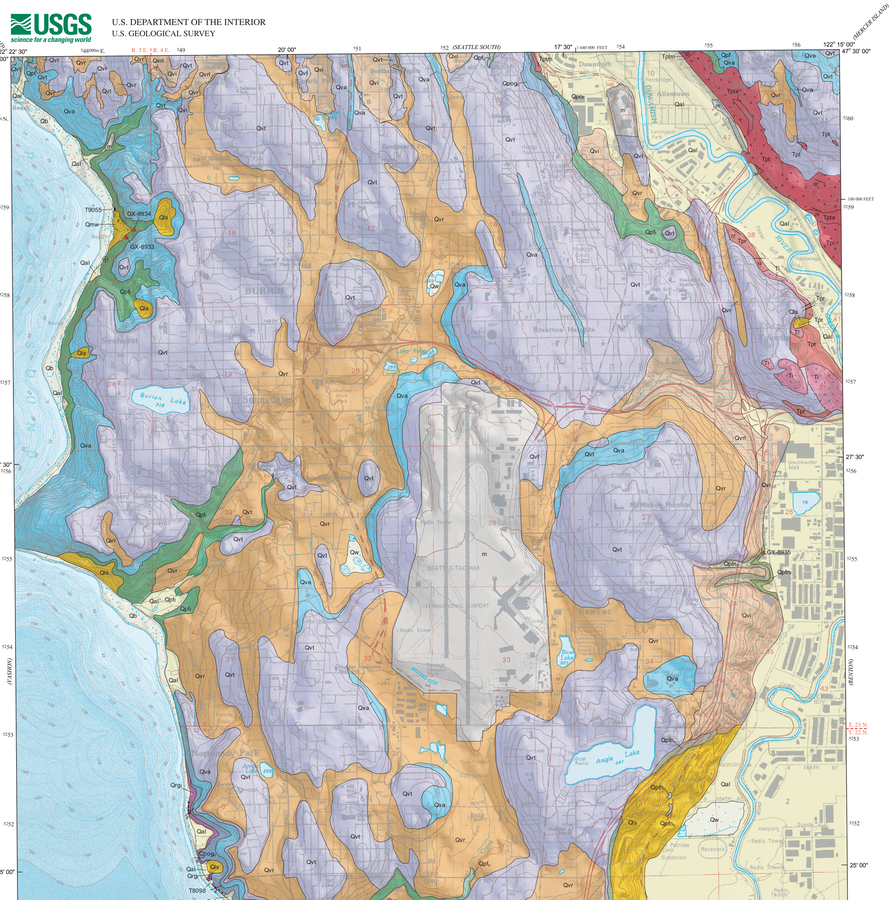
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

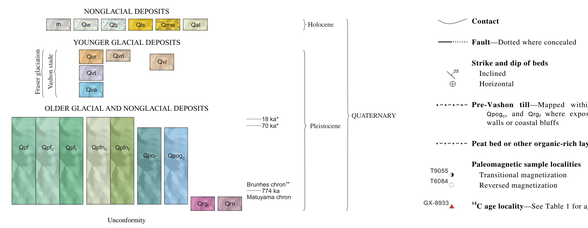


Base extracted from U.S. Geological Survey 1:24,000-scale Digital Raster Graphic (DRG), Des Moines, WA, 1995. Original 1:24,000-scale published by the U.S. Geological Survey, 1949 (revised 1995); topography compiled from aerial photographs taken 1943 and field checked 1949

Shaded relief from U.S. Geological Survey 10-meter Digital Elevation Model (DEM), Des Moines, WA, 1995

Universal Transverse Mercator projection; North American Datum of 1927

CORRELATION OF MAP UNITS



* Dates correspond to boundaries of the Olympia nonglacial interval (Booth and others, 2004a)
** Age of boundary from Sarna-Wojcicki and others (2000)

DESCRIPTION OF MAP UNITS

NONGLACIAL DEPOSITS

m **Modified land (Holocene)**—Sand and gravel as fill, as well as extensively graded natural deposits. Where topographic base map (ca. 1949) does not reflect subsequent human modification, original (unmodified) geologic deposit has been mapped where information is available

Qw **Wetland deposits (Holocene)**—Peat and alluvium, poorly drained and intermittently wet. Grades into unit Qal. Compiled from King County (1983); however, mapped areas are not complete inventory of such deposits

Qb **Beach deposits (Holocene)**—Well-sorted sand, pebbles, silt, and shells deposited or reworked by wave action. Includes upper-beach deposits above mean high-water line, extensive tideflats below mean high-water line, and local thin veneer of modern beach sediment that overlies older deposits. At stream mouths, grades into unit Qal

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 both landslide and related mass-wastage deposits are present along coastal bluffs of Puget Sound, as well as in ravines that drain east to Green River, particularly where coarse deposits (units Qva and $Qpog_g$) overlie fine deposits (particularly unit Qpfs)

Qmw **Mass-wastage deposits (Holocene)**—Undifferentiated colluvium, soil, and landslide debris having indistinct morphology. Mapped along coast 2 km south of north map boundary as fan-shaped deposit where landslide debris intermingles with stream-channel alluvium. Numerous unmapped areas of mass-wastage deposits are present elsewhere in quadrangle along coastal bluffs of Puget Sound and in ravines draining eastward to Green River and Duwamish River valleys. Deposits, both mapped and unmapped, include abundant discrete landslides that are meters to tens of meters in lateral extent

Qal **Alluvium (Holocene)**—Moderately well sorted deposits of cobble gravel, pebbly sand, and sandy silt along flood plain of Green River and Duwamish River, and alluvial fans at mouths of small streams along Puget Sound, where they are gradational with sediments of unit Qb

YOUNGER GLACIAL DEPOSITS

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

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 ice margin during ice retreat. Typically slightly oxidized. Deposits that are less than about 1 m thick not shown on map. Locally subdivided into:

Qvrf **Recessional lacustrine deposits**—Very fine-grained sand, silt, and clay deposited in small lakes during ice recession

Qvi **Ice-contact deposits**—Deposits that are similar in texture to unit Qvr but commonly are less well sorted and have silt-rich matrix. Contains lenses and pods of till. Deposits are present in northernmost part of quadrangle and along Duwamish River and Green River valleys. From Tukwila south to edge of quadrangle, they form a kame terrace that was built against late-recessional ice tongue in Green River valley

Qvt **Till**—Compact diamict containing subrounded to well-rounded clasts in massive, silt- or sand-rich matrix. Glacially transported and deposited. Generally a few meters to a few tens of meters thick, forming an undulatory surface. Also found sporadically within areas mapped as unit Qvi

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

OLDER GLACIAL AND NONGLACIAL DEPOSITS

Qpf **Deposits of pre-Fraser glaciation age (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. Locally mapped as:

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

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

$Qpfs_n$ **Nonglacial deposits**—Abundant organic debris or pumice indicates nonglacial origin

$Qpfs_c$ **Coarse-grained nonglacial deposits**—Predominantly gravel and sand

$Qpfu_c$ **Fine-grained nonglacial deposits**—Predominantly silt and clay

Deposits of Pre-Olympia age (Pleistocene)—

Qpog **Fine-grained deposits**—Silt at north and south edges of map of indeterminate glacial or nonglacial origin; underlies glacial deposits of pre-Olympia age ($Qpog_g$)

Glacial deposits—Weakly to strongly oxidized silt, sand, and sparse gravel of glacial origin as determined by clast provenance. Underlies all Vashon-age deposits and thus also must be of pre-Olympia age

$Qpog_g$ **Coarse-grained deposits**—Predominantly gravel and sand

Reversely magnetized deposits (Pleistocene)—

Glacial deposits—

$Qprg_g$ **Fine-grained deposits**—Fine-grained silt containing dropstones or interstratified with pebbly diamict and so of presumed glacial origin. Reversely magnetized and thus presumably more than 774,000 years old

Qprn **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 Qrg in bluffs near Zenith

BEDROCK

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

Puget Group (Eocene)—Divided into:

Tpr **Renton Formation**—Nonmarine arkosic and feldspathic micaceous sandstone; also siltstone and claystone containing locally abundant coal beds

Tp^c **Tukwila Formation**—Andesitic sandstone, tuff, mudflow breccia, and minor lava flows or sills. Locally subdivided into:

Tp_{sa} **Arkosic sandstone**—Similar to Renton Formation

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

GEOLOGIC SUMMARY

INTRODUCTION

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 (14,000 radiocarbon) years ago during the last occupation of the Puget Lowland by a great continental ice sheet. Incised between the hills of this upland surface, and in places lapping up onto their flanks, are the deposits of long-vanished rivers that issued from the snout of the retreating ice sheet as it withdrew to the north.

Beneath these ice-sheet deposits is a complex sequence of older unconsolidated sediments that extends far below sea level across most of the quadrangle. These older sediments are exposed only where modern erosion has sliced through the younger glacial deposits—notably by the Green River and its precursor, the now-infilled Duwamish estuary, along the southwestern border of the upland plain; by wave action along Puget Sound to the west; and also by Des Moines Creek, Miller Creek, and several smaller drainages. These older sediments are very compact, having been weighted down by one or more episodes of glaciation subsequent to their deposition. Many are also cemented by iron oxides and hydroxides, a consequence of the many tens or hundreds of thousands of years of weathering that they have experienced. Excellent exposures of this older Pleistocene sequence are displayed in the coastal bluffs of the quadrangle, although human activity is concealing these exposures at a rapid rate.

Bedrock is found only in the northeast corner of the quadrangle. Indeed, over most of the map area, rock typically lies at depths of from 300 to more than 1,500 meters (Jones, 1996). Exposed bedrock consists of marine and continental sedimentary 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 one kilometer.

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 kilometers 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 of about 100,000. Seattle-Tacoma International Airport is located near the center of the quadrangle, perched high in the center of the upland plain. Interstate 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.

PREVIOUS MAPPING

This edition of the Des Moines 7.5' quadrangle relies heavily on the mapping of Waldron (1962). Map data from that earlier work are 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 have been changed only slightly, primarily as a result of the dramatic increase in construction-related exposures. Their scales are enlarged a revision in both regional and local interpretation of pre-last-glaciation deposits.

Revised mapping by Booth began sporadically in 1986 and again in earnest in 1988-89, during preparation of watershed planning documents for the south half of the quadrangle on behalf of King County. In 1992, 1993, and 1995, mapping resumed by Booth in the watersheds of Salmon Creek, Miller Creek, and Des Moines Creek. Field work in 1996-98 concentrated on the coastal exposures along Puget Sound. Kathy Goetz Troost (University of Washington) provided additional mapping data in 2004 along the north boundary of the quadrangle.

ACKNOWLEDGMENTS

Particular acknowledgments are due our colleagues who have shared geologic data, insights, and interpretations throughout the current period of additional mapping: Kathy Goetz Troost (University of Washington); Ralph Haugerud, Ray Wells, and Brian Atwater (USGS); Timothy Walsh and Patrick Pringle (Washington State Department of Natural Resources); John Bethel (King County Water and Land Resources Division); and Barry Goldstein (University of Puget Sound). Dave McCormack and Mark Shaffer (Aspect Consulting) generously provided field notes, radiocarbon dates, and interpretive cross sections across the northern part of the quadrangle; Jon Hagstrum (USGS) collected and analyzed paleomagnetic samples.

STRATIGRAPHY AND HISTORY

Bedrock

The east-central Puget Lowland is 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 map area, where younger glacial deposits lap onto the southwest limb of the Newcastle anticline of Weaver (1916), which is expressed as a bedrock high that projects northwest some 50 kilometers from the front of the Cascade Range (Mullineaux, 1970; Booth and Minard, 1992) towards the center of the Puget Lowland.

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 earlier were described by Willis (1886) as the "Coal measures of the Puget Sound basin." As used in this report, the Puget Group includes not only these arkosic rocks but also continental volcanic sedimentary rocks that are interstratified with, and are thought to be stratigraphically equivalent to, part of the Puget Group of White (1888) and Willis (1898a). In the Des Moines quadrangle, two main units were recognized and named by Waldron (1962): a lower assemblage of volcanic sedimentary rocks, the Tukwila Formation; and an upper unit of arkosic sedimentary rocks, the Renton Formation.

Tukwila Formation—The Tukwila Formation 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. At these type sections, the formation primarily consists of a lower volcanic sedimentary rock unit, a middle arkosic unit about 80 m thick that is lithologically similar to arkosic rocks of the overlying Renton Formation, and an upper volcanic sedimentary rock unit that is less than 150 m thick. The total thickness is probably more than 800 m in the quadrangle. The Tukwila Formation is conformably overlain by the Renton Formation.

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

Middle Eocene marine and nonmarine sedimentary rocks crop out at the north edge of the quadrangle in secs. 9 and 10, T. 23 N., R. 4 E. These rocks are part of a sequence of interbedded marine and nonmarine arkosic and volcanic sedimentary rocks that Waldron (1962) and Waldron and others (1962) assigned to an unnamed unit (distinct from the Puget Group), which is herein distinguished as unit Tpbm. Yount and Gower (1991), however, included these rocks in the overlying Tukwila Formation without differentiation.

Renton Formation—The Renton Formation is named for the city of Renton, located about 5 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. The formation is typically exposed in the vicinity of Renton in the adjacent Renton 7.5' quadrangle (secs. 17, 18, and 19, all of T. 23 N., R. 5 E.) (Mullineaux, 1970). The total thickness in the quadrangle is probably more than 1,000 m, but the top is not exposed.

Most of the formation consists of fine- to medium-grained arkosic and feldspathic sandstone, and lesser amounts of siltstone, sandy shale, coal, and carbonaceous shale. Sandstone locally is composed of 40 or more percent subangular to subrounded quartz grains, 10 to 25 percent feldspar, and some mica and rock fragments, in a matrix that consists principally of a mixture of calcite, clay, and silt. Chert fragments constitute as much as 20 percent of some sandstones. The unoxidized rocks are mostly light gray, but they weather to light or dark brown or buff. At most places the sandstone is only weakly cemented, commonly with calcite, but in places silt and clay act as the binding agent. The sandstone is generally massive and poorly 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 and alteration of some minerals to a montmorillonitic clay.

Origin and age of the Puget Group—Mineralogy and lithology of the Puget Group indicate that these rocks were derived chiefly from a distant eastern source of granites or gneisses. Volcanic debris, probably ejected from nearby vents, intermittently clogged the sluggish streams and locally dominated sedimentation. Sediments of the group probably were washed on a low-lying coastal plain that bordered a slowly subsiding 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 15 kilometers southeast 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 eight kilometers north of the Des Moines quadrangle. Waldron (1962) first suggested that marine rocks at the base of the Tukwila Formation (unit Tpbm) might be as old as late middle Eocene; Rau (oral commun., in Yount and Gower, 1991) reported Ulatisian (late early Eocene to middle middle Eocene) foraminifera from these rocks.

Ignevus Rocks

Irregular masses of andesite and basalt crop out at several localities adjacent to the Duwamish River valley and near Tukwila. They appear to have intruded the Puget Group, which would make them to be of late Eocene age or younger. Waldron (1962) reported baked sedimentary rocks within a few centimeters of their contact with one such basaltic mass, which was at one time exposed in a quarry in sec. 10, T. 23 N., R. 4 E. The andesite and basalt rocks generally are massive but have columnar structure in a few place. Their color varies from light gray to various shades of brown. Most are fine grained and porphyritic; visible mineral grains are plagioclase and mafic minerals. The rocks are composed of 50 percent or more of plagioclase, and generally some pyroxene, in either a glassy or altered matrix. Interstitial quartz may be present, but is relatively fresh; in others, it is altered to either palagonite, nontronite, or a mixture of carbonate and clay minerals.

Ice Occupation of the Quadrangle

Stratigraphic Framework

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. 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 of the Des Moines quadrangle display some of the best exposures of glacial and nonglacial deposits in this part of the 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 kilometers 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. Layers of sand, gravel, silt, and clay are finely interbedded, and single 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 80 kilometers 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, which are derived from the North Cascades and Coast Range of British Columbia and which require ice-sheet transport during glacial periods;

Central Cascade provenance, characterized by the volcanic (primarily) and other igneous rocks and minerals of Tertiary age, which compose most of the Cascade Range east and southeast of the quadrangle and which require only river transport for their appearance here; and

Mount Rainier provenance, characterized by hypersthene andesite and pyroclastic rocks from Mount Rainier, which may have been brought into the quadrangle either by normal fluvial transport or by catastrophic volcanic mudflows (lahars).

Local alpine glaciers also may have contributed sediment of both the Central Cascade and Mount Rainier provenances into the quadrangle during periods when these glaciers cannot be recognized on the basis of source area alone.

The naming and regional correlation of individual glacial advances in the Puget Lowland has had a long history, one that is still evolving. Willis (1898b) was first to present evidence for multiple glaciations in the Puget Lowland. More recently, 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 30 kilometers southeast of the quadrangle. Farther north, Easterbrook and others (1967) named and described deposits of three glaciations and their intervening nonglacial intervals. Further efforts at dating these spatially separate stratigraphic sections (Easterbrook, 1968, 1976, 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 (Crandell and others, 1958), which immediately underlies drift of the most recent ice-sheet advance in the Puget Lowland of the Fraser glaciation of Armstrong and others, 1965), has been shown to be more than 774,000 yr old, on the basis of reversely magnetized sediment within the unit (Easterbrook and others, 1981). 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 at between 80,000 and 250,000 yr old using aminoacid racemization and paleomagnetic techniques (Blunt and others, 1987).

Subsequent age determinations in the southern Puget Lowland have made possible a revision in the southern 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 10 kilometers due east of the Des Moines quadrangle) is normally magnetized (D. Easterbrook, written commun., *in* Booth, 1995), which indicates that the entire exposed section of Quaternary sediments in that area is probably post-Salmon Springs in age, in other words, younger than 774,000 yr. 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, in the Des Moines quadrangle we now report reversely magnetized sediment in coastal exposures (samples T6079, T6084, T8098). In particular, the two samples from the 2-kilometer-long bluff just north of Saltwater State Park, which displays one of the most complete sections of Pleistocene strata exposed between Seattle and Tacoma, provide demonstrable evidence of pre-774,000-yr-old glacial material in the central Puget Lowland.

A small number of ^{14}C ages have been determined from deposits in the quadrangle (summarized in table 1). An age of greater than 37,000 yr B.P. was obtained by Rubin and Suess (1956) from a woody peat bed that overlies a mudflow complex in unit Qrv (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 Qpf_f and $Qpfn_f$ and all give ages older than 37,000 yr B.P.

Table 1. *^{14}C ages from the Des Moines quadrangle*

Sample No.	Location	Altitude, meters	Material	Age, in ^{14}C yr B.P.	Map Unit	Collected by	Reference
W-259	SW¼ sec. 17., T. 22 N., R. 4 E.	10	woody peat	>37,000	Qrn	H. Waldron	Rubin and Suess, 1956
GX-8933	SE¼NE¼ sec. 13, T. 22 N., R. 3 E.	55	peat	>37,000	Qpf_f	P. Seabeck	This report
GX-8934	SE¼NE¼ sec. 13, T. 22 N., R. 3 E.	100	peat	>37,000	Qpf_f	P. Seabeck	This report
GX-8935	SW¼SW¼ sec. 26, T. 22 N., R. 4 E.	100	peat	>37,000	$Qpfn_f$	P. Seabeck	This report

Deposits Predating the Vashon Stade of the Fraser Glaciation

Various kinds of waterlain 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 meters to about 10 m, but none can be traced continuously for more than a few kilometers. The sediments are subdivided primarily on the basis of age, but because dating techniques are relatively crude for these sediments, we can specify only coarse stratigraphic divisions at this time.

The oldest sediment in the quadrangle is reversely magnetized, and so it is probably more than 774,000 years old. In places where this has been determined either by direct measurement or by stratigraphic position, the material is mapped as units Qrg and Qrn.

Where paleomagnetic determinations are absent, the pre-Fraser deposits (Qpf) are subdivided on the map, if at all, only on the basis of their presumed depositional environments and not by age. Exposures are not everywhere adequate, however, to make this determination with confidence. Where organic material or volcanic sediment is abundant, we have recognized a likely nonglacial origin (unit Qpfn). Deposits containing sand and (or) gravel lithologies that are indicative of southward transport from the North Cascades or British Columbia, or that display sedimentary features characteristic of glacial or proglacial environments, are 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 are mapped as unit Qpog because the designation "Qpfg" is unnecessarily broad.

Within the pre-Fraser and pre-Olympia deposits, the texture is identified on the basis of grain size: coarse, predominantly gravel and sand (units Qpf_g, $Qpfn_g$, and $Qpog_g$), or fine, predominantly silt and clay (units Qpf_f, $Qpfn_f$, and Qpo_f). The gross lithologic and stratigraphic relations across the quadrangle suggest that the coarse-grained pre-Fraser deposits mapped along the Puget Sound coastline are most commonly of glacial origin (unit $Qpog_g$), and they generally overlie fine-grained pre-Fraser deposits.

Farther east along the Green River valley wall, 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 Zenith, north of Saltwater State Park. Waldron (1962) originally mapped this volcanic-rich material as "Puyallup Formation;" we now map it as unit Qrn. At this location, it consists of silt, fine to medium sand, clay, ash, peat, and a mudflow complex; as much as 30 m of strata are visible, but the base is not exposed. The mudflow complex consists of at least two flows and at one exposure chiefly of rock fragments of Mount Rainier provenance, separated by a meter-thick bed of laminated clays. The best exposures of this mudflow complex were recently destroyed when 1.2 kilometers south of the mouth of Massey Creek, just northwest of the west end of S 240th Street, where the upper mudflow overlies 1 m of thinly laminated peat and silt, which in turn overlie about 1.3 m of sand and mudflow deposits of Mount Rainier provenance. This exposure, locally known as the "Zebra Beds" for their striking alternation of light and dark bands of silt and peat, was covered over 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 meters in length. The tree fragments, still well exposed in the bluffs about 0.5-0.7 kilometers south of the mouth of Massey Creek, are elliptical in cross section; they presumably have been flattened by the weight of overlying sediment, as well as by successive ice-sheet advances. Their uninterrupted transport out to what is now the coast of Puget Sound implies that the sediment within and just exposed below between the Green River valley and Puget Sound must have been above what is now sea level.

We make no effort to assign stratigraphic names to subdivisions of the pre-Fraser deposits because absolute age control is limited at present, and so the likelihood of spurious correlations is high. Layers or lenses of diamict of presumed glacial origin that predate the Vashon stade are shown with a mudflow pattern within areas of units Qpf, Qrg, and Qpog. Their absence elsewhere on the map reflects not only the likely discontinuity of these deposits but also the typically poor exposures across the map area, even under relatively favorable conditions of steep topography and sparse vegetation.

Deposits of the Vashon Stade of the Fraser Glaciation

In contrast to uncertainties in age and stratigraphic assignment of older Pleistocene glacial and nonglacial deposits, the deposits at or near the land surface are readily assigned to the most extensive regionally recognized glacial advance, the Vashon stade of the Fraser glaciation (Armstrong and others, 1965). During this time an ice sheet advanced down the axis of the Puget Lowland from the north (Clague, 1981), reaching its maximum extent about 17,000 (14,000 radiocarbon) yr B.P. and covering the Puget Lowland to a minimum depth of about 1,500 m (Booth, 1987; Porter and Swanson, 1998). Deposits of the Vashon stade have a variety of textural characteristics and topographic expressions, owing to rapidly changing depositional environments caused by the advance and retreat of the ice sheet. As the ice sheet advanced, it blocked northward lowland drainage out the Strait of Juan de Fuca, which presently connects Puget Sound with the Pacific Ocean. In the Des Moines quadrangle, that lowland was a change to southerly drainage out of the Puget Lowland, laminated silt and clay were deposited. This material has been mapped in part to the north and east as either "Qvrf" (see, for example, Waldron and others, 1962) or "transitional beds" (see, for example, Minard and Booth, 1988; Yount and others, 1993). The latter term reflects the possibility that the unit may include deposits of pre-Vashon lowland lakes in addition to those formed in the subsequent ice-dammed environment. 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 these units in the map area, except for a deposit of fine silty sand on Maury Island, located at the extreme west edge of the quadrangle. This deposit was mapped by Booth (1991) as the Olympia beds of Minard and Booth (1988); however, we have remapped this deposit more generally as unit Qpf because we presently lack absolute age control.

The initiation of the Vashon stade is marked by coarse advance outwash deposits (Qva), which were deposited by streams flowing from the advancing ice sheet. Deposits at least a few meters thick (and locally as thick as 150 meters) underlie the broad upland areas in the central part of the quadrangle. They inundated the pre-Vashon topography of the lowland and resulted in a south-sloping surface at an elevation of about 150 m (500 ft) elevation in the map area (Booth, 1994). Most of the bluffs along Puget Sound from the city of Des Moines north to the edge of the quadrangle consist primarily of advance outwash deposits. Most exposures are light-gray to very-light-brown sand or a mixture of sand and pebble to cobble gravel. Northwest of the city of Des Moines, the terrain is chiefly fine- to medium-grained sand, but it also includes some pebble gravel and some laminated silt. It varies from poorly to well sorted, and it is typically moderately well to well bedded.

As ice covered the region, lodgment till (Qvt) was deposited by the wear-out of debris at the base of the glacier. The ground surface underlain by this heterogeneous, compact deposit is locally fluted with elongated hills that have a west-by-northwest to east-by-southeast orientation in quadrangle. Where present at the surface, the till provides a low-permeability cover to underlying aquifers, reducing recharge but also offering protection from surface contaminants. Where it is overlain by more permeable sediment, the till typically is still present at depth, and so it slows groundwater migration and recharge. Measured till thicknesses average about 3 m but are as great as 20 m; the deposit covers about three-quarters of the upland areas of the quadrangle (McCormack and others, 2000).

The matrix of the till differs from place to place in its relative proportions of clay, silt, and sand, but mostly it is made up of silty sand to sandy silt. In many places, the till is substratified and contains lenses of sand, gravel, and silt. Larger rock fragments, which are scattered throughout the till, are mostly pebble to cobble size; boulders more than 1 m in diameter are present but uncommon; a few rare boulders more than 4 m across have been observed. Unoxidized till is light gray and compact; where oxidized, till is light yellowish gray and is generally loosely consolidated. Although a weak brown soil is developed on the till, oxidation rarely extends more than about a meter into the deposit.

Shortly after 17,000 (14,000 radiocarbon) years ago, the ice margin, which by that time had advanced south of the city of Olympia, about 70 kilometers south of the quadrangle, began to recede. Recession of the ice margin was accompanied by both outwash deposits and ice-dammed lakes, analogous to those formed during the ice advance. Water from the melting ice sheet, and also from the Cascade Range, drained southward and westward, spilling over high divides that later were abandoned as ice pullback exposed more low-lying drainage routes farther north.

By the time the area of the Des Moines quadrangle was uncovered by the retreating ice, proglacial drainage was well established across most of the eastern and southern lowland areas. Water was impounded in a large lake that inundated much of the central and southern Puget Lowland and because northward drainage was blocked by more than one thousand meters of glacial ice that still filled the Strait of Juan de Fuca. This water body, called Lake Russell, drained out through the Black Hills, just south of Olympia, into the south- and west-draining Chehalis River (Thorson, 1980). Although an elevation of about 190 m (620 ft) was only about 40 m high, the present-day elevation of the ancient shoreline of Glacial Lake Russell is now higher because the land surface of the entire Puget Lowland has rebounded since the subsequent removal of the weight of the ice sheet. More rebound occurred in the north than in the south because the ice was thicker to the north. In the center of the Des Moines quadrangle, the amount of rebound has been about 80 m, and so the level of Glacial Lake Russell during active deposition of recessional outwash (Qvr) can be recognized today at about 90 m (300 ft) elevation (about the level of the Sea-Tac/Valley Floor Connector, just north of 200th Street).

Discharge of meltwater away from the ice margin was locally channeled around till-capped promontories as it drained into the lake. Across the present-day upland areas of the quadrangle, an anastomosing pattern of outwash channels is prominently displayed by the pattern of the recessional outwash deposits, and they reflect the generally north-to-south-to-southwest drainage (Booth, 1994). The path of one of these major glacial-age outwash channels now forms the upper valley of Des Moines Creek. Two of its tributary valleys, an easterly one, which includes Bow Lake (and is now partly buried by airport fill), and a westerly one, which passes southwest of the airport, met in the area of the Tyee Valley Golf Course and continued south and then southwest approximately to the present-day outlet of Des Moines Creek. As deglaciation continued, the site of major outwash deposition rapidly shifted north, following the retreating ice margin. The next south outwash channel is located to the north in the present-day valley of Miller Creek. The lowering of Puget Sound to its modern elevation in the quadrangle took place relatively soon after this northward shift in outwash deposition; glacial-marine sediment (not to several thousand years more (Thorson, 1981).

During ice recession, thick deposits of ice-contact sediment (Qvi) were laid down, primarily farther east. In the Des Moines quadrangle, the deposits mantle the eastern escarpment of the upland area, marking a late-recessional period of fluvial deposition against an ice tongue that was present in the adjacent Green River valley. Near the edge of the quadrangle in sec. 22, T. 22 N., R. 4 E., now-covered exposures were reported by Waldron (1962) as showing well-defined foreset strata dipping westward into the valley of the hill, suggesting that deltas formed into ice-marginal lakes. The deposits consist mostly of silty sand and pebble to cobble gravel; locally they include lenses and pods of till, as well as lenses and beds of sand, silt, and clay. The deposits extend continuously from Tukwila south to the edge of the quadrangle, having a maximum altitude of 130 m (400 ft) near Angle Lake. In places, the surface of the deposits merges with the adjoining surface underlain by till. These deposits mark the maximum of at least one large postglacial landslide (Qls).

Postglacial Processes and Deposits

Geologic activity since glaciation has included widespread slope failure and stream-channel erosion. As a result of the lowered base level caused by drainage of Glacial Lake Russell, several streams in the quadrangle began to incise the sequence of glacial and nonglacial deposits that underlies the upland surface. On the upland surface, soil formation has proceeded slowly but has had profound hydrologic consequences. Bare, unweathered till absorbs water