Lidar-Revised Geologic Map of the Des Moines 7.5' Quadrangle, King County, Washington

By Rowland W. Tabor and Derek B. Booth

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Introduction

This map is an interpretation of a modern lidar digital elevation model combined with the geology depicted on the Geologic Map of the Des Moines 7.5' Quadrangle, King County, Washington (Booth and Waldron, 2004). Booth and Waldron described, interpreted, and located the geology on the 1:24,000-scale topographic map of the Des Moines 7.5' quadrangle. The base map that they used was originally compiled in 1943 and revised using 1990 aerial photographs; it has 25-ft contours, nominal horizontal resolution of about 40 ft (12 m), and nominal mean vertical accuracy of about 10 ft (3 m). Similar to many geologic maps, much of the geology in the Booth and Waldron (2004) map was interpreted from landforms portrayed on the topographic map. In 2001, the Puget Sound Lidar Consortium obtained a lidar-derived digital elevation model (DEM) for much of the Puget Sound area, including the entire Des Moines 7.5' quadrangle. This new DEM has a horizontal resolution of about 6 ft (2 m) and a mean vertical accuracy of about 1 ft (0.3 m). The greater resolution and accuracy of the lidar DEM compared to topography constructed from air-photo stereo models have much improved the interpretation of geology, even in this heavily developed area, especially the distribution and relative age of some surficial deposits. For a brief description of the light detection and ranging (lidar) remote sensing method and this data acquisition program, see Haugerud and others (2003).

Base Map and Methodology

Geographic features on the topographic map of the Des Moines quadrangle are mislocated by as much as 400 ft (122 m) horizontally in relation to the same features on the lidar DEM. For this reason, contacts adopted in unrevised form from Booth and Waldron (2004) are shown as approximately located. We relocated sample localities and structural data from Booth and Waldron (2004) on the lidar DEM by inspection.

No digital-depiction compilation of rivers and streams adequately matches the DEM, so we relocated drainage lines to match thalwegs discernible on the DEM. We selected rivers and streams to digitize based on drainage shown on the Des Moines 1:24,000-scale topographic map. Road locations and some road names are from King County GIS data, with some locations corrected based on Google Earth views (image date, about 6/13).

We did no additional field work to make this revised map. Specific revisions derived from the lidar DEM are explained in the Description of Map Units and in the discussion in the Stratigraphy and Geologic History section. Much of the text, especially for the pre-Vashon glaciation units, is adapted from Booth and Waldron (2004).

Previous Mapping

The previous geologic map of the Des Moines 7.5' quadrangle (Booth and Waldron, 2004) relied heavily on the earlier mapping of Waldron (1962). Geologic data from the earlier map was used with little or no modification in the east-central part of the quadrangle; across most of the rest of the map area, geologic contacts and lithologic descriptions were revised only slightly by Booth and Waldron, primarily on the basis of extensive new construction-related exposures. However, Booth and Waldron (2004) did substantially revise the genetic classification and related stratigraphic nomenclature of deposits predating the Vashon glaciation, based on regional paleogeographic and stratigraphic models developed since 1962.

Booth revised the Waldron (1962) mapping sporadically in 1986 and more intensively in 1988–89, during preparation of watershed planning documents for the south half of the Des Moines quadrangle on behalf of King County. In 1992–93 and 1995, Booth resumed mapping in the watersheds of Salmon Creek, Miller Creek, and Des Moines Creek. Field work in 1996–98 concentrated on coastal exposures along Puget Sound. In 2004, Kathy Goetz Troost (University of Washington) provided additional mapping data along the north boundary of the quadrangle. Geology within a 0.5-km-wide strip at the north edge of the quadrangle (extending south to about lat 47°29'42.3" N.) is taken, with minor changes, from a preliminary geologic map of the Seattle area (Troost and others, 2005).

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Geologic Summary

The geology of the Des Moines 7.5' quadrangle expresses much of the tremendous range of Quaternary environments and deposits found throughout the central Puget Lowland. The topography is dominated by an extensive upland plain, mantled by a rolling surface of glacial till deposited about 17,000 years (14,000 radiocarbon years) ago during the last occupation of the Puget Lowland by a great continental ice sheet. Between the hills of this upland surface, and in places lapping up onto their flanks, are the remnants of deposits of long-vanished rivers that issued from the southern margin of the ice sheet as it melted and retreated to the north.

Beneath these ice-sheet deposits is a complex sequence of unconsolidated sediments that spans most of the quadrangle and that extends far below sea level. These older sediments are exposed only where streams and waves have eroded through the younger glacial deposits—notably by the Green River and the now infilled Duwamish estuary; along Puget Sound to the west; and along Des Moines Creek, Miller Creek, and several smaller drainages. The older sediments are very dense, having been compacted by thick masses of ice during one or more episodes of glaciation. Many are also cemented by iron oxides and hydroxides, a consequence of many tens or hundreds of thousands of years of surficial weathering and subsurface hydrologic processes. Excellent exposures of this older Pleistocene sequence are displayed in the coastal bluffs, although human activity is concealing these exposures at a rapid rate.

Bedrock is exposed only in the northeast corner of the quadrangle. Indeed, over most of the map area, rock typically lies at depths of from 1,000 to more than 4,900 ft (300 to more than 1,500 m) (Jones, 1996) under the Pleistocene deposits. Exposed bedrock consists of marine and continental sedimentary and minor volcanic rocks and isolated intrusions, all of early Tertiary age. The thickness of these Tertiary rocks cannot be accurately measured in the quadrangle, but more extensive exposures farther east indicate a thickness in excess of 2 km (Mullineaux, 1970).

The quadrangle also is located at the center of the intensively developing urban core of the Puget Lowland region. Only a few kilometers to the north lies the city of Seattle; about 20 km to the south is the city of Tacoma. Within the boundaries of the quadrangle lie all or part of the cities of Kent, Burien, Des Moines, Normandy Park, SeaTac, and Tukwila, having a combined population in the quadrangle in 2010 of almost 208,000. Seattle-Tacoma International Airport is located near the center of the quadrangle, perched high in the center of the upland plain. Interstate 5 (I–5), the main north-south highway through the Pacific Northwest, traverses the entire length of the quadrangle. Increasing population and a strong transportation network have fostered urban and suburban development in almost every area of the quadrangle. This development, in turn, is causing some of the most rapid geomorphic changes to occur since the wastage of the ice sheet.

Stratigraphy and Geologic History

Bedrock

The unconsolidated Pleistocene sediments of the east-central Puget Lowland are underlain by Eocene to Miocene volcanic and sedimentary rocks (Yount and Gower, 1991; Tabor and others, 2000). In the Des Moines 7.5' quadrangle, Tertiary rocks are exposed only in the northeast corner of the Des Moines quadrangle, where younger glacial deposits lap onto them in the southwest limb of the Newcastle Anticline of Weaver (1916). This major regional fold structure is expressed as a bedrock high that projects northwest 50 km into the Puget Lowland from the front of the Cascade Range (Mullineaux, 1970; Booth and Minard, 1992).

Puget Group

The name Puget Group was applied by White (1888) and later by Willis (1898a) to thick, continental and brackish-water, coal-bearing arkosic sandstone and shale that Willis (1886) had previously called the "Coal measures of the Puget Sound basin." As used in this report, the Puget Group includes not only these arkosic rocks but continental volcaniclastic sedimentary rocks that are interstratified with part of the Puget Group of White (1888) and Willis (1898a). Waldron (1962) divided deposits of the Puget Group exposed in the Des Moines quadrangle into two main parts: a lower assemblage of volcanic and sedimentary rocks that he called the Tukwila Formation; and an upper unit of arkosic sedimentary rocks, the Renton Formation.

Tukwila Formation

The Tukwila Formation (unit Tpt) is named for the town of Tukwila, where beds in the lower part of the Puget Group crop out nearby in secs. 11 and 14, T. 23 N., R. 4 E. The formation primarily consists of a lower volcanic sedimentary rock unit; at least two arkosic units (Tpta), about mid-section, that are lithologically similar to arkosic rocks of the overlying Renton Formation; and an upper volcanic sedimentary rock unit. Near or at the bottom of the unit are marine and nonmarine arkosic and volcaniclastic sedimentary rocks (unit Tptm). The total thickness is probably more than 2,600 ft (800 m) in the quadrangle. The Tukwila Formation is conformably overlain by the Renton Formation.

The volcanic sedimentary rocks of the Tukwila Formation mainly consist of sandstone, siltstone, and shale; they also include some conglomerate, tuff, tuffaceous sandstone, and minor amounts of carbonaceous shale. Fragments of wood and other plant remains are widespread. Most rocks are various shades of brown; some of the finer grained tuffs, however, are light gray to light grayish yellow, and a few are almost white. For the most part, the rocks are poorly bedded and poorly sorted; some of the finer grained tuffaceous rocks, however, are thinly bedded and well sorted. Sandstone and conglomerate are composed chiefly of subangular to subrounded fragments of andesite and basaltic andesite embedded in a matrix of silt, iron oxide, and clay minerals; grains of plagioclase, pyroxene, and small amounts of quartz are also present.

Middle Eocene marine and nonmarine sedimentary rocks (unit Tptm) crop out at the north edge of the quadrangle (secs. 9 and 10, T. 23 N., R. 4 E.). These rocks are part of a sequence of interbedded marine and nonmarine arkosic and volcaniclastic sedimentary rocks that Waldron (1962) and Waldron and others (1962) assigned to an unnamed unit distinct from the Puget Group. However, like Yount and Gower (1991), we instead include these rocks in the overlying Tukwila Formation.

Renton Formation

The Renton Formation (unit Tpr) is named for the city of Renton, located a few kilometers east of the Des Moines quadrangle. The formation includes the Renton coal measures, which were extensively mined at and near Renton in the early part of the 20th century. Mullineaux (1970) describes the formation exposed in the town of Renton in the adjacent Renton 7.5' quadrangle, where the total thickness of the formation is probably more than 3,300 ft (1,000 m), but the top is not exposed.

Most of the formation consists of fine- to medium-grained arkosic and feldspathic sandstone, interbedded with lesser amounts of siltstone, sandy shale, coal, and carbonaceous shale. Sandstone typically contains at least 40 percent subangular to subrounded quartz grains, 10 to 25 percent feldspar, and some mica and rock fragments, in a matrix of calcite, clay, and silt. Chert fragments constitute as much as 20 percent of some sandstones. Unoxidized rocks are mostly light gray but are light brown or buff where oxidized. The sandstone is weakly cemented, most commonly with calcite, but in places matrix silt and clay act as the binding agent. The sandstone and siltstone commonly are well sorted and thinly bedded; locally, the sandstone is massive or crossbedded. Some beds in the formation are very soft and plastic when wet, owing to the weathering or alteration of feldspar to a montmorillonitic clay.

Origin and Age of the Puget Group

Detrital mineralogy and lithology of the Puget Group indicate that these sedimentary rocks were derived chiefly from a distant eastern source of granites or gneisses. Volcanic debris, probably ejected from nearby vents, locally dominated sedimentation. Sediments of the group probably were deposited on a low-lying coastal plain that bordered a slowly subsiding marine basin (Weaver, 1937). Turner and others (1983) reported a 41-Ma fission-track age and a 42-Ma hornblende K-Ar age (both late Eocene) from the upper part of the Tukwila Formation near Newcastle, about 9.4 mi (15 km) northeast of the Des Moines quadrangle. They considered both the Tukwila Formation and the Renton Formation to be middle and late Eocene (compare with Wolfe, 1968). Yount and Gower (1991) reported possible Refugian (late Eocene) foraminifera from strata that overlie the Renton Formation 8 km north of the Des Moines quadrangle. Waldron (1962) first suggested that marine rocks (unit Tptm) at the base of the Tukwila Formation might be as old as late middle Eocene; and Rau (unpub. data, *in* Yount and Gower, 1991) subsequently reported Ulatisian (late early Eocene to middle middle Eocene) foraminifera from these rocks.

Intrusive Igneous Rocks

Irregular masses of andesite and basalt (unit Ti) crop out at several localities directly west of the Green and Duwamish Rivers near Tukwila and Duwamish. These bodies appear to have intruded the Puget Group, which would require them to be late Eocene or younger. Waldron (1962) reported a baked zone a few centimeters wide within sedimentary rocks adjacent to one such basaltic mass that was formerly exposed in a quarry in sec. 10, T. 23 N., R. 4 E. The andesite and basalt have columnar structure in some places. Their color varies from black to various shades of brown. Most are fine grained and porphyritic; macroscopic mineral grains include plagioclase and mafic minerals. The rocks contain at least 50 percent plagioclase, generally some pyroxene, and a glassy or altered matrix. Interstitial glass is fairly fresh in some of the rocks; in others it is altered to palagonite, nontronite, or a mixture of carbonate and clay minerals.

Ice Occupation of the Quadrangle

Stratigraphic Framework of the Ice Deposits

Multiple invasions of glacial ice into the Puget Lowland have left a discontinuous record of Pleistocene glacial and interglacial periods. The ice was part of the Cordilleran ice sheet of northwestern North America, which originated to the north in the mountains of British Columbia (Booth and others, 2004). During each successive glaciation, the ice sheet advanced into the lowland as a broad tongue, first called the Puget lobe by Bretz (1913).

The coastal bluffs and valley walls of the Des Moines quadrangle display some of the best exposures of glacial and nonglacial deposits in the south-central Puget Lowland, but their interpretation has proven to be enigmatic to geologists for more than 100 years (for example, Willis and Smith, 1899). By analogy to deposits described in detail by Crandell (1963) along the east wall of the Puyallup River valley, about 30 km south of the quadrangle, the beach-cliff and valley-wall deposits in the map area were subdivided by Waldron (1962) into older glacial ("Salmon Springs") and nonglacial ("Puyallup") units, as originally named by Crandell (1963). However, continued study over the last three decades has suggested that the sequence of older sediments is more complex than originally thought. Conclusive interpretation is hampered by the fact that sand, gravel, silt, and clay tend to be thinly interbedded, and individual layers commonly cannot be traced unequivocally even from one ravine to the next. This sequence of older sediments undoubtedly records the complex interfingering of two unrelated, but overlapping, geologic phenomena—glacial advances from British Columbia and volcanic eruptions from Mount Rainier, about 50 mi (80 km) to the southeast—that are superimposed on the less dramatic, but still ongoing, westward transport of river-borne sediment from the Cascade Range. Glacial deposits can be discriminated from nonglacial deposits in many parts of the Puget Lowland on the basis of rock and mineral assemblages that are related to different source areas.

Three major source areas have been determined as having contributed rock clasts and mineral grains to the lowland deposits:

- *Northern provenance*—characterized by igneous and high-grade metamorphic rocks and minerals derived from the North Cascades and Coast Range of British Columbia that require ice-sheet transport during glacial periods;
- *Central Cascade provenance*—characterized by Tertiary-age igneous rocks and minerals, primarily of volcanic origin, that match rocks of the Cascade Range east and southeast of the quadrangle and require only river transport for their appearance here; and

- *Mount Rainier provenance*—characterized by hypersthene andesite of probable flow and pyroclastic origin from Mount Rainier that may have been carried to the quadrangle, either by normal fluvial transport or by volcanic mudflows (lahars).

Some detritus of both the Central Cascade and Mount Rainier provenances was initially eroded and transported by local alpine glaciers; however, as such detritus was ultimately delivered to the Des Moines quadrangle by lowland streams, it is generally indistinguishable from exclusively stream-transported materials.

The naming and regional correlation of individual glacial advances in the Puget Lowland has a long history that is still evolving. Willis (1898b) was first to describe multiple glaciations in the Puget Lowland. Much later, Crandell and others (1958) proposed a sequence of four glaciations separated by nonglacial intervals, on the basis of stratigraphic sequences in the southern Puget Lowland about 20 mi (30 km) southeast of the Des Moines quadrangle. In the northern Puget Lowland, Easterbrook and others (1967) named and described deposits of three glaciations and intervening nonglacial intervals. Further efforts at dating these spatially isolated stratigraphic sequences (Easterbrook and others, 1981; Westgate and others, 1987), however, have suggested little correlation between the southern and northern sequences. In its type area south-southeast of the Des Moines quadrangle, the Salmon Springs Drift of Crandell and others (1958), which immediately underlies drift of the most recent ice-sheet advance (the Vashon stade of the Fraser glaciation of Armstrong and others, 1965), is inferred to be more than 781,000 years old on the basis of reversely magnetized sediment within the unit that Easterbrook and others (1981) assigned to the Matuyama reversed polarity chron. In contrast, the pre-Vashon glacial deposits in the north-central Puget Lowland (the Possession and Double Bluff Drifts of Easterbrook and others, 1967) have been dated between 250,000 and 80,000 years old with amino acid racemization and paleomagnetic techniques (Blunt and others, 1987).

Subsequent age determinations in the southern Puget Lowland have been relatively sparse. In the northern part of the Maple Valley 7.5' quadrangle, paleomagnetic studies have shown that the lowermost till in a sequence of three tills near the base of the north Cedar River valley wall (sec. 24, T. 23 N., R. 5 E., about 6 mi [10 km] due east of the Des Moines quadrangle) is normally magnetized (D. Easterbrook, written commun., *in* Booth, 1995). This suggests that the entire exposed section of Quaternary sediments in that area is younger than 781,000 years old, thus postdating the Salmon Springs glaciation. In addition, Mullineaux (1970, p. 42–43) judged that sediments immediately west of the Cedar River valley paleomagnetic sample locality did not correlate with the Salmon Springs Drift or any of the other exposed older drift units, although he lacked quantitative evidence to confirm that judgment.

In contrast, Booth and Waldron (2004) reported reversely magnetized sediment in several coastal exposures in the Des Moines quadrangle (samples T6079, T6084, T8098; Hagstrum and others, 2002). In particular, samples T6079 and T6084, from the 1.5-mi-long (2-km-long) bluff between Zenith and the southern quadrangle boundary, provide evidence of pre-781,000-yr-old glacial deposits within one of the most complete Pleistocene successions exposed between Seattle and Tacoma.

Four ^{14}C ages have been determined from deposits in the quadrangle (summarized in table 1). An age of greater than 37,000 yr before present (B.P.) was obtained by Rubin and Suess (1956) from a bed of woody peat that overlies a mudflow complex in unit Qrn (sample W-259). Patrick Seabeck (written commun., 1982) collected three samples of peat (samples GX-8933, GX-8934, and GX-8935) along the proposed alignment of a sewer tunnel that runs from the edge of the Green River valley, just south of Southcenter Mall, west to Puget Sound in Ed Munro Seahurst Park. The three samples are from deposits we map as units Qpff and Qpfnf, and all give ages older than 37,000 yr B.P.; lacking additional stratigraphic constraints, the deposits are either Olympia or pre-Olympia in age.

Table 1. Carbon-14 (^{14}C) ages of samples from the Des Moines quadrangle, Washington.

Sample No.	Location	Lidar DEM elevation, feet (meters)	Material	Age (^{14}C yr B.P.)	Map unit	Collected by	Reference
W-259	SW¼ sec. 17, T. 22 N., R. 4 E.	7 (2)	woody peat	>37,000	Qrn	H. Waldron	Rubin and Suess, 1956
GX-8933	SE¼NE¼ sec. 13, T. 22 N., R. 3 E.	100 (30)	peat	>37,000	Qpff	P. Seabeck	This report
GX-8934	SE¼NE¼ sec. 13, T. 22 N., R. 3 E.	100 (30)	peat	>37,000	Qpff	P. Seabeck	This report
GX-8935	NE¼SW¼ sec. 26, T23N., R. 4 E.	100 (30)	peat	>37,000	Qpfnf	P. Seabeck	This report

Deposits Predating the Vashon Stade of the Fraser Glaciation

Various kinds of water-lain sediments are exposed beneath deposits of the most recent ice-sheet advance, mainly along the Puget Sound coastline but also sporadically across the rest of the quadrangle. The thickness of individual layers ranges from a few feet to about 35 ft (10 m), but none can be traced continuously for more than a few miles. The deposits are subdivided primarily on the basis of age, but because existing age determinations are generally imprecise, Booth and Waldron (2004) specified only coarse stratigraphic divisions.

The oldest deposits in the quadrangle are reversely magnetized and appear to be more than 781,000 years old. In places where reverse polarity has been measured directly or is inferred from stratigraphic position, the material is assigned to reversely magnetized, fine-grained glacial deposits (unit Qrgf) and reversely magnetized nonglacial deposits (unit Qrn). Where no paleomagnetic evidence is available, the pre-Fraser deposits (unit Qpf) are subdivided on the map, if at all, only on the basis of their presumed depositional environments but not by age. Exposures are not everywhere adequate to determine the depositional environment with confidence.

Where organic material or volcanic sediment is abundant, Booth and Waldron (2004) generally inferred nonglacial origins. Deposits containing sand and (or) gravel of North Cascade or British Columbia provenance, or that display sedimentary features characteristic of glacial or proglacial environments, were presumed to be glacial in origin. Because all pre-Fraser glacial periods also precede the Olympia nonglacial interval of Armstrong and others (1965), all pre-Fraser glacial deposits were mapped as unit Qpogc.

Booth and Waldron (2004) divided the pre-Fraser and pre-Olympia deposits into two main groups on the basis of grain size: coarse deposits composed predominantly of gravel and sand (units Qpfc, Qpfnc, and Qpogc) and fine deposits composed predominantly of silt and clay (units Qpff, Qpfnf, and Qpof). Unit Qpone, exposed in the northeast corner of the map, is a mixture of coarse and fine materials with brackish-water fauna and is identified by Troost and others (2005) as estuarine deposits. Most coarse-grained pre-Fraser deposits exposed along the Puget Sound coastline appear to be of glacial origin (unit Qpogc) and, in most places, they overlie fine-grained pre-Fraser deposits.

Along the west wall of the Green River valley, many of the coarse-grained pre-Fraser deposits are volcanic-rich and probably reflect a Pleistocene record of mudflows during nonglacial intervals from the vicinity of the modern Mount Rainier. The best example of such volcanic-rich material crops out laterally along the base of the sea bluff near and south of Zenith; Waldron (1962) originally mapped these deposits as Puyallup Formation. We map them as reversely magnetized nonglacial deposits, unit Qrn. At this coastal location, the unit is silt, fine to medium sand, clay, ash, peat, and a mudflow complex as much as 100 ft (30 m) thick, but the base is not exposed. The mudflow complex consists of at least two flows that are composed chiefly of rock fragments of Mount Rainier provenance, separated by a 1-m-thick bed of laminated clays. The best exposures of this mudflow complex were once visible about 0.75 mi (1.2 km) south of the mouth of Massey Creek, at paleomagnetic sample locality T6084 (see geologic map). At this site, the upper mudflow overlies about 3 ft (1 m) of thinly interlaminated peat and silt, which in turn overlie 4.3 ft (1.3 m) of sand and mudflow deposits of Mount Rainier provenance. This exposure, including the sample site, was locally known as the "Zebra beds" for its alternating light and dark layers of silt and peat, but it was covered by a rock bulkhead sometime between 1988 and 1993. Above the mudflows, lacustrine sediment contains numerous fragments of white pumice and trunks, limbs, and roots of trees, some of which are several feet long. The same wood-bearing lacustrine stratum is presently well exposed in the bluffs about 1,600–2,300 ft (0.5–0.7 km) south of the mouth of Massey Creek; here, the large wood fragments are elliptical in cross section, having apparently been progressively flattened by the weight of overlying sediment and successive ice-sheets. The uninterrupted transport of woody debris out to what is now the coast of Puget Sound implies that the continuous upland area present today between the Green River valley and Puget Sound must have been absent when the lake sediments were accumulating.

We do not assign stratigraphic names to subdivisions of the pre-Fraser deposits, in part because absolute age control is presently limited and the likelihood of spurious correlations is high. Local diamicts of presumed pre-Olympia glacial origin are shown with an X-decorated line within areas of units Qpof and Qpogc. Their absence elsewhere on the map likely reflects the discontinuous nature of these deposits, as well as the generally poor quality of exposure, even on steep sparsely vegetated slopes.

Deposits of the Vashon Stade of the Fraser Glaciation

In contrast to the uncertainties in ages and stratigraphic assignment of older Pleistocene glacial and nonglacial deposits, the deposits at or near the land surface are confidently assigned to the youngest regionally recognized glacial advance, the Vashon stade of the Fraser glaciation (Armstrong and others, 1965). During this time an ice sheet advanced southward along the axis of the Puget Lowland (Clague, 1981). This ice sheet reached its maximum extent about 17,000 (14,000 radiocarbon) yr B.P. and covered the Puget Lowland to a maximum depth of about 5,000 ft (1,500 m) (Booth, 1987; Porter and Swanson, 1998). Deposits of the Vashon stade have various textural characteristics and topographic expressions, owing to rapidly changing depositional environments during the advance and retreat of the ice sheet. As the ice first advanced, it blocked northward lowland drainage out the Strait of Juan de Fuca, which presently connects Puget Sound with the Pacific Ocean. In the impounded lakes that formed during the resulting change to southerly drainage out of the Puget Lowland, laminated silt and clay were deposited. This material has been mapped to the north and east as either the Lawton Clay Member (see, for example, Waldron and others, 1962) or "transitional beds" (see, for example, Minard and Booth, 1988; Yount and others, 1993). Lawton Clay has also been mapped to the west in the Olalla quadrangle (Booth and Troost, 2005; Tabor and others, 2013) and the Vashon quadrangle (Booth and others, 2015). The expression “transitional beds” connotes the possibility that the unit may include deposits of pre-Vashon lowland lakes, in addition to those of the subsequent ice-dammed lakes. Although this depositional environment probably existed in the Des Moines quadrangle during both pre- and early-glacial time, we have recognized no mappable deposits correlative with the Lawton Clay or “transitional beds” in the map area.

Postglacial Processes and Deposits

Most of the lower slopes of both the coastal bluffs and the Green River valley are mantled by colluvial deposits formed by episodic landslides and ubiquitous soil creep. Interbedded coarse- and fine-grained sediment greatly impedes the vertical descent of percolating groundwater, which makes the exposed slopes very susceptible to landslides. In these environments, wave or river erosion has developed and maintained steep slopes, and emergent groundwater promotes continued instability. Several ravines descend these slopes, particularly to the east into the Green River valley, where urban development has occurred in the heads of these ravines, the rate of channel incision has increased dramatically, and the underlying glacial and nonglacial deposits are well exposed.

Older and younger landslide deposits (units Qols and Qls) are concentrated along the relatively steeper slopes bordering Puget Sound and the valley of the Green and Duwamish Rivers. The largest landslide involves ice-contact deposits along the Green River valley wall that may have experienced some collapse immediately following deposition and subsequent ice-sheet retreat. Its distinct headscarp and the topographic character of its slumped deposits, which are comparable in scale and appearance to other large landslides recognized across the region, suggest more recent movement as well.

The large Fenwick block slide, which also collapsed eastward into the Green River valley, is best exposed at Lake Fenwick in the Poverty Bay quadrangle to the south. Units Qva, Qvt, and Qvr of this quadrangle have moved down to the east without disruption, although the scarp is clearly visible in the lidar DEM. As with the massive multiple slides to the north (unit Qols), movement probably followed shortly after an ice tongue melted back in the Green River valley.

Colluvium, a few centimeters to a few meters thick, covers nearly all the valley walls and slopes. It consists of a mixture of locally derived materials, principally loosely consolidated silty sand and gravel. Small landslides, common in the steep bluffs and slopes, consist of slumps and earth flows caused chiefly by surf erosion or spring sapping. The ravines and coastal bluffs are replete with such slides, which, although too small to show on the map, can be extremely hazardous in populated areas. Those steep slopes having fine-grained deposits (for example, units Qpff or Qpfnf) overlain by coarse-grained deposits (for example, units Qpogc or Qva) are particularly susceptible to failure. This condition is found in most of the steeply sloping parts of the map area.

Mount Rainier Mudflows

Mount Rainier has exerted a profound influence on the Quaternary geology of the quadrangle, even though drainage from this active volcano does not currently enter directly into the Green River or Duwamish River. Episodic eruptions have triggered massive landslides on the flanks of the mountain, whose debris materials in turn mix with water from the rapidly melting snowfields and glaciers. The resulting slurry of mixed sediment moves rapidly as mudflows (or “lahars”) down one or more of the river valleys that radiate from the mountain, emerging out onto the lowland.

The Osceola mudflow of Crandell and Waldron (1956) is one of the largest recognized volcanic mudflows in the world. Originally thought to be an alpine till (Willis, 1898b), it was later recognized as a lahar deposit from Mount Rainier. The lahar flowed down the flanks of the volcano largely in the valley of the White River, but it spread mainly northward upon reaching the Puget Lowland. It entered what is today the Green River valley south of Auburn, about 6 mi (10 km) southeast of the quadrangle, and continued north past the city of Kent into the Duwamish River valley. At the time of the eruption about 5,700 years ago, the lahar deposit covered an area of at least 128 mi^2 (330 km^2); its average thickness now is about 25 ft (8 m), and its volume is estimated at nearly 0.96 mi^3(4 km^3) (Dragovich and others, 1994). The deposit can be recognized because of its groundwater-retarding properties, even at depths of more than 200 ft (60 m) below the modern ground surface (Dragovich and others, 1994).

Besides indicating a major volcanic mudflow hazard for many residential communities in the southeastern Puget Sound region (Vallance and Scott, 1997; see also http://volcanoes.usgs.gov/volcanoes/mount_rainier/mount_rainier_geo_hist_79.html), the Osceola mudflow is a useful stratigraphic marker, especially in the lower Green River and Duwamish River valleys. All of the 100–200 ft (30–60 m) of sediment that overlies the mudflow, which now fills these valleys from Auburn northward into the Des Moines quadrangle and farther northwest to the modern shore of Puget Sound, have been deposited by river transport in the last 5,700 years. The mouth of the Green-Duwamish River estuary has advanced northward about 30 mi (50 km) during that time, at a rate of about 30 ft (9 m) per year. This rapid advance reflects the dominant sedimentary contribution of the White River, which flowed northward down the (modern) Green River valley during most of the last 5,700 years. This river carried the voluminous products of both normal fluvial transport and volcanic mudflows throughout much of the late Holocene (Dragovich and others, 1994).

Human Modification of the Landscape

In this highly developed region, human modification of the land surface is ubiquitous. Booth and Waldron (2004) elected to map modified land (unit m) only sparingly, even omitting some of the areas so designated by Waldron (1962), in order to depict more completely the underlying geology. The largest area of modified land by Booth and Waldron (2004) is the Seattle-Tacoma International Airport, which as of 2011 had grown even larger. Our depiction is based on June 2011 Google Earth imagery. We have also mapped other areas as man-modified land, including most of the major highway corridors and clearly adjoining developments, but have indicated concealed geologic contacts beneath fill. Booth and Waldron (2004) mention two local areas of potentially problematic ground response (for example, liquefaction during earthquakes) that they did not map as fill: the Midway Landfill and the Kent Highlands Landfill. The Midway Landfill (E1/2 sec. 21, T. 22 N., R. 4 E.) is shown as a closed depression on the Des Moines 1949 topographic map (revised in 1995). Excavations at the site once revealed a gently east-dipping contact between overlying advance outwash deposits and underlying oxidized gravel and sand (probable unit Qpfc) at about 330 ft (100 m) elevation (Parametrix, 1988). Recent boreholes at the Kent Highlands Landfill show this same contact at an elevation of 200 ft (60 m) (CH2M Hill, 1991). We also have added a diagonal-line pattern to the map over hard-surface areas that generally consist of 80–100 percent concrete or asphalt pavement and large buildings, interspersed with some landscaped areas. The boundaries of the hard-surface areas are only approximately defined, mainly through inspection of Google Earth imagery.

Structure

The bedrock structure of the map area is dominated by the west-northwest-striking Newcastle anticline of Weaver (1916), which extends into the northeast corner of the quadrangle. Several smaller folds, whose axes strike south to southwest, modify this structure. Most of the Tertiary strata in the quadrangle also strike northwest; Waldron (1962) reported southwest dips ranging from 10° to more than 80°.

The quadrangle occupies a seismically active region. A vertical displacement of 7 m has been documented on the Seattle Fault, a major east-west-striking structure about 12 km north of the map area (Bucknam and others, 1992). A network of other faults in the region has been inferred through interpretation of seismic-reflection studies in Puget Sound (Johnson and others, 1996). In this quadrangle, Booth and Waldron (2004) recognized two small bedrock faults north of Interstate 405 (I-405), near the eastern boundary of the map area, and another fault in Pleistocene sediment at Normandy Beach Park, just north of Des Moines. A third fault cuts Tertiary rocks in the northeast corner of the quadrangle (Troost and others, 2005). A probable Pleistocene fault is discussed below.

Pleistocene and Holocene(?) Tectonic Deformation

With the growing recognition of recent seismic activity in the Puget Lowland, workers within the region have begun to pay greater attention to evidence of crustal deformation or displacement. In an area dominated by glacial processes, however, neotectonic studies are fraught with problems of interpretation. Structural features associated with either deep-seated tectonic displacements or earthquake-related ground shaking may also result from glacial loading or basal traction, ice-shove processes, or melt-out of sediment-buried ice (Drewry, 1986). In addition, most structures in the map area are best exposed along the steep beach cliffs of Puget Sound, where much of the observed deformation may be the result of Holocene landsliding instead of tectonic movement

With these concerns in mind, a limited set of structural data collected in the quadrangle and adjacent areas produced no convincing examples of tectonically deformed Vashon-age deposits (~17,000 [14,000 radiocarbon] yr B.P.), which are essentially flat-lying. In the pre-Vashon deposits, however, a consistent pattern of gentle west- to west-southwest-striking folds is shown by dips in sedimentary strata exposed in coastal bluffs between the town of Normandy Park and the southern boundary of the map area (Booth and others, 2004b). In this area, no measured dips are greater than 6°, and most are within a few degrees of horizontal. North of Normandy Park, exposures are poor but the available outcrops suggest there has been little or no folding. In the southern part of the map area, two large-scale synclines and an intervening anticline are inferred: the northern syncline is bracketed by opposing dips just north of Normandy Beach Park (sec. 7, T. 22 N., R. 4 E.), and at the mouth of Des Moines Creek. The southern syncline is approximately parallel to the west-trending valley along the southern map boundary. Mapping south of this boundary in the adjacent Poverty Bay 7.5' quadrangle (Booth and others, 2004c; Tabor and others, 2014) shows north-dipping beds that define the southern limb of this syncline. The intervening anticline is inferred from widely spaced exposures north and south of the city of Des Moines. Dipping beds in these areas include strata dated by paleomagnetic means as older than 781,000 yr B.P. (Hagstrum and others, 2002) overlying sediments that are also involved in the deformation, but these younger deposits have not yet been dated.

Evidence of late Pleistocene to Holocene tectonic deformation in the Des Moines quadrangle is restricted to the sparse inferred faults and broad, very gentle folds already discussed. However, the 1,100-yr-old, 7-m-high topographic offset on the Seattle Fault, located only about 12 km north of the quadrangle (Bucknam and others, 1992), has clearly affected the very recent depositional record of the Duwamish River flood plain north of the map boundary (B. Atwater, oral commun., 1996). This vertical displacement on the Seattle Fault has likely also affected recent sedimentation in the part of the Duwamish River valley lying within the Des Moines quadrangle; however, the research needed to satisfactorily document such a relation still remains to be done.

DESCRIPTION OF MAP UNITS

NONGLACIAL DEPOSITS

m **Modified land (Holocene)—**Sand and gravel as artificial fill, as well as extensively artificially graded natural deposits. In the area derived from Troost and others (2005), includes their units: artificial fill and graded land. Lined pattern denotes nearly continuous hard surfaces, including major roads, parking lots and large buildings

Qw **Wetland deposits (Holocene)—**Peat and alluvium, poorly drained and intermittently wet. Grades into unit Qa. Compiled from county-wide wetlands inventory (King County, 1983); however, areas shown on this map are not complete inventory of such deposits

Qbt **Beach and tidal flat deposits, undivided (Holocene)**—Locally well sorted sand, pebbles, silt, and shells deposited or reworked by wave action. Includes extensive tidal flats below mean high-water line and local thin veneer of modern beach sediment that overlies older deposits. Mapped from lidar and Google Earth; contact with water somewhat arbitrary due to tidal variation and collection time of imagery

Qb **Beach deposits (Holocene)**—Well-sorted sand, pebbles, silt, and shells deposited or reworked by wave action

Qbo **Beach deposits, old (Holocene)**—Lithology similar to unit Qb. Forms elevated beach terrace, mostly separated from unit Qbt or Qb by scarp, 2 to 10 ft high

Qls **Landslide deposits (Holocene)**—Diamict of broken to internally coherent surficial deposits that have been transported downslope en masse by gravity. Numerous unmapped areas of landslide and related mass-wastage deposits are present along coastal bluffs of Puget Sound, as well as in ravines that drain eastward to Green River, particularly where coarse deposits (units Qva and Qpogc) overlie fine deposits (particularly unit Qpff). Many areas shown as mass-wastage deposits by Booth and Waldron (2004) shown here as Qls or Qols. Symbols of displaced units in massive block-slide deposits at south edge of map area are shown in parentheses

Qols **Old landslide deposits (Holocene and Pleistocene)—**Composition and structure similar to Qls, but deposits are more strongly eroded or consist of multiple slides. Some deposits along escarpment above Green River Valley may be sublacustrine landslides as mapped in the Poverty Bay quadrangle (Tabor and others, 2014) to the south at comparable elevation, but none show distinguishing fluidal or subdued topographic appearance in the lidar DEM

Qa **Alluvium (Holocene)—**Moderately well sorted deposits of cobble gravel, pebbly sand, and sandy silt. Underlies broad flood plain of Green and Duwamish Rivers and larger creeks. Deposits in both areas locally grade into wetland deposits (Qw). Upland deposits are probably thin

Qoa **Older alluvium (Holocene and Pleistocene)—**Similar to unit Qa but associated with relatively inactive channels, or forms terraces incised by modern drainages

Qf **Alluvial fan deposits (Holocene)**—Boulders, cobbles, pebbles, and sand; deposited where streams emerge from confining valleys and where reduced gradients cause sediment loads to be deposited

YOUNGER GLACIAL DEPOSITS

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

Qvr **Recessional outwash deposits—**Stratified sand and gravel, moderately well sorted to well sorted; less common silty sand and silt. Deposited in broad anastomosing outwash channels that carried south-draining glacial meltwater away from receding ice margin during ice retreat. Typically slightly oxidized. Deposits that are less than about 1 m thick not shown on map. Unit symbol in parentheses (Qvr) indicates massive slide block. Locally subdivided

Qvrl **Recessional lacustrine deposits—**Silt, clay, and very fine grained sand deposited in glacial Lake Russell or in small lakes during ice retreat. Northwest of Arbor Lake and on the northern map border east of Highway 509, we included deposits mapped as Holocene-age Lake Washington sediments (Ql) by Troost and others (2005)

Qvrlf **Sublacustrine fan—**Small lobe-shaped deposit in Duwamish River valley west of Allentown; subaqueous deposition inferred from unit elevation, limited modern drainage, and shape. Mapped from lidar only

Qvi **Ice-contact deposits—**Deposits similar in texture to those of unit Qvr but generally less well sorted and siltier. Contains scattered lenses and pods of till. Deposits are present in northern part of quadrangle and along Duwamish-Green River valleys. Extensive areas of ice-contact deposits added to those mapped by Booth and Waldron (2004) based on irregular small-scale hills and valleys visible on lidar DEM. Between Tukwila and south edge of quadrangle, ice-contact deposits form a kame terrace deposited against a late recessional ice tongue in Green River valley

Qvt **Till—**Compact diamict containing subrounded to well-rounded clasts in massive, silty to sandy matrix. Glacially transported and deposited. Generally a few meters to a few tens of meters thick, forming an undulatory land surface. Also, unmapped areas occur sporadically within areas mapped as unit Qvi. Unit symbol in parentheses (Qvt) indicates massive slide block

Qva **Advance outwash deposits—**Well-bedded sand and gravel deposited subaqueously or by streams and rivers in front of advancing ice sheet. Almost devoid of silt or clay, except near base of unit. Generally unoxidized. Unit symbol in parentheses (Qva) indicates massive slide block

OLDER GLACIAL AND NONGLACIAL DEPOSITS

Qpf **Deposits of pre-Fraser-glaciation age, undivided (Pleistocene)—**Weakly to moderately oxidized sand and gravel, lacustrine sediments containing local peat layers, and moderately to strongly oxidized diamict composed of silty matrix and rounded gravel clasts. Includes deposits of both glacial and nonglacial origin. Undivided deposits occur in a small area east of Interstate 5 at north edge of map and on Maury Island (see Troost and others, 2005; Booth and others, 2015)

Qpfc **Coarse-grained deposits—**Predominantly gravel and sand

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

Nonglacial deposits (Pleistocene)—Abundant organic debris or pumice indicates nonglacial origin

Qpfnc **Coarse-grained deposits**—Predominantly gravel and sand

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

Qpo **Pre-Olympia deposits, undivided (Pleistocene)—**Interbedded sand, gravel, and diamict (Troost and others, 2005). Forms small outcrop near northwest corner of map area

Pre-Olympia glacial deposits (Pleistocene)

Qpogc **Coarse-grained deposits—**Weakly to strongly oxidized silt, sand, and gravel of glacial origin as determined by clast provenance. Underlies all Vashon-age deposits and, thus, also must be of pre-Olympia age. At north margin of map area west of Duwamish, includes till:

Qpogt **Till**—Localized iron-oxide cemented layers and sandy partings and layers (Troost and others, 2005)

Pre-Olympia deposits of undetermined origin (Pleistocene)

Qpof **Fine-grained deposits—**Silt and clay of uncertain glacial or nonglacial origin; rare sandy interbeds (Troost and others, 2005). Exposed at mouth of Des Moines Creek, at north edge of map near Duwamish, and in ravine at south edge of map; in most places, underlies glacial deposits of pre-Olympia age (Qpogc)

Pre-Olympia nonglacial deposits (Pleistocene)—Exposed only on north boundary of map, west of Duwamish

Qpone **Estuarine deposits—**Sand, silt (locally organic rich), gravel, and peat; discontinuously and thinly interbedded (Troost and others, 2005)

Reversely magnetized deposits (Pleistocene)

Qrgf **Fine-grained glacial deposits**—Fine-grained silt containing dropstones or pebbly diamict. Reverse magnetization implies depositional age is greater than 781,000 years old

Qrn **Nonglacial deposits**—Silt, fine- to medium-grained sand, clay, ash, peat, and mudflow deposits. Abundant wood and volcanic debris demonstrate nonglacial origin. Underlies silt of unit Qrgf in bluffs near Zenith

BEDROCK

Ti **Intrusive rocks (Eocene)—**Irregular masses of porphyritic basalt and andesite

Puget Group (Eocene)

Tpr **Renton Formation**—Nonmarine arkosic and micaceous feldspathic sandstone; also includes siltstone, claystone, and shale, with locally abundant interbedded coal

Tpt **Tukwila Formation**—Andesitic sandstone, tuff, mudflow breccia, and minor lava flows or sills

Tpta **Arkosic sandstone**—Similar to Renton Formation

Tptm **Marine and nonmarine sedimentary rocks—**Volcanic conglomerate and marine sandstone; some siltstone and shale. Mostly composed of volcanic rock fragments and minor arkose. Deposits at north edge of quadrangle contain marine shells

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