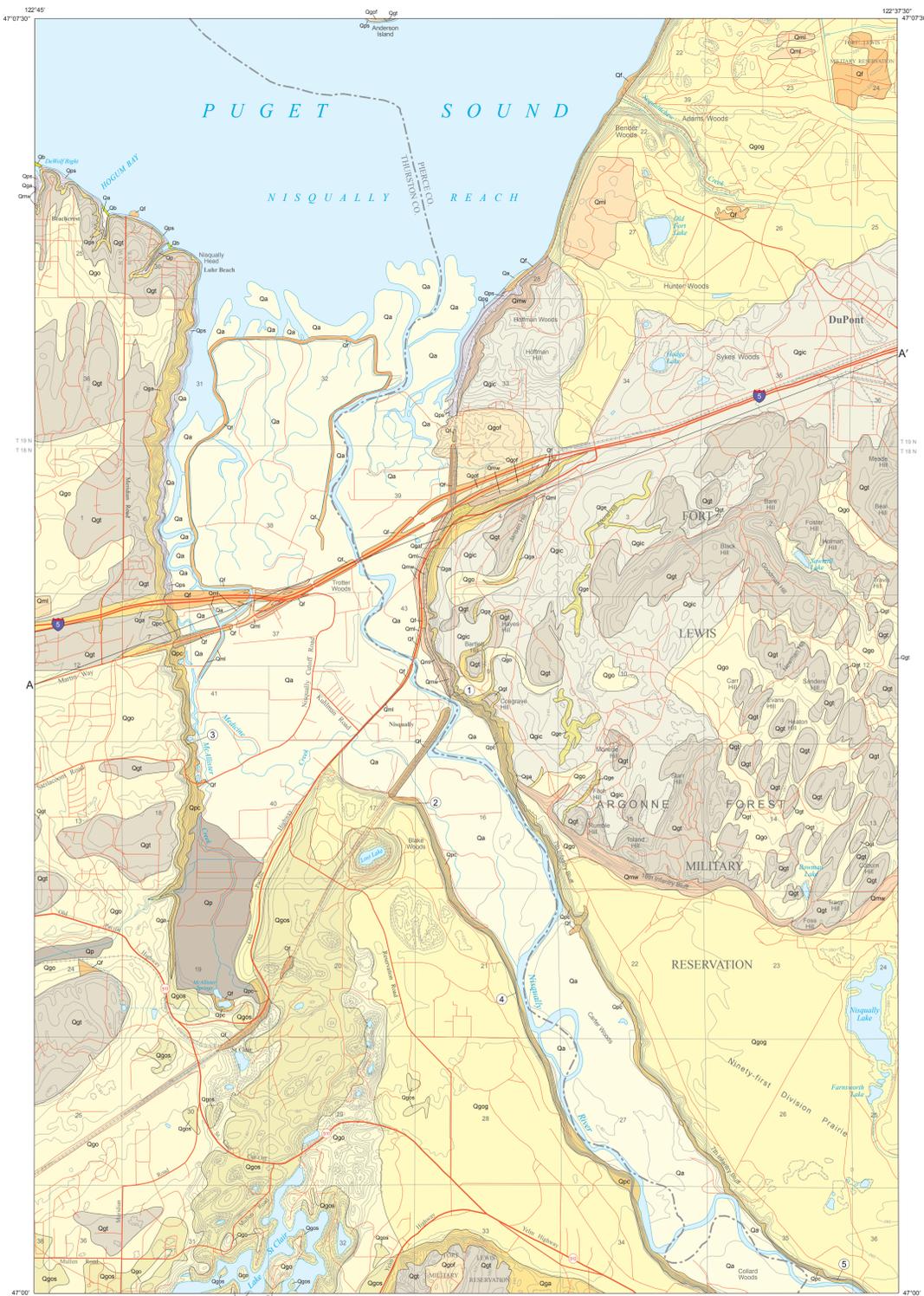


# Geologic Map of the Nisqually 7.5-minute Quadrangle, Thurston and Pierce Counties, Washington

by Timothy J. Walsh, Robert L. Logan, Michael Polenz, and Henry W. Schasse

2003



## INTRODUCTION

The Nisqually quadrangle is located at the south end of Puget Sound, straddling the Nisqually River, which is the boundary between Thurston and Pierce Counties. It includes part of Fort Lewis, which has limited access areas used for military training, and part of the Nisqually Indian Reservation, which also has restricted access. The rest of the quadrangle is rural residential or agricultural land.

## GEOLOGIC HISTORY

Late Wisconsinan-age Vashon Drift covers most of the quadrangle. Pre-Vashon units are generally exposed only along coastal or river bluffs, where mass wasting is common. Landslides and colluvium disrupt and obscure the continuity of exposures so that pre-Vashon geologic history is not easily deciphered. In the Puget Lowland south of Tacoma, all finite radiocarbon ages reported before 1966 are suspect due to laboratory contamination (Fairhall and others, 1966, p. 501). Stratigraphic assignments based on these radiocarbon ages are now questionable and need to be re-evaluated. We have systematically sampled all available material from nonglacial sediments adjacent to the Vashon Drift and found them to be older than previously reported. With a few exceptions, these sediments have been beyond the range of radiocarbon dating. The antiquity of the pre-Vashon units causes radiocarbon dating to be of little help for making correlations, and abrupt facies changes within glacial and nonglacial units also render correlations tenuous. Despite these difficulties, we have developed a conceptual model for the more recent pre-Vashon geologic history that is consistent with our observations but by no means compelling.

The oxygen-isotope stage 4 glaciation, called the Possession Glaciation in northern Puget Sound, was mild relative to stages 2 and 4 (MIS, 1987, and Fig. 1), represented by the Vashon and Double Bluff Drifts respectively in the Puget Lowland. The Possession ice sheet probably did not extend far south of Seattle (Lea, 1984; Troost, 1999). Because the ice sheet blocked drainage out of Puget Sound to the Strait of Juan de Fuca, a proglacial lake was impounded covering most of the southern Puget Lowland. Streams flowing into this lake, such as the Nisqually, Puyallup, and Skokomish Rivers, formed an alluvial plain and delta grading to lake level. These nonglacial sediments, deposited during stage 4, are all radiocarbon-infinite and overlie and interfinger with Possession nonglacial deposits. Once Possession ice no longer impounded the lake (but sea level was still significantly below modern sea level), existing drainages, such as the Nisqually and Puyallup Rivers, deeply and rapidly incised into their former alluvial plains and became entrenched. At least initially, stage 3, called the Olympia Interglaciation locally (Armstrong and others, 1965), was characterized by downcutting and erosion. As sea level began to rise, most deposition was confined to these entrenched channels. Because stage 3 sea level was probably about 100 feet lower than modern sea level (Ludwig and others, 1996, and references therein), stage 3 deposits were actually restricted to a Vashon ice advanced and sea level fell at the beginning of stage 2. These rivers preferentially downcut in the same channels, thereby eroding most of the late Olympia deposits, so that finite-aged Olympia deposits are rare above sea level.

As Vashon ice moved southward and grounded across the Strait of Juan de Fuca during stage 2, it dammed the northern outlet of the Puget Sound basin. Proglacial streams carried fluvial sediments southward into the Puget Lowland filling proglacial lakes and eventually the Puget Sound basin, first with silt, then sands and gravels. These sediments from the 'great lowland fill' of Booth (1994). Ice overrode these sediments, covering most of them with till, or scoured them away to deposit till directly onto pre-Vashon sediments. Subglacial channels were subsequently eroded into the fill. Proglacial lakes became impounded in these channels at different elevations above today's sea level as ice retreated on the valley. The former lakebeds are presently the southernmost of Puget Sound. (For a more thorough discussion of the subglacial channel network, see Booth, 1994, and Booth and Goldstein, 1994.) As these proglacial lakes spilled into lower-elevation basins and channels near the end of the Pleistocene, they deposited coarse, steeply dipping delta gravels along the margins of the channels and basins. Some of these deposits can be found near Skokomish and Fort Lewis.

Much of the drainage originating from the ice sheet flowed southward and southwestward toward the Chehalis River. Some of the drainage probably occurred as glacial-lake outburst floods as valley-blocking ice dams breached during ice retreat. Deep troughs were carved out of the fill by subglacial fluvial erosion and extensive and complex terraces and braided channels were formed. As the ice receded, northward-flowing streams near Olympia filled the deep troughs with sandy sediments characterized by northward-directed paleocurrent indicators. These sediments provide evidence that drainage reorganized to flow northward through the recently formed outwash plain. The thickness of these sediments (unit Ogp) varies substantially throughout the area, reaching more than 400 ft just south of the map area at the Port of Olympia.

In the waning stages of the Fraser glaciation, glacial Lake Russell covered a large area of the southern Puget Lowland and deposited a relatively thin layer (1-10 ft) of fine grained varved sediments (unit Ogp) to an elevation of about 140 ft. These lacustrine silt (and rare clay) and peat commonly overlie unit Ogp sands and Vashon till (unit Ogt). Unit Ogp is important because it is widespread throughout the Puget Sound area and appears to behave differently from the rest of the Vashon Drift during earthquakes (Palmer and others, 1999a; Bodle, 1992; King and others, 1996).

The oxygen-isotope stage 6 glaciation, called the Double Bluff Glaciation in northern Puget Sound, was probably as extensive as the stage 2 or Vashon Stage of the Fraser Glaciation (MIS, 1987, Fig. 1). The time and manner of this glaciation lie a short distance beyond the inferred limit of the Vashon ice in the vicinity of Tenno (Lea, 1984). Subglacial erosion was probably similar to the erosion that Booth (1994) documented beneath Vashon ice and would have left more accommodation space for deposition during the interglacial time of oxygen-isotope stage 5. For pre-Vashon nonglacial deposits that are radiocarbon-infinite, therefore, it is difficult to distinguish deposits of stage 3 from deposits of stage 5 and we have not attempted to do so in the present mapping.

In some outcrops, however, terraces are present that provide a tool for geochronological correlation to known eruptions on nearby Cascade stratovolcanoes. Tephra correlations appear promising but will require more data.

## PREVIOUS GEOLOGIC MAPPING

The glacial history and geology of south Puget Sound are well-summarized by Bretz (1913), who mapped the entire Puget Sound basin in reconnaissance. Noble and Wallace (1966, 1:72,000) and Walters and Kimmel (1968, 1:48,000) produced small-scale water resources studies. The Coastal Zone Atlas (Washington Department of Ecology, 1979, 1:800) provides mapping of a 2000-ft-wide strip along the shoreline at a scale of 1:24,000. Walsh (1987, 1988) and others (1987, 1988), and Palmer and others (1999a) compiled and augmented previous mapping.

## MAPPING METHODS

For the present map, we inspected available construction site excavations, gravel pits, and roadcuts. We surveyed the shorelines by boat and took samples and measured sections at cliff exposures. Contacts between map units are commonly not exposed and are only approximately located. They are generally located by outcrop mapping, air photo and lidar interpretation, interpretations of water well logs from Washington Department of Ecology geotechnical site reports, and, in part, modified from Drost and others (1998). USDA soil maps (Pringle, 1990; Zahutal, 1979) helped guide the location of peats and the contacts between sandy and gravelly units. Location accuracy of contacts is judged to be about 200 ft in general. In addition, the contacts between some units are gradational. We have tried to consider geotechnical significance in mapping geological units and have attempted to show units only where they are thicker than 5 to 10 ft or mark the underlying lithology.

## ACKNOWLEDGMENTS

Nick Fort (Wash. State Univ.) and Andrej Samaj-Wojcicki and Tom Sisson (U.S. Geological Survey) provided support for identification of tills. We benefited greatly from discussions with Derek Booth and Kathy Troost (Univ. of Wash.) and Kay Wells and Brian Stierrod (U.S. Geological Survey). Thanks also to Jeff Foster of the Fort Lewis Forestry Program for gaining us crucial access and for his enthusiastic support. This map was supported by the National Geological Mapping Program (Cooperative Agreement No. GCH0AG0047) of the U.S. Geological Survey. New radiocarbon ages were provided by Beta Labs, Inc.

## DESCRIPTION OF UNITS

### Quaternary Unconsolidated Deposits

#### HOLOCENE NONGLACIAL DEPOSITS

- Ot Fill—Clay, silt, sand, gravel, organic matter, shells, rip-rap, and debris; includes engineered and non-engineered fills, shown only where fill placement is extensive, sufficiently thick to be of geotechnical significance, and readily verifiable.
- Omi Modified fill—Silt, sediment, or other geologic material that has been locally reworked to modify the topography by excavation and (or) redistribution.
- Oa Alluvium—Silt, sand, gravel, and peat deposited in stream beds and estuaries; may include lacustrine and beach deposits.
- Ocb Beach deposits—Mud and sand deposited in the intertidal zone or residual gravel on a wave-cut platform.
- Omw Colluvium and alluvial fans—Loose soil and glacial sand and gravel deposited by soil creep and shallowaveling on hillslopes and alluvial fan deposits, some of which occurred during the waning stages of the Vashon Stage of the Fraser Glaciation. Shown where colluvium or fan deposits are of sufficient thickness to mask underlying geologic strata.
- Ope Peat—Organic and organic-matter-rich mineral sediments deposited in closed depressions; includes peat, muck, silt, and clay in and adjacent to wetlands.

### PLEISTOCENE GLACIAL DEPOSITS

#### Deposits of Continental Glaciers—Cordilleran Ice Sheet

VASHON STAGE OF THE FRASER GLACIATION  
Glacial sediments described in this section consist mostly of rock types of northern provenance, most from the Canadian Coast Range. A wide variety of metamorphic and intrusive igneous rocks not indigenous to the Puget Lowland and generally southerly directed current indicators help distinguish these materials from the volcanic-lithic-rich sediments of the eastern Puget Lowland and the Crescent Basalt/Olympic cone-rich sediments of the western Puget Lowland.

Ogof Latest Vashon fine-grained sediments—Lacustrine clayey and (or) fine sandy silt with sparse, disseminated dropstones; laminated and commonly vertically jointed; medium gray to fresh to pale yellow where dry and oxidized. In both fresh and oxidized exposures, this unit is distinguished by relatively darker (brown to black) in oxidized exposures horizontal bands about 1 in. thick that may represent annual winter depositional layers in a varve sequence; no more than about 20 apparent varves were counted in any exposure, suggesting a short life for the glacial lakes in this unit. Ogp was deposited, present in deposits ranging up to 10 ft thick over much of southern Puget Lowland and most commonly found at elevations below about 140 ft; mapped where it is thought to be at least about 5 ft thick or where it masks the underlying geomorphology; includes deposits of glacial Lake Russell and other lakes of the Vashon glacial recession.

Ogpa Latest Vashon recessional sand and minor silt—Moderately well-sorted, moderately to well-sorted, fine- to medium-grained sand with minor silt; noncohesive and highly permeable; thickness inferred from wells reaches up to 100 ft, deposited in and around the margins of glacial lakes; surrounds numerous steep-walled valleys and depressions (kettles); evidence that this unit was largely deposited during deglaciation when there was stagnant ice occupying much of the southern Puget Lowland.

Ogpb Vashon recessional outwash gravel (Stickeen Gravel)—Boulder to boulder gravel exposed in the southeast corner of the Lacey quadrangle and the eastern half of the Nisqually quadrangle. At DuPont, just outside of the map area, the gravel is about 200 ft thick with large boulders that dip west-northwest toward Puget Sound, forming the Squiggleway. Dating of Bretz (1913), who interpreted it as discharge from glacial Lake Puyallup.

Ogpc Vashon recessional outwash—Recessional and proglacial stratified, moderately to well-sorted, poorly to moderately sorted outwash sand and gravel of northern or mixed northern and Cascade source, locally containing silt and clay; also contains lacustrine deposits and ice-contact stratified drift. Some areas mapped as unit Ogp may instead be advance outwash (unit Ogp) as it is difficult to tell the difference between the two without the presence of an intervening till.

Ogt Vashon till—Unstratified and, in most exposures, highly compacted mixture of clay, silt, sand, and gravel deposited directly by glacier ice; gray where fresh and light yellowish brown where oxidized; unsorted and, in most exposures, of very low permeability; most commonly matrix-supported but may be clay-supported; matrix generally has a more gritty feel than outwash sands when rubbed between fingers, due to being more angular than water-worked sediments; cobbles and boulders commonly faceted and (or) striated; ranges in thickness from wavy, discontinuous layers less than 1 in. to more than 30 ft thick; thicknesses of 2 to 10 ft are most common; mapped till commonly includes outwash clay, silt, sand, gravel, or abrasion till that is too thin to substantially mask the underlying, rilling till plan; erratic boulders are commonly associated with till plains but may also occur as lag deposits where the underlying deposits have been modified by meltwater; typically, weakly developed modern soil has formed on the cap of loose gravel, but the underlying till is unweathered, local textural features in the till include flow banding and apophyses commonly extending 10 to 15 ft downward into underlying sand and gravel that are oriented transverse to ice flow direction.

Ogc Ice-contact deposits—Mix of deposits from undifferentiated dynamic ice and dead ice. Dynamic ice deposits include lodgment till, drumlins, and advance outwash; dead-ice deposits include abrasion till, subglacial water flow deposits (such as eskers), and recessional outwash, typically lacks thick, continuous, or widespread deposits of lodgment till at the ground surface, though small till exposures and detrital till fragments are common; topography formed by a mix of ice-marginal and recessional processes.

Oge Eskers—Sigmoid, steep-walled mounds of loose gravel and sand deposited in ice-confined channels by glacial meltwater.

Ogn Vashon advance outwash—Sand and gravel and lacustrine clay, silt, and sand of northern or mixed northern and Cascade source, deposited during glacial advance; locally contains nonglacial sediments, typically by silt rip-ups, cobbles, and peat rip-ups as lag along channel sides and bottoms; gray where fresh, light yellowish gray where stained; oxidized sections of lacustrine silt and clay (unit Ogp) resemble older glaciolacustrine units. Age of maximum Vashon ice advance in the map area was previously estimated to be approximately 14,000 radiocarbon yr B.P., based on apparent post-depositional dating of lacustrine silt and clay (unit Ogp) from radiocarbon dated at about 13,600 radiocarbon yr B.P. (Porter and Swanson, 1998). However, five more recently obtained radiocarbon dates from deposits that underlie Vashon till in the southern Puget Lowland, including a deposit of unit Ogp in this quadrangle, indicate a maximum ice advance after about 13,400 radiocarbon years B.P. (Boeders and Troost, 2001, and this study), leaving very little time for the glacial advance and recession into the southern Puget Lowland; most exposures mapped as Vashon till lack geomorphologic data and are interpreted as Vashon till based on occurrence at or near the top of the stratigraphic section.

Ogs Pre-Vashon sand-size or finer deposits—Massive to cross-bedded sand interbedded with lacustrine silt; minor peat, diatomite, and gravel; immediately adjacent to Vashon Drift and generally overlying unit Ogp. This unit is thought to be of nonglacial origin, and is dominated by varied Cascade-source volcanic lithic rock types. These sediments have previously been referred to the Kitsap Formation and were inferred to be of Olympia age, although all known deposits in the south Puget Lowland are older than the type section of the Olympia lacustrine (Armstrong and others, 1965) and most are radiocarbon-infinite or suspect. Previously reported finite radiocarbon ages in the southern Puget Sound area range from 27,500 to 50,500 yr B.P. (Yount and others, 1980; Walsh, 1987), although all finite ages are older than the 50,500 yr B.P. age are suspect due to laboratory contamination (Fairhall and others, 1966, p. 501). We have obtained two finite radiocarbon ages on this quadrangle (Table 1). Deeter (1979) has shown that the type locality of the Kitsap Formation includes radiocarbon-infinite sediments of both glacial and nonglacial origin, and we follow his suggestion that the name be abandoned. Because we cannot establish that all pre-Vashon lithic sediments are correlative, we have chosen not to assign them a stratigraphic name.

Ogr Pre-Vashon gravel—Gravel and sand, generally of mixed northern and Cascade Range provenance; moderately to poorly sorted, commonly cross bedded but may lack primary sedimentary structures; commonly dated gravels with iron-oxide staining; stratigraphically underlying the Vashon Drift; most commonly exposed immediately underneath exposures of unit Ogp; gravels typically of unit Ogp are relatively resistant to erosion, inferred to be of glacial origin because interglacial conditions do appear conducive to streams with sufficient competency to deposit widespread gravels in most of the Puget Lowland and because the majority of the exposures include northern-source metamorphic rock clasts.

Ogq Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogk Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogl Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogm Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogn Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogo Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogp Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogq Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogr Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogs Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogt Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogc Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Oge Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

Ogn Pre-Vashon sediment of Cascade Range source, undifferentiated—Gravel, sand, silt, clay, peat, and diatomite; lithologically dominated by volcanic lithic rocks of Mount Rainier or other Cascade Range sources; paleocurrent indicators at a prominent exposure near the southeast corner of the quadrangle suggest a southerly source (Fig. 2, 3); large boulders (8 ft in diameter) in this unit are deeply weathered (notches with chisel-edged hammer to a depth of at least several inches); most cobbles and boulders, however, have weathering rinds less than 1 mm; some boulders are glacially striated, suggesting that this unit may be a Cascade (Mount Rainier) source; some alpine drift, weathering rinds suggest both late Pleistocene and early Pleistocene drifts (Colman and Peck, 1981); we tentatively suggest correlations to Hayden Creek and Muga Hill Drifts, but this unit also contains scattered exposures of lahars deposits, lake sediments, and alluvium of both glacial and interglacial origin.

## REFERENCES CITED

Armstrong, J. E., Crandell, D. R., Easterbrook, D. J., Noble, J. B., 1965. Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington. Geological Society of America Bulletin, v. 76, no. 3, p. 321-330.

Bodle, T. R., 1992. Microzonation of the likelihood of strong spectral amplification of earthquake motions using MMI surveys and surface geology. Earthquake Spectra, v. 8, no. 4, p. 501-527.

Booth, D. B., 1994. Glaciolacustrine filling and scour of the Puget Lowland, Washington, during ice-sheet glaciation. Geology, v. 22, no. 8, p. 695-698.

Booth, D. B., Goldstein, B. S., 1994. Patterns and processes of landscape development by the Puget lobe ice sheet. In Lamas, Raymond, Cheney, E. S., coauthors, Regional geology of Washington State. Washington Division of Geology and Earth Resources Bulletin 80, p. 207-218.

Boeders, R. K., Troost, K. G., 2001. Late Pleistocene stratigraphy in the south-central Puget Lowland, Pierce County, Washington. Washington Division of Geology and Earth Resources Report of Investigations 33, 33 p. (On the DGEER website at <http://www.dnr.wa.gov/geology/pdri33.pdf>)

Bretz, J. H., 1913. Glaciation of the Puget Sound region. Washington Geological Survey Bulletin 8, 244 p., 3 plates.

Colman, S. M., Peck, K. L., 1981. Western United States on andesitic and basaltic stones in a Quaternary age indicator. Western United States. U.S. Geological Survey Professional Paper 1210, 36 p.

Deeter, J. D., 1979. Quaternary geology and stratigraphy of Kitsap County, Washington. Western Washington University Master of Science thesis, 175 p., 2 plates.

Don, T. F., Fairhall, A. W., Schell, W. R., Takahashi, Y., 1962. Radiocarbon dating at the University of Washington I. Radiocarbon, v. 4, p. 1-12.

Dross, B. W., Turney, G. L., Dion, N. P., Jones, M. A., 1998. Hydrology and quality of ground water in northern Thurston County, Washington. U.S. Geological Survey Water-Resources Investigations Report 92-109 (revised), 230 p., 6 plates.

Fairhall, A. W., Schell, W. R., Young, J. A., 1966. Radiocarbon dating at the University of Washington III. Radiocarbon, v. 8, p. 498-506.

Garing, M. E., Molenaar, Doe, and others, 1965. Water resources and geology of the Kitsap Peninsula and certain adjacent islands. Washington Division of Water Resources Water-Supply Bulletin 18, 309 p., 5 plates.

King, K. W., Tarr, A. C., Carter, D. L., Williams, R. A., Worley, D. M., 1990. Seismic ground-response studies in Olympia, Washington, and vicinity. Seismological Society of America Bulletin, v. 80, no. 5, p. 1057-1078.

Lea, P. D., 1984. Pleistocene glaciation at the southern margin of the Puget lobe, western Washington. University of Washington Master of Science thesis, 96 p., 3 plates.

Ludwig, K. R., Mads, D. R., Simmons, R. H., Halley, R. B., Shim, E. A., 1996. Sea-level records at ~80 km from tectonically stable plateaus—Florida and Bermuda. Geology, v. 24, no. 3, p. 211-214.

Mix, A. C., 1987. The oxygen-isotope record of glacialation. In Ruddiman, W. F., Wright, H. E., Jr., editors, North America and adjacent oceans during the last deglaciation. Geological Society of America DNAG Geology of North America, v. K-3, p. 111-125.

Morrison, R. B., 1991. Introduction. In Morrison, R. B., editor, Quaternary nonglacial geology—Continental U.S. Geological Society of America DNAG Geology of North America, v. K-2, p. 1-12.

Noble, J. B., Wallace, F. F., 1966. Geology and ground-water resources of Thurston County, Washington, Volume 2. Washington Division of Water Resources Water-Supply Bulletin 10, v. 2, 141 p., 5 plates.

Palmer, S. P., Walsh, T. J., Gerstel, W. J., 1999a. Geologic foliation of the Olympia-Lacey-Tumwater urban area, Washington—liquefaction susceptibility map. Washington Division of Geology and Earth Resources Geologic Map GM-47, 1 sheet, scale 1:48,000, with 16 p. text.

Palmer, S. P., Walsh, T. J., Gerstel, W. J., 1999b. Investigation of earthquake ground motion amplification in the Olympia, Washington, urban area (abstract). Seismological Research Letters, v. 70, no. 2, p. 250.

Porter, S. C., Swanson, T. W., 1986. Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation. Quaternary Research, v. 50, no. 3, p. 205-213.

Pringle, E. F., 1990. Soil surveys of Thurston County, Washington. U.S. Soil Conservation Service, 283 p., 49 plates.

Troost, K. G., 1999. The Olympia glacial interval in the southeastern Puget Lowland, Washington. University of Washington Master of Science thesis, 123 p.

Walsh, T. J., compiler, 1987. Geologic map of the south half of the Tacoma quadrangle, Washington. Washington Division of Geology and Earth Resources Open File Report 87-3, 10 p., 1 plate, scale 1:100,000.

Walsh, T. J., Kenner, M. A., Phillips, W. M., Logan, R. L., Schasse, H. W., 1987. Geologic map of Washington—Southwest quadrant. Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, scale 1:250,000, with 28 p. text.

Walters, K. L., Kimmel, G. E., 1968. Ground-water occurrence and stratigraphy of unconsolidated deposits, central Pierce County, Washington. Washington Department of Ecology, 1979. Coastal zone atlas of Washington, volume 7, Pierce County. Washington Department of Ecology, 1 v., maps, scale 1:24,000.

Washington Department of Ecology, 1980. Coastal zone atlas of Washington, volume 8, Thurston County. Washington Department of Ecology, 1 v., maps, scale 1:24,000.

Yount, J. C., Marcus, K. L., Mosley, P. C., 1980. Radiocarbon-dated localities from the Puget Lowland, Washington. U.S. Geological Survey Open-File Report 80-70, 51 p., 1 plate.

Zahutal, A. S., 1979. Soil survey of Pierce County area, Washington. U.S. Soil Conservation Service, 131 p.

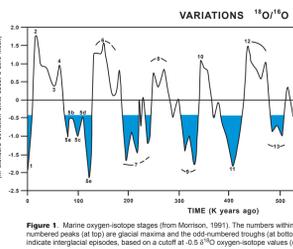


Figure 1. Marine oxygen-isotope stages (from Morrison, 1991). The numbers within the graph are stage numbers; the blue areas indicate interglacial episodes, based on a cut at 0.5 ‰ oxygen-isotope values (equivalent to Holocene interglacial values).

