ~1100 yr ago resulted in as much as 7 m of uplift at Restoration Point on Bainbridge Island, creating marine terraces, over 4 m of uplift at Alki Point, creating an uplifted beach platform, and 1–1.5 m of subsidence at West Point. This earthquake also generated a tsunami in Puget Sound. Recent work by Sherrod (2005), Sherrod et al. (2001), and Nelson et al. (2003) indicates that known active strands of the Seattle fault in Bellevue and on Bainbridge Island have produced surface rupture, and some strands have been reactivated by multiple earthquake events. Ten Brink et al. (2006) concluded that the surface rupture that occurred 1100 yr ago on at least two strands of the Seattle fault resulted from a moment magnitude Mw 7.5 earthquake.

Troost et al. (2005) designated the Seattle fault zone as a zone, rather than specific lines, because of the uncertainty in the postulated fault models and the uncertainty in precise locations of fault strands; however, all of the postulated models present four or more possible east-west–trending strands or a large area over which deformation could possibly occur due to movement on deeper portions of the Seattle fault. Surface rupture is possible along existing strands within the Seattle fault zone and less likely along new faults within the zone.

The estimated probabilities of an earthquake with $M > 6.5$ occurring on the Seattle fault zone or from a random shallow-crustal source in the Puget Sound region are ~5% in 50 yr (recurrence interval of 1000 yr) and 15% in 50 yr, respectively (Stewart, 2005). These probability estimates have large uncertainties. The probability estimate for a $M > 6.5$ earthquake on the Seattle fault zone is based on trenching studies at a small number of locations as well as a slip rate estimate that has a large uncertainty. The probability estimate of a random shallow earthquake with $M > 6.5$ in the Puget Sound region is based on extrapolation of the rate of observed earthquakes with magnitudes 4 and above (Frankel, 2007).

Landslides. Landslides in the Seattle area are discussed in detail in many manuscripts within this volume, and so they will not be discussed in detail here. Seattle's geologic, climatic, and social settings combine to produce areas with high landsliding susceptibility, such as: highly permeable deposits over low-permeability deposits that intersect steep slopes and abundant rainfall to raise pore pressures via groundwater and springs at the aforementioned contact; abundant colluvium on slopes and fill at the tops of steep slopes readily saturated by rain and drains; undercut toes of slopes as a result of wave action or construction of view properties; stripped vegetation from slopes and cut slopes for building; and seismic shaking.

Several types of landslides are common in the Seattle area, in order of occurrence: mudflows (referred to as "shallow colluvial" or "skin slides" by Shannon & Wilson, 2000), deep-seated rotational and translational, debris flows (referred to as "groundwater blowout" landslides by Shannon & Wilson, 2000), and block fall/topple (referred to as "high bluff peeloff" landslides by Shannon & Wilson, 2000). A common theme in many of the area's landslides is indeed a human component. Shannon & Wilson (2000) found that 84% of the landslides they inventoried, from a century's worth of reports, involved some degree of human influence. Shannon & Wilson (2000) also found that most of the reported landslides occurred in January, in accord with the heavy precipitation months of November, December, and January.

Some areas of Seattle have been subject to repeated landslides, including those with steep slopes, a groundwater perching layer (geologic contact between sandy unit over fine-grained unit), springs, undercutting at the toe, and possibly along strands of the Seattle fault. In many areas, landslide and mass-wastage deposits are thick enough to obscure natural hillside morphology (Plate 1 and Plate 2H [see footnote 1). These deposits are naturally less stable than in situ deposits. For more information about specific areas with repeated landslide occurrences, the Shannon & Wilson (2000) landslide inventory maps are available through the City of Seattle Public Utilities Web Site.

Volcanic Events. The southern city limit of Seattle is 79.5 km (49 mi) from the peak of Mount Rainier; downtown Seattle is another 12.5 km (8.5 mi). Volcanic events from Mount Rainier could impact the city in several ways, including ash fall, sedimentation in the Duwamish waterway, and flooding in the Duwamish waterway. Mount Rainier is particularly prone to lahars because it has a large volume of snow and glacier ice (more than the combined volume of glacier ice on the other Cascade volcanoes) available for melting during an eruption and a large volume of hydrothermally altered rock. It also stores water beneath its glaciers, which is sometimes released as outburst floods. Lahars from Mount Rainier historically have flowed down the White, Carbon, and Puyallup River valleys (Hoblitt et al., 1998) into the Green River nearly to Renton (Dragovich et al., 1994; Vallance and Scott, 1997). The Osceola lahar, 5700 yr ago, is the best documented and largest (in the last 10,000 yr) of the Mount Rainer lahars. Zehfuss (2005) found that at least four post-Osceola lahar deposits are present within Seattle city limits in the Duwamish valley. However, no primary lahar deposits have been documented within city limits; the deposits Zehfuss (2005) describes appear to have been reworked and redeposited by postlahar floods. The Osceola lahar deposited a layer of sediment (up to 100 ft thick beneath Sumner) in the Green River valley beneath the modern towns of Kent and Auburn when the Green River valley was a deep trough. Deposits from this event are estimated at 0.89 mi^3 and covered an area of ~550 km^2 (212 mi^2) (Dragovich et al., 1994). If such a lahar were to occur today, with the Green River valley aggraded to near sea level, the extent of primary and secondary sedimentation is hard to predict.

Volcanic ash has also fallen on the Seattle landscape at several times throughout the Quaternary from several different, but as-of-yet unknown, source volcanoes, most likely Cascade arc volcanoes. The Hamm Creek ash, described later, is evidence of one such event 200,000 yr ago (and in 1980, from Mt. St. Helens). Other ash deposits are present in the Olympia deposits and in nonglacial deposits tentatively correlated with the Whidbey Formation. Although over one hundred tephra samples have been analyzed, reworking, alteration, and vent antiquity (no matches in the U.S. Geological Survey database) have rendered most of the samples of relatively low quality for chemical comparisons and correlations (Sarna-Wojcicki, 2004).

Compressible and Expandable Soil. Former postglacial bogs and recessional lake deposits frequently contain compressible deposits of peat and organic-rich silt. These material types are present in relatively isolated but widespread locations throughout the city (Plate 2G). Groundwater withdrawal from thick peat deposits has been known to cause damaging settlement in overlying and nearby structures in the Greenwood bog (Shannon & Wilson, 2004). Peat occurs in bogs and as discontinuous lenses in lacustrine deposits; in the latter case, mapping of the discrete peat lenses is not plausible. In Seattle, five types of former bogs are recognized based on their formation: (1) those formed at the heads of modern streams, (2) those formed at the heads of recessional streams, (3) those formed in apparently isolated upland depressions, (4) those formed in the Duwamish Valley floodplain, and (5) those formed adjacent to Lake Washington related to the lowering of the lake. Most of these bogs began at the close of the last glacial period but are now covered by fill, in some cases 9 m (30 ft) thick. The thickest (18.3 m [60 ft]) and most continuous peat deposits are types 4 and 5. However, continuous peat deposits on the order of 7.6 m (25 ft) thick are present as types 1 and 2. Type 3 deposits are the least continuous of the five types, and they tend to be the thinnest.

Expandable clay in the form of montmorillonite and vermiculite is present in surficial and subsurface geologic units. Vashon recessional lacustrine deposits locally contain expandable clay minerals (Smith, 2004), and interglacial paleosols typically contain expandable clay. Near Steilacoom, damage to a school's floor was attributed to expandable clay minerals from the alteration of tephra in Vashon recessional lacustrine deposits. This deposit normally consists of fine sand, silt, and clay-sized particles of nonexpandable minerals (Mullineaux, et al., 1964). During construction of I-5, Mullineaux (1967) noted the presence of fat clay at the top of the Olympia beds, the paleosol marking that unit's uppermost surface. All interglacial units mapped in the Seattle area contain tephras and, therefore, the feldspars that alter to expandable clay minerals.

Mullineaux (1967) and Mullineaux et al. (1964) also noted that interglacial clays have two origins: detrital and weathering. In either case, these clays can contain enough expandable minerals to be a concern for construction. However, most pre-Vashon deposits have been glacially overridden and are therefore hard or very dense. If pre-Vashon deposits are exposed in an excavation or on a slope, and alteration has occurred, then limited expansion and slippage could occur.

Tsunamis and Seiches. Tsunamis have been known to occur in Puget Sound and inundate a small part of Seattle, and seiches have been documented in Lakes Washington and Union. Several triggering mechanisms can cause these different wave types: fault rupture with subaqueous bottom offset, delta-front failure, subaqueous and/or subaerial landslides, and seiches can also be caused by earthquake shaking.

Walsh et al. (2003) prepared a map showing the tsunami inundation area in Seattle based on modeling by Titov et al. (2003) using the Seattle fault event 1100 yr ago. The modeling yielded: wave-amplitude fluctuations at 6 m, a maximum vertical runup at 10 m, current speeds ranging from 1.5 to 15 m/s (maximum listed is 30 m/s), and the first wave landfall 2 min and 20 s after generation.

Numerous submarine landslides (large block slides, sediment slumps, and debris flows) are present throughout Lake Washington and are attributed to large earthquakes that have occurred in the Puget Sound region about every 300–500 yr (Karlin et al., 2004). Many of these landslides are large enough to have displaced enough water to have generated tsunamis, particularly those that involved subaerial and submarine components. Benioff zone (e.g., 1949, 1965, or 2001 Nisqually) earthquakes have not caused large block slides in Lake Washington, so it is clear that the prehistoric earthquakes that triggered these slides had stronger ground motion than any earthquakes this century. The 1100-yr-old Seattle fault event triggered large landslides off of Mercer Island that drowned trees in nearly upright position (Jacoby et al., 1992; Karlin and Abella, 1992). Many large bays on Lake Washington, such as Andrews Bay next to the Bailey Peninsula in Seattle, are the headscarps of large subaqueous landslides (Karlin et al., 2004).

Barberopoulou (2006) found that seiche waves on Lake Union were highest after subduction-zone earthquakes, where modeled water waves reached heights of 1.2 m (3.9 ft). Long-amplitude earthquake waves, such as those that accompanied the Denali earthquake of 2002, also produced high wave heights, modeled at 0.43 m (1.41 ft). Benioff zone and Seattle fault earthquakes had the lowest seiche effects of the four earthquake types studied, with modeled wave heights of 0.14 m (0.46 ft). Barberopoulou et al. (2004) documented damage to 20 houseboats in Lake Union from seiche activity resulting from the 2002 Denali earthquake. Their analysis of this event showed substantially increased shear and surface-wave amplitudes coincident with the Seattle sedimentary basin, indicating that the size of the water waves may have been increased by local amplification of the seismic waves by the basin.

STRATIGRAPHY AND DEPOSITS IN SEATTLE

Geologic Map of Seattle

A new detailed geologic map (Plate 1; Fig. 9) for the city of Seattle (Troost et al., 2005) combines new geologic field mapping with a database of more than 35,000 subsurface data points from geotechnical boreholes and test pits (Booth et al., 2006). Properties of each of the map units are described in Table 2, and additional information about the stratigraphic record is provided next.

Tertiary Bedrock

The depth to bedrock in the Seattle area varies from zero at Alki Point to ~550 m (1800 ft) at both the north and south ends of the map area (Jones, 1996), with a steep drop at the north end of the Seattle uplift (Plate 2B).

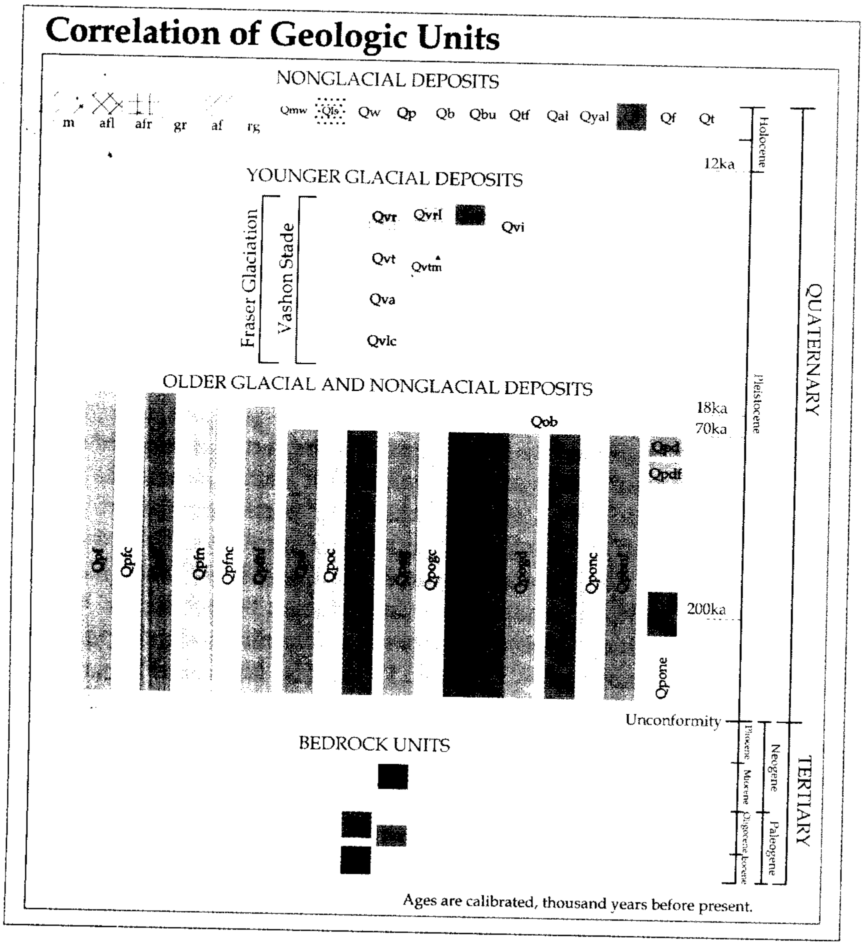
Middle and late Eocene (ca. 50–42 Ma) volcaniclastic rocks of the Puget Group, Tukwila Formation (Plate 2B; Fig. 8), are exposed in Seattle at Seward Park, along I-5, and in the bedrock knobs, labeled Poverty Hill and North Hill (Fig. 3), which protrude above the Duwamish valley fill (Table 3). The Tukwila Formation is largely a sedimentary deposit that accumulated near a volcanic center; its lower part is marine (Nesbitt, 1998).

Oligocene bedrock is most prominently exposed at Alki Point on the western tip of West Seattle, where the Seattle fault has raised bedrock at the north edge of the Seattle uplift up into contact with Quaternary deposits at the south end of the Seattle basin (Plate 2B). The bedrock had been previously mapped as the Blakeley Formation of Weaver (1916a, 1916b) on the basis of foraminiferal and molluscan assemblages (Waldron, 1967). The Blakeley Formation at Alki Point is now correlated with the late Zemorian–Saucesian benthic foraminiferal zone at the Oligocene-Miocene boundary (E. Nesbitt, 2007, written commun.). The Blakeley Formation consists of marine sedimentary and volcaniclastic rocks deposited in a nearshore to shallow-marine shelf environment. Blakeley Formation rocks are best exposed at low tide on the beach immediately south of Alki Point, and in a knob protruding 15 m (50 ft) above the uplifted beach terrace, just inland of Alki Point. At Alki Point, bedrock ranges from steeply dipping to overturned, and it is gently folded at the north end as it approaches a strand of the Seattle fault. The thickness of the Blakeley Formation cannot be accurately measured in the Seattle area, but more extensive exposures farther east suggest thicknesses locally may be in excess of 760 m (2500 ft) (Waldron et al., 1962).

Rocks of the Blakeley Formation are exposed over a wide area, but in generally poor outcrops, in the southeastern part of Seattle. Outcrops along the base of the Seward Park peninsula are particularly easily accessed. The pattern of outcrops also follows the east-trending trace of the Seattle fault, reflecting continued uplift of the crustal block on the south side.

Deep saprolite has developed on the bedrock, often making the distinction between bedrock and Quaternary deposits difficult since glacially overridden deposits such as glaciomarine drift and glaciolacustrine clay are commonly stronger and more competent than weathered bedrock in the Seattle area. Weathering profiles commonly extend ten meters into bedrock, rendering the bedrock more "soil"-like in behavior. Weathering effects include loss of

A



B

Map Units

Nonglacial Deposits (Holocene)

water
Qw - Wetland deposits
Qp - Peat
Qb - Beach deposits
• Qbu - Uplifted beach deposits
Qtf - Tideflat deposits
Qal - Alluvium
Qyal - Younger alluvium
■ Ql - Lake deposits
Qf - Fan deposits
Qt - Terrace deposits

Younger Glacial Deposits (Fraser Glaciation, Pleistocene)

Qvr - Vashon recessional outwash deposits
Qvrl - Vashon recessional lacustrine deposits
■ Qvrc - Vashon recessional coarse-grained deposits
Qvi - Vashon ice-contact deposits
Qvt - Vashon subglacial till
Qvtm - Vashon subglacial meltout till
Qva - Vashon advance outwash deposits
Qvlc - Lawton Clay member of the Vashon Drift

Older Glacial and Nonglacial Deposits (Pleistocene)

Qpf - Pre-Fraser glaciation age deposits
Qpfc - Pre-Fraser coarse-grained deposits
▨ Qpff - Pre-Fraser fine-grained deposits
Qpfn - Pre-Fraser nonglacial deposits
Qpfnc - Pre-Fraser coarse-grained nonglacial deposits
▨ Qpfnf - Pre-Fraser fine-grained nonglacial deposits
Qob - Olympia beds
▨ Qpo - Pre-Olympia deposits
Qpoc - Pre-Olympia coarse-grained deposits
■ Qpof - Pre-Olympia fine-grained deposits
▨ Qpog - Pre-Olympia glacial deposits
Qpogc - Pre-Olympia coarse-grained glacial deposits
■ Qpogf - Pre-Olympia fine-grained glacial deposits
■ Qpogt - Pre-Olympia glacial till
▨ Qpogd - Pre-Olympia glacial diamict
■ Qpon - Pre-Olympia nonglacial deposits
Qponc - Pre-Olympia coarse-grained nonglacial deposits
▨ Qponf - Pre-Olympia fine-grained nonglacial deposits
▨ Qpdf - Possession drift fine-grained deposits
■ Qhc - Hamm Creek formation
Qpone - Pre-Olympia estuarine deposits

Bedrock (Tertiary)

■ Tb - Blakeley Formation
■ Tva - Andesite
■ Tpt - Tukwila Formation

Overprints

Mass wastage deposits
⁚ Landslide deposits
Modified land
af - artificial fill
afl - landfill debris
afr - filled river channels
graded land
regraded land

Symbols

-+- anticline, approx. located
(McWilliams, 1971)
— fault, approx. located
(Waldron and others, 1962; McWilliams, 1971)
inclined bedding
vertical bedding
inclined jointing
vertical joint

Contact
---- Scarps
.... Peat bed
-.-.-.- Till bed
Seattle Fault Zone
------ Seattle City Limit

Figure 9. (A) Correlation of map units for the geologic map of Seattle (Plate 1 [see footnote 1]). (B) Legend for the geologic map of Seattle (Plate 1).

TABLE 2. DESCRIPTION OF MAP UNITS FOR GEOLOGIC MAP OF SEATTLE

Age & geologic unit	Name	Summary description	Thickness	Density/hardness	Permeability factors
Holocene	NONGLACIAL DEPOSITS				
m	Modified land	Fill and/or graded natural deposits that obscure or alter the original deposit. Locally divided into:			
af	Artificial fill	Gravel, sand, silt, concrete, garbage, slag, and other materials, placed as a direct result of human activity, of substantial areal extent or thickness. Mapped where boring data provide sufficient information to delineate extent or where topography and overlying development suggests likelihood of fill, and where greater than ~2 m in thickness. Thin deposits of fill are commonly present elsewhere throughout the map area but were not mapped due to lack of information. Locally divided into:	Mapped where >2 m; but 1 m of fill common across most of the city; 3 m to >15 m on slopes, in gullies, and capping peat beds	Very soft to stiff or very loose to dense	Voids common; variable and unpredictable grain size; angular and large particles common
afl	Landfill debris	Gravel, sand, silt, concrete, bricks, coal, wood, garbage, and other debris, placed in upland and low-elevation peat bogs, gullies, ravines, river valleys, and other low-lying places.	<1 m to 16 m; several locations across the city	Very soft to stiff or very loose to dense	Voids common; variable and unpredictable grain size; angular sand- and gravel-sized fragments
afr	Artificial fill in historic river channels	Gravel, sand, silt, concrete, bricks, coal, wood, garbage, and other materials, placed in historic Duwamish River channel concurrent with straightening of the river by U.S. Army Corps of Engineers in the 1930s. Former channel location was digitized from georectified 1898 and 1908 U.S. Geological Survey (USGS) topographic maps.	7 m to 10 m; Duwamish Valley	Very soft to stiff or very loose to dense	Voids common; variable and unpredictable grain size; angular sand- and gravel-sized fragments
gr	Graded land	Land substantially altered by excavation or grading, may include substantial thicknesses of fill too subtle to map or where boring data are insufficient to delineate extent. Gradational with units "af" and "rg."	Large areas for I-5 and other highways	Very soft to hard or very loose to very dense	Depends on thickness of material removed
rg	Regraded land	Land substantially altered by excavation or grading during the Seattle regrades of 1876–1928 (Morse, 1989); may include substantial thicknesses of fill that are too subtle to map or where boring data are insufficient to delineate extent. Locally more than 150 vertical feet removed.	Variable but indistinct	Stiff to hard or loose to very dense	Depends on thickness of material removed
Qmw	Mass-wastage deposits	Colluvium, soil, and landslide debris with indistinct morphology. Mapped on steep slopes. Numerous unmapped areas of mass-wastage deposits occur elsewhere in quadrangle along ravines and the sidewalls of the Duwamish River valley. Deposits, both mapped and unmapped, include abundant discrete landslides up to 300 m (1000 ft) in lateral extent. Locally subdivided into:	Typically about 3 m, locally >10 m; along steep slopes	Loose to dense and soft to stiff	Intermixed fine- and coarse-grained deposits
Qls	Landslide deposits	Diamict of broken to internally coherent surficial deposits transported downslope en masse by gravity. Blocks of native material are commonly fractured, have rotated or deformed bedding, and have abundant slickensided surfaces. Numerous unmapped areas of both landslide and related mass-wastage deposits occur along slopes and ravines draining east to the Duwamish River valley and Lake Washington and draining west into Puget Sound, particularly where coarse-grained deposits overlie fine-grained deposits. Vegetation, such as trees and roots, is commonly incorporated into the deposit.	Variable, up to 20 m; along steep slopes	Very loose to very dense or soft to hard	Intermixed fine- and coarse-grained deposits; voids common
Qw	Wetland deposits	Organic-rich sediment, peat, and fine-grained alluvium, poorly drained and intermittently wet. Areas identified from vegetation, maps, and topography; not all such deposits have been delineated.	1 to 7 m; typically 2 to 3 m	Very soft to medium stiff or very loose to medium dense	Commonly saturated
Qp	Peat	Predominantly organic matter consisting of plant material and woody debris, accumulated in bodies greater than about 1 m in thickness and of mappable extent. Accumulations are greatest in the floors of recessional-outwash channels and where lowering of Lake Washington has exposed extensive lake-floor deposits. Commonly interbedded with silt and clay. Gradational with units Qw, Ql, Qal, and Qvrl.	>1 to 10 m	Very soft to medium stiff or very loose to medium dense	Commonly saturated

(*continued*)

TABLE 2. DESCRIPTION OF MAP UNITS FOR GEOLOGIC MAP OF SEATTLE (*continued*)

Age & geologic unit	Name	Summary description	Thickness	Density/hardness	Permeability factors
Qb	Beach deposits	Loose sand and gravel deposited or reworked by modern wave action. Shown in the map area along the Puget Sound shoreline, on the east side of Duwamish Head, west of Harbor Island, and along Lake Washington, where it is commonly overlain by fill.	<3 to 10 m; some as thick as 17 m	Loose to dense	Uniformly to well graded
Qbu	Uplifted beach deposits	Loose sand and gravel deposited by wave action and subsequently uplifted above modern tide level by tectonic movement	<3 to 10 m	Loose to dense	Uniformly to well graded
Qtf	Tide-flat deposits	Silt, sand, organic sediment, and detritus, with some shells, historically exposed in broad coastal benches at low tide and now fill covered. Along Duwamish River valley, thickens to north at mouth; initially deposited postglacially when marine water extended up the Duwamish valley to Georgetown. Aggraded northward with rising sea level and alluvial filling of the Duwamish valley. Elsewhere, present along much of Puget Sound coastline and now fill covered.	50 m at the mouth of the Duwamish; 65 m at the N end of Harbor Island	Very loose to dense or and very soft to stiff	Micaceous, saturated, lenses of shell and wood debris
Qal	Alluvium	Sand, silt, gravel, and cobbles deposited by streams and running water. May include landslide debris and colluvium at margins. Locally contains very soft peat lenses. Locally subdivided into:	A few m to 30 m; in river and stream valleys	Loose to dense or soft to stiff	Predominantly sandy and horizontally bedded, fine- and coarser-grained lenses
Qyal	Younger alluvium	Sand, silt, gravel, and cobbles deposited by streams and running water. Locally contains soft peat lenses.	Mapped in bottoms of filled Duwamish River channels	Loose to dense or soft to stiff	Predominantly sandy and horizontally bedded, fine- and coarser-grained lenses
Ql	Lake deposits	Silt and clay with local sand layers, peat, and other organic sediments, deposited in slow-flowing water. Most mapped areas are lake-bottom sediments exposed by the lowering of Lake Washington in 1916. Locally gradational with units Qvrl, Qal, and Qp.	Typically 3 to 5 m on upland in recessional channels; 1 to 3 m adjacent to Lake Washington	Very soft to medium stiff or very loose to medium dense	Predominantly fine grained and horizontally bedded
Qf	Fan deposits	Sand, silt, gravel, and cobbles deposited in lobate form where streams emerge from confining valleys and reduced gradients cause sediment loads to be deposited. Gradational with unit Qal.	3 to 5 m	Loose to dense or soft to stiff	Variable grain size
Qt	Terrace deposits	Sand, silt, gravel, and cobbles, deposited by streams and running water; elevated bench forms resulting from subsequent downcutting. May include slide debris and colluvium. Locally gradational with unit Qal.	2 to 6 m, along modern river valleys	Loose to dense or soft to stiff	Predominantly sandy and horizontally bedded, fine- and coarser-grained lenses
Pleistocene	YOUNGER GLACIAL DEPOSITS				
Qv	Deposits of Vashon stade of Fraser glaciation of Armstrong et al. (1965), not used as a map unit				
Qvr	Recessional outwash deposits	Stratified sand and gravel, moderately sorted to well sorted, and less common silty sand and silt. Deposited in 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. Discontinuous. May include thin lag on glacial till uplands, although deposits less than about 1 m (3 ft) thick are not shown on map. Locally divided into:	~1 to 6 m; typically in channels	Loose to dense	Horizontally bedded to cross-bedded, uniformly to well graded; channelized, coarse lag deposits common
Qvrl	Recessional lacustrine deposits	Laminated silt and clay, low to high plasticity, with local sand layers, peat, and other organic sediments, deposited in slow-flowing water and ephemeral lakes. Locally includes high-plasticity clay with swell potential. Lenses and layers of ash and diatomite may be present. Gradational with units Qvr, Qp, and Ql.	5 m typically on uplands; up to 16 m at the heads of recessional channels; locally 18 m in Rainier valley	Very soft to stiff	Horizontally bedded; sandy channels may breach the lacustrine deposits
Qvrc	Recessional coarse-grained deposits	Predominantly sand and gravel, clean to silty, horizontally to cross-bedded, deposited in outwash channels and in deltas.	4 to 10 m	Loose to dense	Interspersed silt and open-work gravel layers

(*continued*)

TABLE 2. DESCRIPTION OF MAP UNITS FOR GEOLOGIC MAP OF SEATTLE (*continued*)

Age & geologic unit	Name	Summary description	Thickness	Density/hardness	Permeability factors
Qvi	Ice-contact deposits	Intercalated till and outwash, irregularly shaped bodies of till and outwash. Outwash consists of sand and gravel, clean to silty, horizontally bedded to steeply dipping. The till consists of matrix-supported gravelly sandy silt that may or may not have been glacially overridden. Deposits intermittently flank the west margin of the Duwamish River valley south to the edge of quadrangle and are common on the upland southwest of the Duwamish River. Gradational with units Qvr and Qvt.	3 to 15 m; in patches on the upland	Loose to very dense	Intermixed irregularly shaped bodies of till and coarse-grained deposits
Qvt	Vashon till	Compact diamict of silt, sand, and subrounded to well-rounded gravel, glacially transported and deposited under ice. Commonly fractured and has intercalated sand lenses. Generally forms undulating, elongated surfaces. Upper 1 m of unit generally weathered and only medium dense to dense. Locally divided into:	Typically 1 to 10 m	Very dense	Vertical fractures, sand lenses, and crude subhorizontal bedding common
Qvtm	Subglacial meltout till	Deposit consists of compact diamict (gravel and sand in a silt matrix) with large, often tabular, sand and gravel bodies, cobbles common. Coarse-grained layers may exceed 50% of the volume of the deposit. Locally identified as "sandy till." Locally gradational with units Qvt and Qva.	Typically 1 to 10 m	Dense to very dense; sand is commonly less dense	Vertical fractures, sand bodies, and irregular bedding common
Qva	Advance outwash deposits	Well-sorted sand and gravel deposited by streams issuing from advancing ice sheet. May grade upward into till. Silt lenses locally present in upper part and common in lower part. Generally unoxidized to only slightly oxidized. May be overlain by Vashon till in areas too small to show at map scale. Includes Esperance Sand Member of the Vashon Drift of Mullineaux et al. (1965). Grades downward into unit Qvlc with increasing silt content.	Locally over 60 m thick; widespread	Dense to very dense	Predominantly medium-grained sand, horizontally to cross-bedded, hard silt beds common throughout
Qvlc	Lawton Clay of Mullineaux et al. (1965)	Laminated to massive silt, clayey silt, and silty clay with scattered dropstones deposited in lowland proglacial lakes. 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 older fine-grained units where evidence of age and/or depositional environment is absent. Locally may include fine-grained sediment of unit Qob or distal deposits from the Cascade Mountains where indistinguishable from Qvlc.	>30 m; generally present in pre-Vashon valleys below 240 ft in elevation	Very stiff to hard	Vertical fractures, fine sand partings common near top and bottom of unit
Pleistocene	OLDER GLACIAL AND NONGLACIAL DEPOSITS				
Qpf	Deposits of pre-Fraser glaciation age	Interbedded sand, gravel, silt, and diamicts of indeterminate age and origin. Locally divided into:	3 to >50 m	Very dense and hard	Localized iron-oxide–cemented layers, interbedded and intermixed fine- and coarse-grained layers
Qpfc	Coarse-grained deposits	Sand and gravel, clean to silty, with some silt layers, lightly to moderately oxidized.	Up to 15 m	Very dense	Localized iron-oxide–cemented layers and channels
Qpff	Fine-grained deposits	Silt and clay, may have sandy interbeds, laminated to massive.	Up to 7 m	Hard	Localized iron-oxide–cemented layers and sandy partings
Qpfn	Nonglacial deposits	Sand, gravel, silt, clay, and organic deposits of inferred nonglacial origin, based on the presence of peat, paleosols, and tephra layers; or a southern Cascade Range provenance for sedimentary clasts.	3 to 7 m	Very dense and hard	Localized iron-oxide–cemented layers, interbedded and intermixed fine- and coarse-grained layers
Qpfnc	Coarse-grained nonglacial deposits	Sand and gravel, clean to silty, with some silt layers, with peat and tephra layers, lightly to moderately oxidized.	3 to 10 m	Very dense	Localized iron-oxide–cemented layers
Qpfnf	Fine-grained nonglacial deposits	Silt and clay, with peat and tephra layers, with some sandy interbeds, laminated to massive.	15 to 25 m	Hard	Localized iron-oxide–cemented layers and sandy partings

(*continued*)

TABLE 2. DESCRIPTION OF MAP UNITS FOR GEOLOGIC MAP OF SEATTLE (*continued*)

Age & geologic unit	Name	Summary description	Thickness	Density/hardness	Permeability factors
Qob MIS 3 15–65 ka	Olympia beds of Minard and Booth (1988)	Sand, silt (locally organic-rich), gravel, and peat, discontinuously and thinly interbedded; may contain tephra and/or diatomaceous layers. Sand and gravel clast lithology varies depending on source area, from volcanic to reworked northern lithologies. Assigned to the Olympia interglaciation of Mullineaux et al. (1965) on the basis of stratigraphic position, correlation, and radiocarbon dates. Distinguished from Qvlc on the basis of coarser grain size and presence of organics. Locally identified previously as the "sandy phase of the Lawton."	Absent to 25 m	Very dense and hard	Localized iron-oxide–cemented layers, interbedded and intermixed fine- and coarse-grained layers
Qpo	Deposits of pre-Olympia age	Interbedded sand, gravel, silt, and diamicts of indeterminate age and origin. Locally divided into:	3 to >50 m	Very dense and hard	Localized iron-oxide–cemented layers, interbedded and intermixed fine- and coarse-grained layers
Qpof	Fine-grained deposits	Silt and clay, may have sandy interbeds, laminated to massive.	5 to 75 m	Hard	Localized iron-oxide–cemented layers and sandy partings
Qpoc	Coarse-grained deposits	Sand and gravel, clean to silty, with some silt layers, lightly to moderately oxidized.	3 to 22 m	Very dense	Localized iron-oxide–cemented layers and channels
Qpog	Glacial deposits	Silt, sand, gravel, and till of glacial origin. Weakly to strongly oxidized. Underlies Vashon-age deposits and thus must also be of pre-Olympia age. Sediment is of inferred glacial (northern) origin, based on presence of clasts or mineral grains requiring southward ice-sheet transport.	7 to >33 m	Very dense and hard	Localized iron-oxide–cemented layers, interbedded and intermixed fine- and coarse-grained layers
Qpogc	Coarse-grained glacial deposits	Sand and gravel, clean to silty, with some silt layers, moderately to heavily oxidized.	1 to 15 m	Very dense	Localized iron-oxide–cemented layers and channels
Qpogf	Fine-grained glacial deposits	Silt and clay, may have sandy interbeds, laminated to massive.	2 to 25 m	Hard	Localized iron-oxide–cemented layers and sandy partings
Qpogt	Till deposits	Till thick enough to show at map scale. Most extensive on west slopes of Queen Anne Hill, and in the west wall of the Duwamish valley.	Discontinuous, 1 to 10 m	Very dense and hard	Localized iron-oxide–cemented layers, sandy partings, and lenses
Qpogd	Glacial diamict	Till-like material, but finer grained and with fewer gravel clasts than most Puget Lowland tills.	Discontinuous, 3 to 7 m	Very dense and hard	Localized iron-oxide–cemented layers, sandy partings and lenses
Qpon	Nonglacial deposits	Sand, gravel, silt, clay, and organic deposits of inferred nonglacial origin, based on the presence of paleosols and tephra layers; or a southern Cascade Range provenance for sedimentary clasts.	3 to 23 m	Very dense and hard	Localized iron-oxide–cemented layers, interbedded and intermixed fine- and coarse-grained layers
Qponc	Coarse-grained nonglacial deposits	Sand and gravel, clean to silt, with silt layers, with peat and tephra layers, moderately to heavily oxidized.	3 to 13 m	Very dense	Localized iron-oxide–cemented layers, and channels
Qponf	Fine-grained nonglacial deposits	Silt and clay, may have sandy interbeds, with peat and tephra layers, laminated to massive.	3 to 23 m	Hard	Localized iron-oxide–cemented layers and sandy partings
Qpone	Estuarine deposits	Sand, silt (locally organic-rich), gravel, and peat, discontinuously and thinly interbedded. Identified on the basis of obligate brackish-water fossils (*Saltiniferous aquinus*). Qpone, as seen in this map area, is likely older than Qhc.	>10 m; outcrops in base of stream west of Poverty Hill	Very dense and hard	Localized iron-oxide–cemented layers

(*continued*)

TABLE 2. DESCRIPTION OF MAP UNITS FOR GEOLOGIC MAP OF SEATTLE (*continued*)

Age & geologic unit	Name	Summary description	Thickness	Density/hardness	Permeability factors
Qpd MIS 4, 70 ka	Possession Drift of Easterbrook et al. (1967)	Till, outwash, and glaciolacustrine deposits correlative with marine oxygen isotope stage (MIS) 4. May include glaciomarine drift. Possession-age deposits are likely more extensive than mapped, but deposits without age control are included in units Qpf or Qpo.	Not a surficial geologic map unit	Very dense and hard	Interbedded and intermixed fine- and coarse-grained layers
Qpdf	Possession glaciolacustrine deposits	Laminated silt and clay exposed along the west, north, and east faces of Beacon Hill; assigned to this unit based on a single infrared stimulated luminescence date just southeast of the Interstate 5–Interstate 90 junction. Correlative with marine isotope stage (MIS) 4, with an age range from 60 to 80 ka. Dated exposure displays strongly contorted and faulted beds, plausibly related to motion on the Seattle fault but also possibly a result of glaciotectonic shear or postglacial landsliding. Correlative diamict (unit Qpdt) is identifiable in subsurface borings and in outcrop to the south and is assigned to this unit based on spatial and stratigraphic proximity to dated exposure.	>34 m	Hard	Localized iron-oxide–cemented layers and sand partings; locally deformed and jointed
Qhc MIS 7, 200 ka	Hamm Creek formation	Interbedded gravel, sand, silt, clay, peat, and tephra beds. Informally named interglacial deposits corresponding to MIS 7, on the basis of two Ar/Ar dates each on pumice and tephra from three sites in southwest Seattle above the west edge of Duwamish River valley. Deposits of this stage have also been identified near Redondo, 23 km south of the city of Seattle and in south Snohomish County, 29 km north of the city of Seattle (Troost et al., 2003).	3 to 25 m; 2 m of tephra	Very dense and hard	Localized iron-oxide–cemented layers, interbedded and intermixed fine- and coarse-grained layers
Tertiary	BEDROCK				
Tbh Miocene	Blakely Harbor Formation of Fulmer (1975) (in the subsurface)	Interbedded terrestrial sandstone, siltstone, and shale, recognized only in subsurface data and assigned to this unit on the basis of lithology and stratigraphic position.	In the subsurface	Weakly lithified	Clayey when weathered, poorly cemented, jointed, folded, locally steeply dipping, shear zones
Tb Oligocene	Blakeley Formation of Weaver (1916a, 1916b)	Medium-grained sandstone, coarse-grained sandstone, conglomerate, and minor siltstone, fresh to highly weathered, fossiliferous. Massive to well bedded. Deposited in a shallow-marine nearshore sandy shelf environment. Distinguished from rocks of underlying Puget Group by presence of marine fossils and absence of volcanic-flow rocks and breccias.	>1000 m	Weakly to moderately lithified	Weathered zone is friable or soft and plastic, locally poorly cemented, jointed and folded, locally steeply dipping, shear zones
Tva L. Eocene or younger	Andesite	Dark gray basaltic andesite forming sills or dikes, intrudes younger Eocene rocks. Aboveground exposure mined from a hill in Duwamish valley	>100 m	Well lithified	Jointed
Tp Eocene	Puget Group of White (1888)	Micaceous feldspathic subquartzose sandstone, siltstone, claystone, and coal. Tabular beds of sandstone are massive to cross-bedded and occasionally exhibit channel cut-and-fill structures. Light to dark siltstones form poor outcrops, are commonly thinly laminated, and contain organic matter. Coal beds are as thick as 5 m. Locally divided into:	>1000 m	Moderately lithified	Variable permeability, jointed, folded
Tpt	Tukwila Formation of Vine (1962); Waldron (1962)	Andesitic sandstone, tuff, mudflow breccia, and minor lava flows or sills. Includes some marine and nonmarine sandstone, siltstone, and shale with scattered marine shells. Volcanic breccia, conglomerate, sandstone, and flows with intercalated feldspathic sandstone and impure coal beds. Tuff and breccia with clasts of porphyritic andesite and dacite and polymictic volcanic conglomerate appear to predominate, but flow rocks (in part sills or dikes) form resistant layers.	>1000 m	Moderately to well lithified	Variable permeability, jointed, folded

TABLE 3. DESCRIPTION OF BEDROCK UNITS IN THE SEATTLE AREA

Formation	Lithologic description	Distribution	Depositional environment	Thickness range	Elevation range	Type section loc./ref.
Blakely Harbor Formation (early Miocene)	Massive to thick-bedded pebble, cobble, and boulder conglomerate, interbedded with a few thin beds of mudstone, carbonaceous siltstone, coal, and sandstone. Conglomerate clasts are well rounded and composed almost entirely of basalt of the Crescent Formation (Olympic Peninsula). The basal part of this unit is poorly exposed dark gray carbonaceous siltstone with thin coal layers.	Around Blakely Harbor on Bainbridge Island, not recognized in Seattle	Nonmarine, fluvial	1035 m (3400 ft) exposed on Bainbridge Island	Not recognized above sea level in Seattle. 0 to 45 m (0 to 150 ft) on Bainbridge Island.	Shores of Blakely Harbor, Bainbridge Island; Fulmer (1975)
Blakeley Formation (late Eocene and Oligocene)	Medium-grained sandstone, coarse-grained sandstone, conglomerate, and minor siltstone, fresh to highly weathered. Lapilli tuff in Seward Park. Massive to well bedded. Fossiliferous in places. Cascade arc–derived (volcanic) clasts.	Newcastle Hills, Alki Point, southeast Seattle, Bainbridge Island	Near-shore marine, through deeper shelf, slope/apron (submarine fan)	>2135 m (>7000 ft)	0 to >455 m (0 to >1500 ft). 0 to ~105 m (0 to ~350 ft) in Seattle.	Restoration Point and Sinclair Inlet; Weaver (1916a, 1916b)
Puget Group (late and middle Eocene)	Micaceous feldspathic subquartzose sandstone, siltstone, claystone, and coal. Tabular beds of sandstone are massive to cross-bedded and occasionally exhibit channel cut-and-fill structures. Light to dark siltstones form poor outcrops, are commonly thinly laminated, and contain organic matter. Coal beds are as thick as 5 m. Locally divided into:	Coal Creek/Newcastle Hills area	Continental, arkosic debris and intra-basinal volcanics	See below	See below	White (1888)
Renton Formation (late and middle Eocene)	Fine- to coarse-grained feldspathic to lithofeldspathic subquartzose sandstone with interbedded siltstone, claystone, and coal. Leaf fossils.	Renton, Newcastle Hills, and Issaquah	Fluvial to nearshore marine rocks	640 m to 1220 m (2100 to 4000 ft)	90 m up to 465 m (300 ft to 1525 ft)	Southeast Renton between Cedar River and the I-405/ SR-161 interchange; Waldron et al. (1962)
Tukwila Formation (late and middle Eocene)	Volcanic breccia, conglomerate, sandstone, and flows with intercalated feldspathic sandstone and impure coal beds. Tuff and breccia with clasts of porphyritic andesite and dacite and polymictic volcanic conglomerate appear to predominate, but flow rocks (in part sills or dikes?) form resistant layers.	Tukwila, along I-5, south of Boeing access rd.; ridge former of Newcastle Hills	Sedimentary near volcanic center, lower part is marine (Nesbitt, 1998)	760 to 2135 m (2500 to 7000 ft)	Near sea level in Tukwila, up to 915 m (3000 ft)	Duwamish valley walls in north Tukwila near I-5/ SR-599 interchange; Waldron et al. (1962)
Tiger Mountain Formation (middle Eocene)	Light-colored, medium-grained, micaceous feldspathic subquartzose sandstone interbedded with siltstone, minor pebble conglomerate, and coal beds.	Tiger and Taylor Mountains, the Newcastle Hills	Prodelta? marine-shelf, fluvial	~610 m (~2000 ft)	Up to 855 m (2800 ft)	East and southeast slopes of Tiger Mountain; Vine (1962)
Raging River Formation (middle Eocene)	Shallow-marine and alluvial volcanic-rich sandstone, siltstone, shale, and minor conglomerate. Locally highly fossiliferous; plant remains common. Minor conglomerate predominantly consists of volcanic clasts but locally contains chert pebbles.	Newcastle Hills along Raging River	Shallow-marine transgression, fluvial, and marine shelf to bathyal slope	>915 m (>3000 ft)	275 m up to 490 m (900 ft to 1600 ft)	Above Raging River on east slopes of Tiger Mountain; Vine (1962)
Crescent Formation (early and middle Eocene)	Submarine and subaerial basalt flows, breccia, and interbedded sedimentary rocks. The submarine part consists of pillow lava, pillow and lapilli breccia, amygdaloidal lava flows, calcareous mudstone, basaltic siltstone, and sandstone.	Not exposed in the Seattle area, but underlies the Seattle sedimentary basin fill; exposed near Bremerton and east and north rims of the Olympic Mountains	Ocean ridge, accreted sea mount? Rift inside continental margin?	>16.1 km (>10 mi)	Sea level just southwest of Bremerton up to 2350 m (7700 ft)	Crescent Bay on the Strait of Juan de Fuca, north of Lake Crescent; Arnold (1906); Tabor and Cady (1978)

strength through alteration and decomposition of cementation, fracturing, and secondary FeO_2 mineralization.

Quaternary Deposits

At least seven invasions of glacial ice and intervening nonglacial episodes in the Puget Lowland (Fig. 6) have produced a discontinuous and complicated Quaternary stratigraphic record.

Strata predating the Vashon stade of the Fraser glaciation (Armstrong et al., 1965) are assigned to undivided pre-Fraser deposits (older than 14 ka), Olympia beds (following the time-stratigraphic nomenclature of Armstrong et al., 1965) (14 ka to 60 ka), or pre-Olympia deposits (older than 70 ka). Relatively little is known about the deposits older than ca. 20,000 yr in the Seattle area because they are largely buried by Vashon deposits or lie below sea level. Assignment of formal stratigraphic names is limited for the pre-Olympia deposits in Seattle because of a paucity of absolute age control and an abundance of unconformities. Pre-Vashon deposits cover ~9% of the land area of Seattle, and most of that area is on steep slopes (Plate 2C [see footnote 1]).

Pre-Olympia Deposits

Optically stimulated thermoluminescence (OSL), paleomagnetic measurements, and argon/argon dating are effective tools for subdividing pre-Olympia deposits in the Seattle area (Hagstrum et al., 2002; Mahan et al., 2003; R. Fleck, 2004, written commun.). Whidbey-age deposits, confirmed at the south end of Magnolia Hill near sea level, are too limited in extent to show at map scale. Reverse magnetization of a unique character correlating with the Blake subchron (Fig. 4) helps to identify Whidbey-age deposits in the Puget Lowland (Hagstrum et al., 2002). Possession-age fine-grained glaciolacustrine deposits are exposed under I-5 on the west side of Beacon Hill. Both of these geologic units were recently confirmed in the subsurface using OSL on samples from exploratory boreholes for the rapid transit tunnel in the University of Washington and Capitol Hill areas (D. McCormack and S. Mahan, 2008, written commun.).

Two other pre-Olympia–age deposits have also been recognized in Seattle: Hamm Creek ash and a pre-Olympia estuarine deposit. The informally named Hamm Creek interglaciation is based on ash deposits first identified in southwest Seattle in three different stream valleys; all named Hamm Creek (Troost et al., 2005). Argon/argon analyses on multiple samples yielded an average age of 200,000 ± 10,000 (Fleck, 2004, written commun.). The ash layers occur in a thick nonglacial deposit that has also been identified using OSL in other areas of the Puget Lowland (Mahan et al., 2003; Troost et al., 2003). Pre-Olympia estuarine deposits containing obligate species (E. Nesbitt, 2004, written commun.) have been identified below the Hamm Creek deposits. No age has been obtained on this unit.

Olympia Beds

The Olympia nonglacial interval (Armstrong et al., 1965) is defined as "the climatic episode immediately preceding the last major glaciation, and represented by nonglacial strata beneath Vashon Drift." The type section is at Fort Lawton at Discovery Park in Seattle (Fig. 10; Table 1). Olympia-age deposits accumulated between ca. 65,000 yr B.P. and 15,000 yr B.P. across the Puget Lowland, closely approximating the limiting ages for marine oxygen isotope stage 3. Sea level during the coldest part of the Olympia nonglacial interval (~40,000 yr ago) was ~65 m (213 ft) lower than today (Lambeck et al., 2002), so the amount of relief on the pre-Vashon topography was perhaps 500 m (1600 ft) across the Puget Lowland (Troost, 2006), with narrow channels and ridges and broad troughs. Many Puget Lowland troughs are ~65 m (200 ft) deep (Troost, 2006), consistent with the maximum low sea level during the Olympia nonglacial interval.

Environments represented by deposits of the Olympia nonglacial interval in the Seattle area include peat bogs, river valleys with floodplains, low-lying areas, lakes, and uplands. During at least part of the Olympia interval, the eastern side of the main trough of Puget Sound hosted north- and west-flowing streams. Macrofossil and pollen evidence at the type section (Armstrong et al., 1965) and on the beach opposite Me Kwa Mooks Park in West Seattle indicates a freshwater fluvial environment and climate somewhat cooler than today. The deposit on the beach in West Seattle consists of interbedded peat and organic silt (Fig. 11) that can be traced inland for 2 km where it is part of a thick unit that also contains gravel layers. The folding seen on the beach likely records movement in the Seattle fault zone; it could be related to paleolandsliding or glaciotectonic deformation.

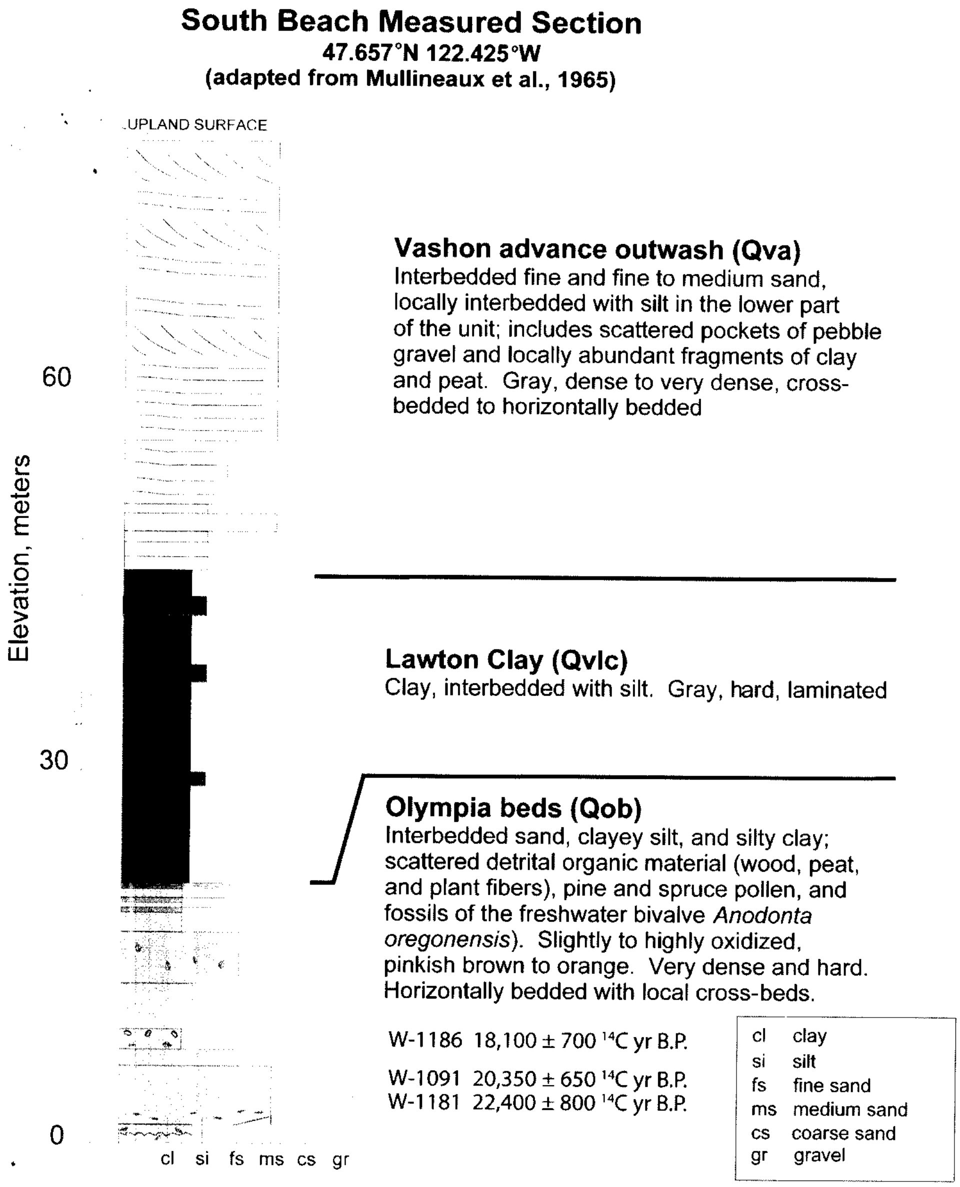
Olympia-age paleosols have been traced in the Capitol Hill subsurface for 2 km (Shannon & Wilson, 1999). Other organic-bearing deposits, older than 40,000 ^{14}C yr B.P., are exposed just above the Lake Washington shoreline in the northeast part of Seattle; they may reflect deposition during the first half of the Olympia nonglacial interval or, alternatively, during an older interglacial interval.

Pre-Fraser Deposits

The designation, "Pre-Fraser deposits," is a map unit used where no age control is available other than that the deposits are older than Vashon Drift, and that the deposits' origins are indistinguishable between glacial and nonglacial. Pre-Fraser deposits may be further subdivided by grain size.

Vashon Stade Deposits

During the Vashon stade of the Fraser glaciation (Fig. 6), ice advanced over Seattle. The stratigraphic record of this advance consists of proglacial lacustrine silt and clay, advance outwash sand and gravel, till, ice-contact deposits,



Vashon advance outwash (Qva)
Interbedded fine and fine to medium sand, locally interbedded with silt in the lower part of the unit; includes scattered pockets of pebble gravel and locally abundant fragments of clay and peat. Gray, dense to very dense, cross-bedded to horizontally bedded

Lawton Clay (Qvlc)
Clay, interbedded with silt. Gray, hard, laminated

Olympia beds (Qob)
Interbedded sand, clayey silt, and silty clay; scattered detrital organic material (wood, peat, and plant fibers), pine and spruce pollen, and fossils of the freshwater bivalve *Anodonta oregonensis*). Slightly to highly oxidized, pinkish brown to orange. Very dense and hard. Horizontally bedded with local cross-beds.

W-1186 18,100 ± 700 ^{14}C yr B.P.
W-1091 20,350 ± 650 ^{14}C yr B.P.
W-1181 22,400 ± 800 ^{14}C yr B.P.

cl	clay
si	silt
fs	fine sand
ms	medium sand
cs	coarse sand
gr	gravel

Figure 10. Measured section of the Esperance Sand and Lawton Clay Member of the Vashon Drift at Discovery Park (modified from Mullineaux et al., 1965).

and recessional deposits including outwash sand and gravel and lacustrine silt and clay (Plate 2D–2G). The Vashon advance outwash and proglacial lacustrine deposits were formally named as the Esperance Sand Member of the Vashon Drift and the Lawton Clay Member of the Vashon Drift by Mullineaux et al. (1965). The type section is at Fort Lawton at Discovery Park (Fig. 10; Table 1). The Lawton Clay was originally called the Pilchuck Clay Member of the Vashon Drift by Newcomb (1952). Vashon till was named for excellent exposures of till on Vashon Island, ~10 km west and southwest of Seattle (Fig. 7; Table 1).

Elevations at the top of the Lawton Clay are generally ~60 m (200 ft) above sea level and show little north-to-south variation since isostatic adjustments probably postdate most of the interval of deposition. Given this elevation, only the pre-Vashon–age valleys would have been inundated with water and therefore received this deposition. During ice advance, however, other upland lakes were also filling with sediment. Thus, time-correlative lacustrine deposits have been found at many elevations. Where Lawton Clay is encountered at high elevation (i.e., >60 m), and it is part of a main valley fill deposit, then tectonic uplift may have been involved.

Deposition of Lawton Clay marks a period of transition from interglacial to glacial climate and hence a change in vegetation. Wood debris is present but not common in the base of the Lawton Clay. The mineral vivianite is

Figure 11. Annotated photograph of doubly plunging syncline on low-tide beach across from Me Kwa Mooks Park in West Seattle. Boulder near center of syncline is 1.5 m high. This site is 1.5 km south of Alki Point and the northern edge of the Seattle uplift. Multiple folds are visible in 0.75 km of beach outcrop in the Olympia beds, which have been radiocarbon dated at 23,000–28,000 yr old. View is to southwest across Puget Sound. AMS –accelerator mass spectrometry.

also present, which is a secondary mineral resulting from the decay of organic matter in the presence of phosphate. Often, this chalky mineral (white, oxidizing to blue) is all that remains of organic matter. Another characteristic of the Lawton Clay, and other glaciolacustrine deposits, is the presence of calcareous concretions.

The term Esperance Sand was first used to describe the sand below the Vashon till in Snohomish County as having both an advance outwash origin and perhaps an older, pre-Vashon source (Newcomb, 1952). The term Esperance Sand was further defined to mean the Vashon advance outwash, the formal name first given to a distinctive sandy facies exposed in the cliffs of Fort Lawton (Mullineaux et al., 1965). This glaciofluvial deposit prograded in front of the advancing Vashon-age ice sheet, filling the lowland valleys and covering all but the bedrock promontories in the Puget Lowland (Booth, 1994). Outcrops of the Esperance Sand display evidence of braided and high-energy streams, deltas, and lacustrine environments. Deep channels cut into the underlying Lawton Clay (or older deposits) filled with advance outwash are present throughout Seattle, and they do not always coincide with the locations of previous channels or of modern valleys.

The advance outwash is predominantly permeable, clean, uniform sand. It is also the most voluminous deposit in Seattle. Where it rests on fine-grained material, groundwater accumulates, often emerging from hillsides in the form of springs and seeps.

Sandy advance outwash underlies most of the area, ranging in thickness from a few meters to 60 m (200 ft). Thick advance outwash is present under ~50% of the hills in Seattle, and elsewhere Vashon deposits drape pre-existing hills (Troost, 2006). Advance sand is now recognized at the ground surface across ~17% of the land surface of the city (Plate 2D [see footnote 1]), which is substantially more than the 11% mapped by Waldron et al. (1962).

Vashon till, formed at the base of the Puget Lobe, is predominantly a massive matrix-supported mixture of gravel, sand, and silt. Cobbles and boulders are present scattered throughout the till; however, boulders more than 3 m (10 ft) in diameter are uncommon. Till is present at the surface over ~40% of the city, commonly draping the topography, and even extending to below sea level. Based on >20,000 borings that penetrate the Vashon till, thickness varies from 1 to 30 m (3–100 ft) thick, averaging ~10 m.

The distribution of till across the landscape is neither regular nor continuous, even in drumlinized terrain (Troost et al., 2005); rather, it displays wide variations in thickness and has broad areas with no apparent deposition at all. Such patterns are well displayed across the geologic map of Seattle, particularly in areas of northwest and west Seattle. The surface underlain by till is locally fluted, with elongated hills displaying a prominent, north-south orientation. However, the surface underlain by Vashon advance outwash is also locally fluted, so this is not a reliable predictor of the presence of till, but it is a good indication of the type of outwash present, advance or recessional. The long axes of these drumlins and fluted topography record the ice-flow direction (Fig. 8).

Vashon till mantles the landscape and drapes the underlying topography, following slopes down to (and below) sea level, as seen in the west-central and east-central parts of the city. It rests both conformably and unconformably on the underlying outwash and unconformably on the pre-Vashon topography (Plate 2D–2E).

Where present at the surface, the till provides a low-permeability cover to underlying aquifers, reducing recharge but also offering some protection from surface contaminants. Abundant discontinuities within the till can increase its permeability by several orders of magnitude, however, allowing faster transmission of water and contaminants than the unfractured till matrix. Depending on subglacial conditions, the discontinuities may consist of intercalated sand and silt layers, joints, and/or bedding. Vashon till commonly contains sand lenses and fractures; outcrops of till without sand lenses and fractures are rare. Voids, reported by consultants and excavating contractors at 2–8 m in diameter, are uncommon in the till and presumably came from the melting of buried blocks of ice. W. Laprade (2004, personal commun.) reported that on the lee sides of drumlins in Seattle, Vashon till contains an abundance of sand bodies (Troost et al., 2004).

Subhorizontal to vertical joints are common in the Vashon till. Many primary and secondary processes create joints in till, including isostatic loading and unloading, glaciotectonic deformation, subglacial shearing, dewatering, frost-cracking and weathering, tectonic deformation, and stress release from adjacent landsliding (McGown and Derbyshire, 1977).

Ice-contact and recessional deposits are common in Seattle, constituting 12% of the map area (Plate 2F). Many of the recessional deposits occupy channels that are interconnected, particularly in the southeast part of Seattle. These interconnected channels also tie into former glacial lake elevations and often contain peat deposits where lakes have evolved to bogs. Rainier Valley in southeast Seattle is a good example of a former recessional lake channel that is filled with 18 m (60 ft) of soft silt and clay and contains isolated peat deposits. Kettle lakes occupy depressions once filled with blocks of ice; Green and Haller Lakes are good examples (Plate 2F).

The origin of the northwest-trending ship canal valley (Fig. 8) is unknown. However, its orientation parallels that of many other northwest-trending valleys, beach cliffs, and stream bends. This northwest strike is perpendicular to the direction of the subducting Juan de Fuca plate, consistent with the northwest-trending folds in the Eocene bedrock, and parallel to the Southern Whidbey Island fault zone and other major faults that cross Washington State, suggesting that bedrock structure may be reflected at the ground surface. More significantly, the natural segment of the ship canal aligns with the ice limit during the maximum extent of Lake Russell (Fig. 2). Depressions (Fig. 8) line the valley beneath the postglacial fill, suggesting that these depressions were scoured subglacially or as part of a subglacial trough during ice occupation. Other valleys in Seattle exhibit these same types of depressions.

Holocene Deposits

Since deglaciation, deposition includes alluvium, beach deposits, lake deposits, peat, topsoil development, colluvium, landslide debris, and artificial fill (Plate 2F–2H). On the upland surface, soil formation has proceeded slowly but with locally profound hydrologic consequences. The upper meter or so beneath an undisturbed surface usually consists of a poorly to well-developed A horizon underlain by silty weathered parent material. Unweathered Vashon till 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.

Colluvium. A few centimeters to several meters thick, colluvium covers nearly all of the slopes in Seattle. Colluvium is derived from creep and weathering; hence, it is a mixture of local materials. Colluvium and mass-wasting deposits are widespread, though seldom thick or continuous enough to map. However, where repeated landsliding has obscured the underlying geology and topography and discrete landslides are hard to differentiate, colluvium has been mapped (Plate 1, overprint pattern). This material is often unstable on steep slopes during repeated rainfall episodes.

Landslide Debris. Small landslides (<8 m across) are common on steep slopes; they consist of slumps and earth flows caused chiefly by wetting/saturation from heavy rainfall, surface erosion during long periods of rain, and (or) spring sapping. The large landslides that are the primary subject of this volume are found preferentially where subglacial erosion or wave erosion, stream erosion, or human activity has created steep slopes. They are enhanced wherever permeable deposits, most commonly Vashon advance outwash, overlie less permeable deposits that perch groundwater (Tubbs, 1974). They are also more common where groundwater flow is localized at the face of steep slopes, which is the topic of another chapter in this volume. Where landslides are young enough that debris and distinct morphology can be outlined on a map, the deposits are mapped using an overprint pattern (Plate 1). Landslide debris is also potentially unstable when it rests on a steep slope and becomes saturated. In many areas of Seattle, landslide deposits are known to exceed 20 m in thickness.

Artificial Fill. The landscape of Seattle has been significantly impacted by placement of fill and excavation during the early part of the century. Galster and Laprade (1991) presented an excellent description of the major fill and land modification events that have taken place in Seattle. For that reason, only a brief summary will be described here. The geologic map (Plate 1) shows different types of modified land as overprints, allowing the underlying geologic unit to be seen (Figs. 9A and 9B). Most of the land surface of Seattle has been altered in some way, if only for houses, landscaping, and streets. This ubiquitous but small amount of modified land is not mapped, even though it is enough to mask fault scarps.

Several scales of filling, landfilling, excavation, grading, and regrading are present in Seattle (Plate 2H). The "mega-scale events" took place from 1878 through the 1930s, and these include: regrading, and sluicing away of, Denny Hill, reclamation of the Duwamish tide flats, fill placement for the railroads, excavation for the Lake Washington ship canal, straightening of the Duwamish River into the Duwamish waterway by the U.S. Army Corps of Engineers, excavation of the Montlake cut and ship canal, and sluicing of the Dearborn cut (Morse, 1989). The "large-scale events" took place in the early to mid-1900s, and these include the construction of I-5 (1960–1966 inside city limits) and I-90, and many of the downtown buildings and shopping centers. Many "medium-scale events" took place throughout the 1970s for development of the city; these include the formation of landfills, and the placement of fill over bogs and soft ground to build shopping centers, parks, and schools. Many "small scale-events" include filling of the upper ends of gullies and ravines to provide more buildable land and extend yards and roads.

Prior to the excavation of the Montlake cut and the Lake Washington ship canal (Fig. 3), connecting Lake Washington to Lake Union, the elevations of the lakes were 9.1 m (30 ft) and 6.4 m (21 ft), respectively (Chrzastowski, 1983). When this project was completed by the U.S. Army Corps of Engineers in 1916, the level of Lake Washington was lowered by 3 m (10 ft). Several areas of bogs and soft ground were exposed when the lake was lowered, including Matthews Beach, Magnusson Park, south of University Village, Foster Island, Genesee Park, Atlantic City Park, and Lakeridge. Construction debris and other garbage were dumped on some of these low-lying areas, in particular, the area south of University Village and the Genesee playfields area.

Approximate reconstructions of Denny Hill and the north end of Beacon Hill (Plate 2K) can be made by evaluating construction records from the regrade activities, including sluicing and excavations (Morse, 1989; Beaton, 1914; Morse, 1928). These reconstructions show that just over 33 m (107 ft) were removed at the highest point of Denny Hill, which was south of Blanchard and 4th Avenue. In all, an area of 62 city blocks was affected, and 4.5 million m^3 (6 million yd^3) of drift were removed by pick and shovel, sluicing, and electric shovel (Galster and Laprade, 1991). Beacon Hill was originally continuous with First Hill at about elevation 52 m (170 ft) (Plate 2K) prior to the Beacon cut in 1907–1912, which was accomplished by sluicing material into the Duwamish tide flats to reclaim the tideland. The cut is ~27 m (90 ft) deep, exploiting an original low area along the hilltop, and it connects Rainier valley with the downtown and waterfront area, the original goal of then-city engineer R.H. Thomson.

Morse (1989) provided a summary of methods, contractors, politics, and geographic changes that occurred as a result of these and other monumental regrade projects in the city of Seattle. According to Morse (1989), ravines along Westlake and Fairview Avenues were filled in 1907 and 1908 in an effort to make the city more transportation friendly; combined, this required more than 88,000 m^3 (115,000 yd^3) of material. Material removed during the regrades was placed in several areas: offshore in Elliott Bay (as much as 23m [75 ft] thick; Morse, 1989), in the tide flats to reclaim the land (up to 12 m [40 ft] thick), on the waterfront to create land (up to 9 m [30 ft] thick), and along city streets to improve street grade (6 m [20 ft] common).

Much of the fill that was placed prior to the 1970s was not monitored for quality of materials or degree of compaction and therefore is of variable density and composition. Often, garbage and construction debris was used to fill ravines. Fill thickness and composition vary across the city. The presence of fill and fill/grading type are shown as overprints on the geologic map (Plate 1). Generally, fill is thicker in young valleys and on young geologic landforms where fill has been added to make an otherwise less suitable foundation material more suitable. Several landfills were also mapped based on identification of garbage in the borehole data.

FINDINGS OF THE NEW MAPPING

The following is a summary of the major findings resulting from the new geologic mapping and interpretations of the geology of Seattle.

Glacial Channels

The Duwamish River valley is a former subglacial trough and as such has an irregularly shaped bottom with depressions and ridges (Plate 2L [see footnote 1]). It filled postglacially with a combination of reworked outwash then with estuarine sediment from the north and alluvial sediment from the south, topped with reworked lahar deposits. Other large glacial channels have depressions lining their bottoms, for example, the northwest-southeast ship canal valley. These depressions make estimating the depth to glacially overridden material difficult when the depth can vary by as much as 30 m (100 ft) in short horizontal distances.

Channels similar to those present on the modern landscape are known to occur in the subsurface, often in seemingly random locations. For example, Shannon & Wilson (1999) found that a northwest-trending Vashon advance outwash sand-filled channel cuts through the north end of Capitol Hill. It rests upon a pre-Vashon sand-filled channel. The ground surface at the top of the hill belies the presence of these stacked channels.

Paleotopography and Unconformities

The modern topography is a good analog for the general characteristics of the paleotopography of previous interglacial periods—not every hill and valley has remained fixed in space, but the general organization of topographic elements and relief appear to be consistent. Multiple unconformities exist in the subsurface due to multiple dynamic periods of glacial occupation and long interglacial periods. The amount of relief on any of the paleotopographic surfaces could be as much as 500 m (1600 ft), a scale that is similar to that of the modern landscape. Steep angular unconformities should be expected, and they are well-documented in the subsurface and at outcrops throughout Seattle. Half of the hills in Seattle have thick Vashon-aged deposits and half are simply draped by thin Vashon-aged deposits.

Deposits

The sequence of glacial deposits is predictable, but long intervals of geologic time are commonly unrepresented by deposits in any given exposure or subsurface exploration. Lateral facies changes are common, and the locations are not predictable, except at the scale of the entire lowland itself. The distribution of till across the landscape and in the subsurface is neither predictable nor continuous. The spatial distribution of interglacial deposits is particularly problematic because we typically have no prior knowledge of the paleotopography.

Thick channel deposits are common in the subsurface: former subglacial troughs have been typically filled with silt and clay from subsequent proglacial lakes or by alluvial or volcanic silt, sand, and lahars; ice-recessional channels can be filled with coarse gravel and cobbles, gravel, sand, or silt. Every ravine, lake basin, stream and river channel, glacial flute, and subglacial trough will be filled during subsequent glaciations, giving rise to numerous buried "channels." Likewise, paleohills are common in the subsurface, but they may be cored with coarse-grained advance outwash or fine-grained proglacial lacustrine deposits of a previous glaciation, with a variety of interglacial deposits, or with a mix of deposits.

Some of the hills in Seattle are almost entirely cored by outwash sand, while others are cored by overconsolidated silt/clay; these differences are likely to affect earthquake-shaking amplification.

Distribution of Surficial Map Units

Across the surface of Seattle, beneath the fill, landslide debris, and colluvium, the distribution of geologic materials is as follows, based on the mapping by Troost et al. (2005): Holocene deposits 16%, Vashon deposits 72%, pre-Vashon deposits 9%, bedrock 3%. This differs in distribution from the 1962 map by Waldron et al. in several ways (Table 4). The most striking difference is that more pre-Vashon deposits were identified on the 2005 map by some 3000%.

One way to quantify the differences between the two maps is to compare the distribution within the Vashon deposits. More recessional and advance outwash and less till and Lawton Clay were mapped on the 2005 map than on the 1962 map. This difference in less till and more outwash is a common finding with the new era of geologic mapping.

Another way to quantify the differences between the two maps is to compare the distribution by lithologic parameters, such as the percentage of glacially overridden material (GOM), and also grain size (Table 4). As would be expected given the previous statement about outwash and till, more sandy material and less fine-grained material is mapped on the 2005 map (Plate 2M). With respect to non-overconsolidated deposits, the new map depicts 122% more recessional and postglacial deposits than the 1962 map (Plate 2F).

New Map Units

Several new geologic units have been identified in the Seattle area as a result of renewed interest in geologic mapping in the region and, hence, resources for geochronology. Both the Whidbey Formation and the Possession Drift have been confirmed in the Seattle area. In addition, a new geologic unit was identified, the Hamm Creek interglacial unit at ca. 200,000 yr. Somewhat younger than this, there is an estuarine deposit of an unknown age with obligate estuarine shells. Certainly, other named geologic units are present in the subsurface.

CONCLUSIONS AND IMPLICATIONS

Seattle has a rich geologic history complete with an active tectonic setting, active crustal faults, and multiple glaciations, all of which have left a variety of deposits at the surface and in the subsurface.

The distribution of Quaternary deposits in Seattle at a regional or local scale is controlled by unconformities and discontinuities, and their locations cannot be predicted without direct observation. Neither deductive nor inductive reasoning gives much basis to make predictions in the absence of site-specific data. About 50% of the hills in the Puget Lowland are cored with pre-Vashon–age deposits, and 50% are cored with Vashon-age deposits. In such an environment, there is no substitute for site-specific data.

TABLE 4. COMPARISON OF DISTRIBUTION OF GEOLOGIC MATERIALS BETWEEN 2005 AND 1962 GEOLOGIC MAPS OF SEATTLE[*]

Unit	2005 map %[†]	Difference %[§]	1962 map %[#]	Comment
Holocene deposits	16	94	17	Postglacial deposits, includes 8.5% mapped as modified land on the 1962 map
Vashon deposits	72	90	80	
Pre-Vashon deposits	9	3000	0.3	
Bedrock	3	111	2.7	
Qvr + Qvi	12	200	6	Qvr—Vashon recessional outwash; Qvi—Vashon ice-contact deposits
Qvt	41	73	56	Qvt—Vashon till
Qva	17	147	11.6	Qva—Vashon advance outwash, aka Esperance Sand
Qvlc	2.5	38	6.5	Qvlc—Lawton Clay
Non-GOM	28	122	23	Non-GOM—not overridden/compacted by the Vashon glacier
GOM	72	94	77	GOM—glacially overridden material
Fine-grained deposits	49	78	63	
Intermediate/interbedded	19	559	3.4	Includes bedrock
Coarse-grained deposits	32	128	25	
Unknown grain size	–	na	8.5	Includes the area mapped as modified land on the 1962 map
m	19.7	232	8.5	M—modified land; all fill (af) and modified land types were combined for this category; these are mapped as overprints on the 2005 map
Qls	5.3	3786	0.14	Qls—landslide debris or landslide, mapped as a geologic unit on the 1962 map but as an overprint on the 2005 map
Qmw	3.6	3600	–	Qmw—mass-wastage deposits, mapped as an overprint on the 2005 map

[*] Troost et al. (2005), *Geologic Map of Seattle*, and Waldron et al. (1962), *Preliminary Geologic Map of Seattle.*

[†] As a percentage of land area, exclusive of area covered by lakes.

[§] Difference from 1962 to 2005 map in percent.

[#] As a percentage of land area, exclusive of area covered by lakes.

Our knowledge of the geology of Seattle has expanded exponentially in the last decade for several reasons: improvements in technology, unprecedented expenditures on geologic mapping and hazards investigations, collaboration between researchers and consultants, and data sharing. Data sharing substantially improves new geologic mapping and our collective understanding of the geology of a region.

Many questions remain about the geology of Seattle. More absolute ages are needed, as are simple techniques for identifying glacial versus nonglacial deposits. Research is ongoing into to the geomorphic, tectonic, stratigraphic, and chronologic situation of the Seattle area and the Puget Lowland.

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