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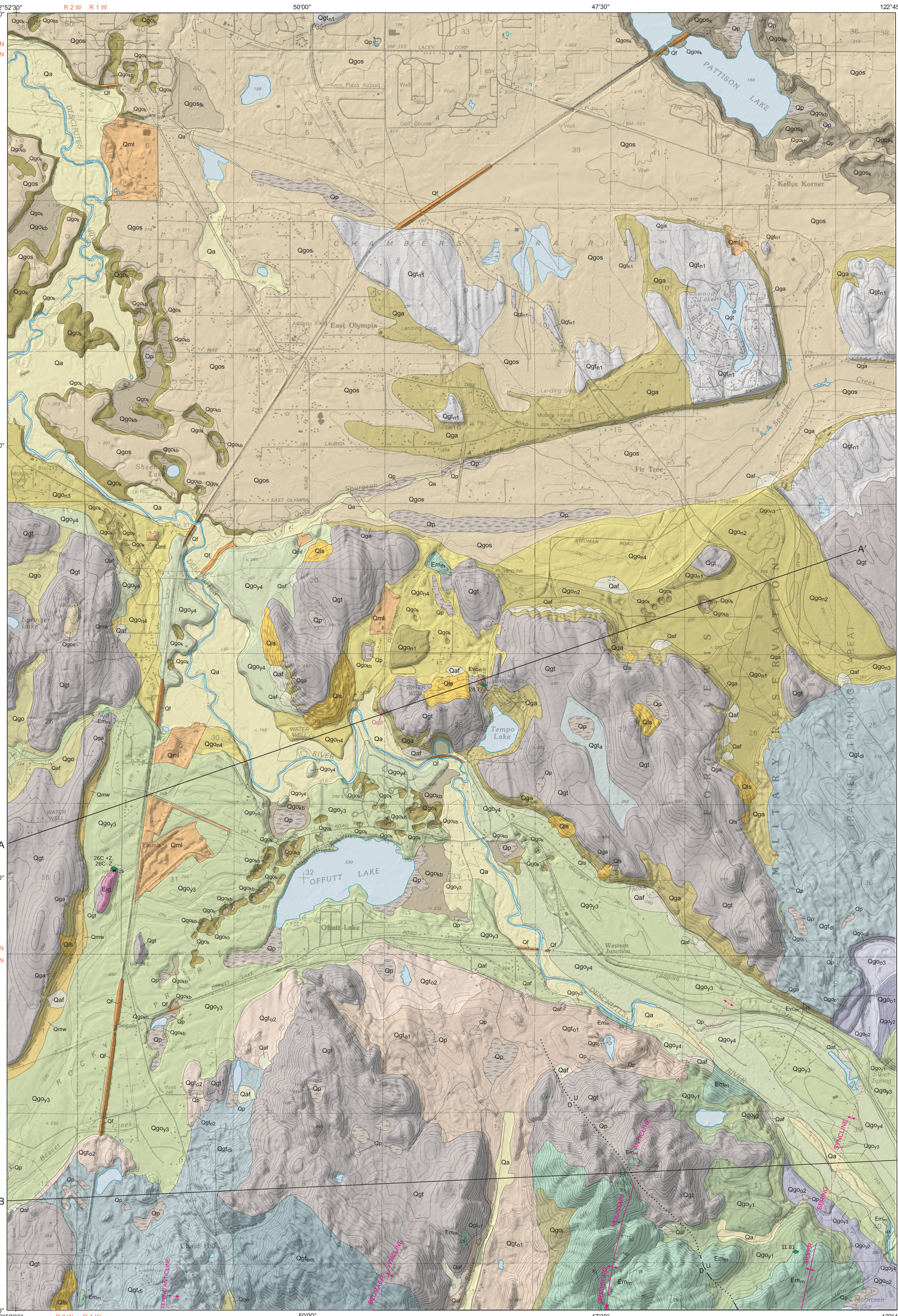
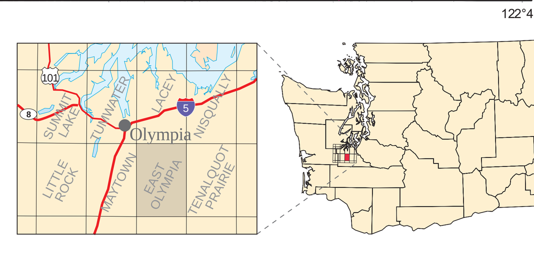


Universal Transverse Mercator, zone 10 projection
North American Datum of 1927; to place on North American Datum of 1983, move the projection lines 20 meters north and 95 meters east as shown by crosshair corner ticks
Base map from scanned and rectified U.S. Geological Survey 7.5-minute East Olympia quadrangle, 1990
Shaded relief generated from lidar; vertical exaggeration 3x
Digital cartography by J. Eric Schuster, Anne C. Heinitz, and Charles G. Caruthers
Editing and production by Jaretta M. Roloff and J. Eric Schuster



Geologic Map of the East Olympia 7.5-minute Quadrangle, Thurston County, Washington

by Timothy J. Walsh and Robert L. Logan

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SCALE 1:24,000

contour interval 20 feet
supplementary contour interval 10 feet

INTRODUCTION

The East Olympia quadrangle is traversed by the geophysical lineament known as the Olympia structure (Logan and Walsh, 2004; Magsino and others, 2003; Sherrod, 2001) (Fig. 1). An aeromagnetic and gravity lineament along the projection of the Olympia structure occurs to the northeast of the Eocene-bedrock-cored hills near Tenino (Gower and others, 1985), but is masked by glacial drift, which covers most of the area. Glacial ice and meltwater deposited drift and carved extensive areas into a complex geomorphology that provides insight into the glacial processes that occurred at the end of the Pleistocene. The many streamlined elongate hills (drumlins) reveal the direction of ice movement throughout the map area. Mima mounds (Washburn, 1988) cover terraces in parts of the quadrangle. Lidar imagery was used to interpret and map landforms, which were then field mapped and checked against water-well logs to confirm their inferred underlying geologic materials.

GEOLOGIC HISTORY

Bedrock exposure is most abundant in the hills southeast of Offutt Lake and in the upper reaches of the Deschutes River where it consists primarily of thinly bedded siltstone, tuff breccia, and thick sandstone of the Eocene McIntosh Formation (unit Em_m), which was named and mapped by Snavely and others (1958) south of the project area. Additional isolated outcrops, mostly of volcanic breccia, are scattered throughout the glacially scoured hills north, east, and west of Offutt Lake and are mostly interpreted as McIntosh Formation interbeds. However, an outcrop due west of Offutt Lake contains a porphyritic volcanic rock of unknown affinity with a chilled margin in contact with a coarse-grained mafic intrusive (unit Eig). Although unit Eig has similar mineralogy and petrographic texture (subophitic) to gabbro and diabase found in the Crescent Formation, the chemistry of this unit is much more mafic (Table 1) (Phillips and others, 1989) and a radiometric age of 38.76 ±2.50 Ma obtained in this study indicates that is too young to be Crescent, but is about the same age as either the volcanic rocks of Grays River (Walsh, 1987; Phillips, 1987) or Northcraft Formation, both of which are present nearby. Chemically, it is strongly tholeiitic, like the volcanic rocks of Grays River and unlike the Northcraft Formation, which is transitional tholeiitic to calc-alkaline. Unit Eig also contains large (1–2 cm) augite crystals similar to those found in some volcanic rocks of Grays River in the Doty Hills (Walsh and others, 1987), so we tentatively correlate these rocks with the volcanic rocks of Grays River. This exposure is somewhat outside of the outcrop area of Grays River, however, and may represent a different pile extruded in the same tectonic environment.

The Pleistocene history of the Puget Lowland was described in detail by Bretz (1913). He noted a "western lobe" and an "eastern lobe" of the "Puget Sound Glacier" that were separated by the Black Hills northwest of the map area where recent mapping by Logan (2003) and Logan and Walsh (2004) refined the ice margin. Bretz (1913) also recognized an interlobe terrain on the eastern flank of the map area (Fig. 1). This interlobe area, characterized by abundant eskers, kettles, deranged drainage patterns, and generally higher elevations than surrounding ground moraine, was continuous from the Steilacoom area northeast of the East Olympia quadrangle to the area of maximum ice extent south of the town of Rainier. The continuity of the interlobe terrain is interrupted only by subsequent outwash channels that dissect the feature near the lower reaches of the Nisqually River valley (Fig. 1). Noble and Wallace (1966) referred to the lobes that were separated by the interlobe terrain as the Yelm lobe and the Olympia lobe. We continue use of this terminology in describing the rock units and outwash channels in the map area.

At the glacial maximum, about 13,500 yr B.P. (Walsh and others, 2003), Olympia lobe ice impinged on and partially spilled over the hills north of Tenino (this study; Bretz, 1913) (Fig. 1). Outwash was directed south and westward through Bretz's Stony Point channel and the prairie occupied by Scatter Creek west of Tenino. Ice-scoured moraine occupies the valley that contains the headwaters of Scatter Creek in the south-central part of the map area, and outwash gravels crop out on the southern map border south of Chain Hill, indicating that glacial meltwater emerged from both of these valleys at glacial maximum.

The hills west of the upper part of Scatter Creek are covered by an unknown thickness, but locally at least 20 to 25 ft, of till and possibly older glacial drift of the Double Bluff glaciation (Easterbrook and others, 1967; Lea, 1984). The hills east of Scatter Creek have less extensive accumulations of Pleistocene deposits, and bare bedrock outcrops of McIntosh Formation sandstone and siltstone are present. Nevertheless, glacially transported boulders and pockets of northern-provenance-rich gravel are disseminated throughout the area northwest of McIntosh Lake. Noble and Wallace (1966) interpreted most of the glacial deposits in the south half of the quadrangle as pre-Vashon on the basis of their erosion characteristics. Because of the clear and continuous geomorphic signature of the ice-scoured ground moraine, the deranged characteristics of end-moraine deposits, and the strong evidence of ice-marginal meltwater erosion at and soon after glacial maximum, we interpret most glacial units in the quadrangle as Vashon age. Lea (1984) mapped pre-Vashon drift south of the quadrangle where it is beyond the Vashon ice-limit. We mapped pre-Vashon deposits (unit Qpg) only in limited exposures along the Deschutes River.

A description of the rock units in the East Olympia quadrangle would not be adequate without including a discussion of the surrounding region. Lidar imagery of part of the southern Puget Lowland (Fig. 1) should help the reader understand the complex nature of the processes that occurred at the end of the Pleistocene. According to Bretz (1913) and our observations, the maximum extent of the Olympia lobe reached nearly to Tenino, while the maximum extent of the Yelm lobe reached at least as far south and west as the city of Rainier. The glacial maximum was followed by a steady and rapid retreat of the ice front from the area. The ice-front retreat resulted in construction of extensive terraces by ice-marginal streams. The streams were generally bounded on one side by ice and cutting terraces into moraine deposits on the other, leaving asymmetric valleys (channels) with unmatched terraces. This type of activity was extensive in the interlobe terrain and formed Tenalquot Prairie immediately east of the quadrangle (Fig. 1). There, meltwater formed the Yelm channel of the Yelm lobe and flowed southward through the Stony Point channel, depositing units Qgo_{y1} and Qgo_{y2} on the east side of the hills north of McIntosh Lake. As the ice front retreated northward, meltwater emanating from the snout of the Olympia lobe, just east of the quadrangle (Fig. 1), was able to flow northwestward around the hills south of Offutt Lake, where it formed terraces capped by units Qgo_{o1} and Qgo_{o2} and deposited a veneer of sediment on ground moraine to form units Qgt_{o1} and Qgt_{o2}. After further ice retreat, meltwater was still blocked by ice that occupied the valley in the vicinity of Offutt Lake and was forced to flow southwestward, skirting the east side of Rocky Prairie. Continued ice retreat and a shift in source to the Rainier channel of the Yelm lobe (Fig. 1) resulted in truncation of Olympia-lobe-channel and Yelm-channel terraces by streams occupying the Rainier channel (southeast corner of map). The Rainier channel waters hastened the northward migration of the ice front and erosion of a channel through the Offutt Lake area and eventual deposition of units Qgo_{y3} and Qgo_{y4}. Shortly before unit Qgo_{y4} was deposited, some meltwater escaped westward through the narrow channel currently occupied by McCorkle Road (Fig. 1).

The stream that deposited unit Qgo_{y3} was probably fed by a glacial outburst flood (Tanwax flood of Pringle and Goldstein, 2002; Pringle and others, 2000), because it was strong enough to carry and deposit boulders as large as 2 to 3 ft in diameter in the Deschutes River valley and icebergs in the vicinity of Offutt Lake. The icebergs were aligned with the southerly turn of the channel and covered by unit Qgo_{y3} to form the concave-to-the-south kettle field that includes Offutt Lake (Fig. 1). The floodwaters were blocked by ice that occupied the entire western side of the map area, including the western part of Rocky Prairie. As a result, outwash flow was slowed dramatically, forming a temporary lake that caused a delta to prograde westward across Rocky Prairie and water to temporarily spill through the narrow valley currently occupied by the rail line in the southwest corner of the quadrangle and into the valley occupied by Tenino. As the hydraulic head increased in the Rocky Prairie area, water began flowing beneath the ice in sec. 12, T16N R2W, eventually breaching the ice dam and continuing its flow westward to the Chehalis River (not shown).

The ice blockage of Rocky Prairie and the McCorkle Road channel was short lived, and so was the outwash flow through them. As the glacier melted back to the north near Sheehan Lake (sec. 18, T17N R1W), meltwater could then flow northward through to a lower base level, eventually cutting downward through the terrace represented by unit Qgo_{y4}. Ice must have continued to impinge on the hills southeast of Sheehan Lake, causing ice-marginal meltwater from the Nisqually and Lake St. Clair area (Fig. 1) to flow south through sec. 21, T17N R1W, into the Deschutes River valley, eventually leaving unmatched terraces of outwash gravel in that section.

The ice that blocked the flow from the east probably occupied a depression that was a continuation of present-day Budd Inlet (Fig. 1). Evidence of this is a train of kettles that reaches from the modern southern tip of Budd Inlet to at least as far south as Sheehan Lake and probably almost as far south as Offutt Lake. The modern Deschutes River flows through many of these kettles to reach Puget Sound. Kettle trains similar to the one south of Budd Inlet also formed south of Nisqually Reach (forming Lake St. Clair, Fig. 1) and south of Henderson Inlet forming Pattison Lake as glacial ice occupying these depressions was buried by recessional outwash. Continued retreat of the ice front allowed ice marginal streams originating in the Nisqually and Lake St. Clair area and farther east from glacial Lake Puyallup to flow westward across the northern half of the map area, cutting channels through the Vashon ground moraine and into underlying advance outwash. As the energy of these streams waned, they eventually deposited sand and gravel, followed by sand and silt, around the remaining stagnant ice blocks. As the ice melted away, the Budd Inlet, Henderson Inlet, and Nisqually kettle chains were formed.

Soils capping bedrock areas tend to be reddish brown, but those capping most glacial outwash deposits tend to be very dark brown to black. The soils covering unit Qgo_{y3} are formed into mounds about 2 to 6 ft high and 10 to 30 ft across. The mounds are referred to as Mima mounds and have been extensively studied by previous workers (summarized in Washburn, 1988; and discussed in Bretz, 1913). It is notable that unit Qgo_{y3} is the only unit within the East Olympia quadrangle on which the Mima mounds formed (this study; Pringle and Goldstein, 2002). The mounds must have formed very shortly after unit Qgo_{y3} was deposited, because (1) they did not form within kettles, which clearly formed after unit Qgo_{y3} was deposited (kettles crosscut meltwater channels); (2) they appear to be partially buried by alluvial fans near the margins of the unit Qgo_{y3} channel; and (3) they did not form in unit Qgo_{y4} channels that cut the surface of unit Qgo_{y3}.

Snavely and others (1958) mapped broad southward-plunging folds in bedrock directly south of and projecting into the map area. The few attitudes collected from sparse outcrop during this study support the general structural interpretation of these earlier workers.

We have mapped a northwest-trending fault in the southeast corner of the quadrangle (cross section B), based on its topographic expression and oil and gas test well logs. The fault is covered by Quaternary sediment and was not observed in outcrop. It parallels the upper Deschutes River valley, which dissects the till-covered hills in the south half of the quadrangle and is itself parallel to and along trend with the structure known as the Olympia structure (Magsino and others, 2003; Sherrod, 2001). Based on continuity of bedrock structure across the Deschutes River valley and interpretation of aeromagnetic data of Blakely and others (1999), we place the Olympia structure northeast of the hills containing Tempo Lake as shown in Fig. 1, although no surficial expression other than the northwest trend of the hills was detected in lidar imagery or on the ground.

DESCRIPTIONS OF MAP UNITS

Quaternary Unconsolidated Deposits

HOLOCENE NONGLACIAL DEPOSITS

Qf — **Fill**—Generally large engineered fills of unknown materials associated with railroads; shown only where fill placement is relatively extensive.

Qml — **Modified land**—Soil, sediment, or other geologic material that has been locally reworked to modify the topography by excavation and (or) redistribution. *Note:* Only major gravel pits were shown as unit Qml in this quadrangle, although there are large areas of regrading associated with golf courses and housing developments, especially in the northern half of the map area.

Qls — **Landslide**—Generally loose, jumbled, tan to gray, silty sandy gravel with few to no discernible sedimentary structures; surfaces of landslides are generally undulatory; most occur along steep sides of outwash channels and may have occurred shortly after ice retreated from the map area.

Qmw — **Colluvium**—Loose soil and glacial sand and gravel deposited by soil creep and shallow raveling on hill slopes; entirely postglacial. Shown where colluvium is of sufficient thickness to mask the underlying geologic strata.

Qa — **Alluvium**—Silt, sand, and gravel deposited in streams; may include some lacustrine deposits and organic materials, such as peat.

Qp — **Peat**—Organic-matter-rich sediments deposited in closed depressions; includes peat, muck, silt, and clay in and adjacent to wetlands.

Qaf — **Alluvial fan**—Silt, sand, and gravel deposited at the confluence of upland streams with outwash channels and terrace edges. Commonly capped by dark brown to black, mucky loamy soils.

PLEISTOCENE GLACIAL DEPOSITS

Vashon Recessional Outwash, Nisqually/Lake St. Clair Source

There were five distinct trains of recessional outwash from the Nisqually/Lake St. Clair area. They are represented, from youngest to oldest, by units Qgos, Qgo_{n4}, Qgo_{n3}, Qgo_{n2}, and Qgo_{n1}.

Qgos — **Vashon recessional outwash sand and silt**—Loose sand and silt with minor gravel interbeds; tan to brown; clasts moderately to well rounded; generally well sorted; clasts and grains consist of northern-source plutonic and metamorphic rock and polycrystalline quartz carried by Vashon ice and porphyritic volcanic rock from the Cascade Range; varies in thickness from about 4 to 20 ft. This unit covers much of the north half of the quadrangle and was probably deposited by meltwater derived from stagnant ice south of Lake St. Clair (Fig. 1) and drainage from glacial Lake Puyallup farther east, possibly grading to glacial Lake Nisqually (Bretz, 1913) and glacial Lake Russell. Locally derived and relatively small patches of ice-contact sand are also included in this unit. Locally divided into:

$Qgos_{fk}$ — **Vashon recessional outwash sand and silt kettle-fill**—Sand and silt filling of a kettle in the direct path of a late stage outwash flood.

Qgo_{kb} — **Vashon kettle-bottom silt and peat**—Mostly silt and peat in flat bottoms of kettles. Some kettle bottoms may consist of sand and gravel with or without a fine-grained cover; generally found in large-diameter kettles where buried ice must have been thick relative to its depth of burial.

$Qgos_k$ — **Kettle walls and rounded kettle bottoms in Vashon recessional outwash sand and silt**—Sandy silt and silty sand deposited around and over ice that was grounded in outwash channels and in ice-filled inlets where glacial ice must have formed keel-like features; unit is differentiated from other kettle-related units by sediments that are generally finer grained than deposits that are not immediately adjacent to kettles; found mostly in the northern half of the map area. The kettles that form Pattison Lake and the adjacent weakly kettled terrain are surrounded by tan silt and fine sand. Farther west, in and near the Deschutes River valley, similar tan silt and fine sand, up to about 20 ft thick, overlie, in sharp contact, the recessional sand and gravel that form the lower kettle walls. Near Offutt Lake, materials surrounding kettles are generally coarser grained than those farther north and commonly contain cobbles and boulders (see unit Qgo_k).

Qgo_{n4} — **Vashon recessional outwash gravel, train 4**—Loose sandy gravel forming a bar in N½ sec. 22, T17N R1W, and channel deposits elsewhere; gray to tan; moderately to well rounded; generally well sorted; clasts consist of plutonic and metamorphic rock and polycrystalline quartz, carried from the north by Vashon ice, with minor porphyritic volcanic rock from the central Cascade Range. Little else is known about this unit due to poor exposure. No known wells are drilled in this unit, and the only outcrops observed were in 1- to 2-ft-high cuts in loose sandy gravel along Stedman Road. However, because part of this unit is a bar, it is probably fairly well sorted and stratified. The elevation of the top of the bar is about 20 to 30 ft higher than the top of the channel that contains unit Qgos and about the same elevation as the outwash gravels in the W½ sec. 21, T17N R1W. Next to unit Qgos, this unit is the youngest of the glacial outwash trains from the Nisqually/Lake St. Clair area. The waters that deposited this unit were blocked by ice that impinged on the hills west of sec. 21, T17N R1W.

Qgo_{n3} — **Vashon recessional outwash gravel, train 3**—Loose sand and gravel, tan to gray; moderately to well rounded; consists of plutonic and metamorphic clasts transported from the north by Vashon ice and deposited by meltwater. This channel deposit is both truncated by younger channels containing units Qgo_{n4} and Qgos and cut into the older terrace gravels of units Qgo_{n2} and Qgo_{n1}. The channel that contains unit Qgo_{n3} is nearly horizontal, with a slight gradient at its northern end, and was probably formed by meltwater derived from stagnant ice south of Lake St. Clair (Fig. 1). This unit was identified from the lidar imagery; no outcrop was found and only traces of sand and gravel were found on the surface of this channel.

Qgo_{n2} — **Vashon recessional outwash gravel, train 2**—Loose sandy gravel; tan to gray; moderately to well rounded; moderately to well sorted; consists of plutonic and metamorphic clasts transported by Vashon ice and deposited by meltwater. Because the unit is so flat and loose, outcrops are rare and limited to surficial regolith. This unit forms a terrace that resulted from the northward migration of and downcutting by the same ice-marginal streams that deposited unit Qgo_{n1}. Stagnant ice from south of Lake St. Clair (Fig.1) was the probable source for most of the ice-marginal flow. This terrace was formed as the snout of the glacier was retreating northward. Several kettles formed in this unit, indicating that stagnant ice was trapped during the deposition of the unit.

Qgo_{n1} — **Vashon recessional outwash gravel, train 1**—Loose sand and gravel; tan to gray; moderately sorted; moderately to well rounded. Sand grains from a gravel pit in sec. 26, T17N R1W, are about 90 percent northern source, being dominated by polycrystalline quartz, with about 10 percent or less glassy, porphyritic volcanic clasts, probably from the local Cascade Range, indicating that the unit was deposited mostly from glacial meltwater from stagnant ice south of Lake St. Clair (Fig. 1). The unit forms terraces that were probably deposited by earlier stages of the same ice-marginal streams that deposited sediment on unit Qgt_{n2}.

Qgo_k — **Vashon recessional outwash gravel in kettle walls**—Loose sand and gravel; tan to gray; moderately to well rounded and sorted; consists of northern-source plutonic and metamorphic rock carried by Vashon ice and porphyritic volcanic rock from the Cascade Range. In the northwestern part of the map, where exposed near the Deschutes River valley, consists of sandy gravel; farther south near Offutt Lake, kettle sides contain boulder and cobble clasts.

Vashon Recessional Outwash, Yelm and Olympia Lobe Sources

There were four distinct trains of recessional outwash from the Yelm lobe. They are represented, from youngest to oldest, by units Qgo_{y4}, Qgo_{y3}, Qgo_{y2}, and Qgo_{y1}. Meltwater from the Olympia lobe incised into units Qgo_{y1} and Qgo_{y2} depositing units Qgo_{o1} through Qgo_{o3}. Subsequent meltwater from the Yelm channel truncated both the earlier Yelm and Olympia lobe outwash channels and deposited units Qgo_{y3} and Qgo_{y4}. The listing below reflects the chronologic order of these events.

Qgo_{y4} — **Vashon recessional outwash, Yelm lobe, Rainier channel, Deschutes River**—Loose sand and gravel; grains and clasts well rounded; moderately to well sorted; restricted to channel deposits that cut unit Qgo_{y3} and form terraces that grade to an outlet in the northwest corner of the map where, at the time of deposition, glacial ice had melted back to a point north of the East Olympia/Sheehan Lake area. This unit contains fewer boulders than unit Qgo_{y3}. The outwash originated both from the Yelm lobe, Rainier channel, and the upper Deschutes River (Fig. 1).

Qgo_{y3} — **Vashon recessional outwash, Yelm lobe, Rainier channel, Tanwax Creek–Ohop Valley flood**—Bouldery and cobbly sand and gravel; clasts and grains well rounded; moderately to well sorted; capped by silty Mima mounds. Boulders are both Cascade-derived andesite and plutonic and metamorphic rock deposited by Vashon ice. Regional geomorphology indicates that the waters that deposited the unit came from both the Rainier channel of the Yelm lobe (Fig. 1) and the Tanwax Creek–Ohop Valley glacial outburst flood (Pringle and Goldstein, 2002; Pringle and others, 2000). This unit traces the path of the Deschutes River when it flowed from the McIntosh Lake area northwestward through Offutt Lake. Ice west of Offutt Lake blocked the flow, forcing it south toward Tenino (Fig. 1). The Tenino flow was short lived, and its path is delineated by the Offutt Lake kettle chain. As the ice melted, the prehistoric Deschutes River flowed from Rocky Prairie westward.

Qgo_{o3}, Qgo_{o2}, Qgo_{o1} — **Vashon recessional outwash, Olympia lobe**—Sand and gravel with cobbles; mostly northern-source plutonic and metamorphic material; moderately sorted; well rounded. Deposited in outwash channels that emanated from the snout of the Olympia lobe (Fig. 1) and now form terraces. These channels were eroded into outwash from the Yelm channel of the Yelm lobe (Fig. 1) (units Qgo_{y1} and Qgo_{y2}), Vashon ground moraine and advance outwash gravel, and possibly pre-Vashon sediments. The Olympia lobe channel deposits are truncated in turn by the Rainier channel and (or) Tanwax Creek–Ohop Valley flood channel (Pringle and Goldstein, 2000), in which units Qgo_{y3} and Qgo_{y4} were deposited.

Qgo_{y2}, Qgo_{y1} — **Vashon recessional outwash, Yelm lobe, Yelm channel**—Loose sand and gravel with cobbles; moderately sorted; well rounded; consists of plutonic and metamorphic sediment deposited by Vashon meltwater in channels that emanated from the snout of the Yelm lobe about 2 mi west of Yelm. These sediments constructed a terraced fan that crossed and filled the Deschutes River valley, allowing the meltwater to flow southward through the Stony Point channel (Bretz, 1913) (Fig.1).

Qgo — **Vashon recessional outwash sand and gravel**—Loose sand and gravel; tan to gray; moderately to well sorted and rounded; consists of plutonic and metamorphic sediment deposited by Vashon meltwater occupying outwash channels and terraces of various elevations, but formed after glacial ice retreated. Difficult to distinguish from advance outwash without intervening layers of till, however, it contains no glassy volcanic porphyry from the Cascade Range.

Qgo_i — **Vashon recessional outwash sand and gravel, ice-contact deposits**—Gray sand and gravel deposited from ice-contact channels, generally in areas occupied by stagnant ice; includes eskers and kames.

Vashon Drift

Qgt_{o2}, Qgt_{o1} — **Vashon till covered by recessional outwash from the Olympia lobe, Tenalquot Prairie channel**—Outwash-modified till; gray; compact; unsorted mixture of clay through boulder-size plutonic and metamorphic rock deposited by Vashon ice. Forms drumlins in ground moraine, but is covered by gray to tan, northern-source-dominated, pebbly sandy gravel that was deposited by glacial meltwater from the Olympia lobe on the west side of Tenalquot Prairie (Fig. 1). Relief of drumlins relative to areas not subject to floods is subdued by sediment cover. This unit covers a terrace that was probably formed by the same glacial meltwaters that formed the terrace containing unit Qgo_{o2}, based on similarities of surface elevations of the terraces.

Qgt_{n1} — **Vashon till covered by recessional outwash from the Lake St. Clair/ Nisqually source**—Outwash-modified till; gray; compact; unsorted mixture of clay through boulder-size plutonic and metamorphic rock deposited by Vashon ice. Forms drumlins in ground moraine, but is covered by northern-source-dominated, pebbly gravelly sand that was deposited by glacial meltwater from Olympia lobe ice in the Lake St. Clair area and drainage from glacial Lake Puyallup that crossed the Nisqually area (Fig. 1). Relief of drumlins relative to areas not subject to floods is subdued by sand or gravel cover. Part of this unit comprises a terrace that was probably formed by the same meltwaters that deposited unit Qgo_{n1}, based on similarities of terrace surface elevations.

Qgt_a — **Vashon ablation till**—Loose, moderately to well rounded sand and gravel of unknown thickness covering an unknown thickness of lodgement till. The presence and extent of this unit is inferred from lidar imagery and scattered stones on the ground surface. This unit is located within the boundaries of Fort Lewis where lack of roads, outcrop, and well data prevented direct observation of the units.

Qgt_{di} — **Vashon till, dead-ice terrain**—Gravelly till associated with eskers and kettles and loose sand and gravel. In the southeastern part of the map area, this unit was deposited beneath stagnant ice at the snout of the Olympia lobe. Angular, glacial erratic boulders, mostly of coarse-grained intrusive affinity are disseminated on the surface of this unit.

Qgt_{em} — **Vashon till, end moraine**—Pebbly to cobbly till; tan to gray; clast-supported; compact. True thickness is unknown, but one outcrop is about 20 ft thick. This unit was formed by ice spilling over the crest of the hills at the south-central part of the map area. Lack of drumlins on the surface is characteristic of this unit and distinguishes it from tills in ground moraine and dead-ice terrain. Angular, glacial erratic boulders, mostly plutonic, are scattered on the surface of this unit.

Qgt — **Vashon till, drumlinized ground moraine**—Till; gray to tan, unstratified, compact, unsorted mixture of clay, silt, sand, and gravel deposited directly by glacial ice; nearly everywhere in sharp contact with underlying units; permeability and porosity are low; sand and finer size grains are very angular; pebble- to boulder-size clasts are commonly striated and faceted; boulders are generally disseminated and relatively rare; may contain interbeds of sand and gravel. The surface of this unit is characterized by streamlined drumlins and striations that are generally hundreds to thousands of feet long. Angular glacial erratic boulders, mostly plutonic, are on the surface of this unit.

Qga — **Vashon advance outwash**—Sand and gravel and lacustrine clay, silt, and sand; gray to light brown, compact, well rounded mostly polycrystalline quartz, plutonic, and minor metamorphic grains; deposited during Vashon glacial advance; most easily distinguished from recessional outwash if covered directly by Vashon till. This unit may also contain pre-Vashon drift (unit Qpg) at its base, but poor outcrop due to raveled terrace scarps prevented differentiation of these units.

Pre-Vashon Drift

Qgp — **Pre-Vashon drift (cross section A only)**—Till and well-rounded sand and gravel with some clay and silt; light brown or gray to yellowish-brown; generally compact; dominated by northern-source polycrystalline quartz and plutonic and minor metamorphic grains. Exposure in the Deschutes River channel consists of rip-up blocks of deeply weathered compact silt, till, and gravelly sand, up to 10 ft in diameter, surrounded by younger, fresh alluvial deposits; unit is also exposed to a limited extent along the Chehalis Western Trail on the west side of the hill west of Tempo Lake as a compact, weathered sand and gravel of northern provenance. Shown only in cross section because exposures were not mappable at this scale.

Tertiary Sedimentary and Volcanic Rocks

Em_m — **McIntosh Formation (Eocene)**—Volcanic lithic sandstone, siltstone, and volcanic breccia; locally fine to medium grained; gray green; contains interbeds of volcanic breccia (similar to unit Evc_m) that are not mappable due to poor outcrop, but are found in oil and gas test wells, such as the two in cross section B. Although no macrofossils were found, foraminifera were found in thin section.

Evc_m — **Volcanic breccia interbeds (Eocene)**—Dacitic volcanic breccia (Table 1); dark gray-green with angular red clasts; fragments consist mostly of euhedral, commonly twinned and zoned plagioclase phenocrysts and euhedral twinned augite phenocrysts in a glassy matrix with minor ghost grains of another mineral, possibly an amphibole; unit is interbedded with volcanic lithic sandstone of the McIntosh Formation and forms a substantially thick bed in the subsurface (cross section B).

Eig — **Volcanic rocks of Grays River (Eocene)**—Black to dark gray-green, ophitic to subophitic, tholeiitic gabbro; coarse-grained augite (≤2 cm) and plagioclase grains in equal abundance, about 40 percent of each; an opaque iron-oxide mineral with graphic texture comprises about 15 percent, with the remainder composed of zeolite minerals? with undulatory extinction and fine-grained secondary mineralization. A fine-grained volcanic porphyry is in contact with the gabbro; the margin of the porphyry is chilled. This unit is exposed only in a small rock quarry in sec. 31, T17N R1W. The unit's chemistry is shown in Table 1. A radiometric age of 38.76 ±2.50 Ma obtained in this study indicates that it is too young to be Crescent but about the same age as volcanic rocks of Grays River (Walsh, 1987; Phillips, 1987).

Ev_c — **Crescent Formation (Eocene) (cross section B only)**—Zeolitic and chloritic basalt flows, tuff, and volcanic breccia; as interpreted by Snavely and others (1958)

GEOLOGIC SYMBOLS

- Contact
- U/D — High-angle dip-slip fault—Relative motion shown by U and D; dashed where approximately located; dotted where concealed
- Anticline—Dotted where concealed
- Syncline—Dotted where concealed
- Qgp — Geologic unit too small to show as a polygon at map scale; located near midpoint of cross section A.
- WATER WELL — Water well
- T-6 — Hydrocarbon exploration dry hole
- 26C +Z — Whole rock geochemistry sample location—Numbers correspond to sample numbers in Table 1
- 20 — Inclined bedding—Showing strike and dip
- 25 — Jointing—Showing strike and dip

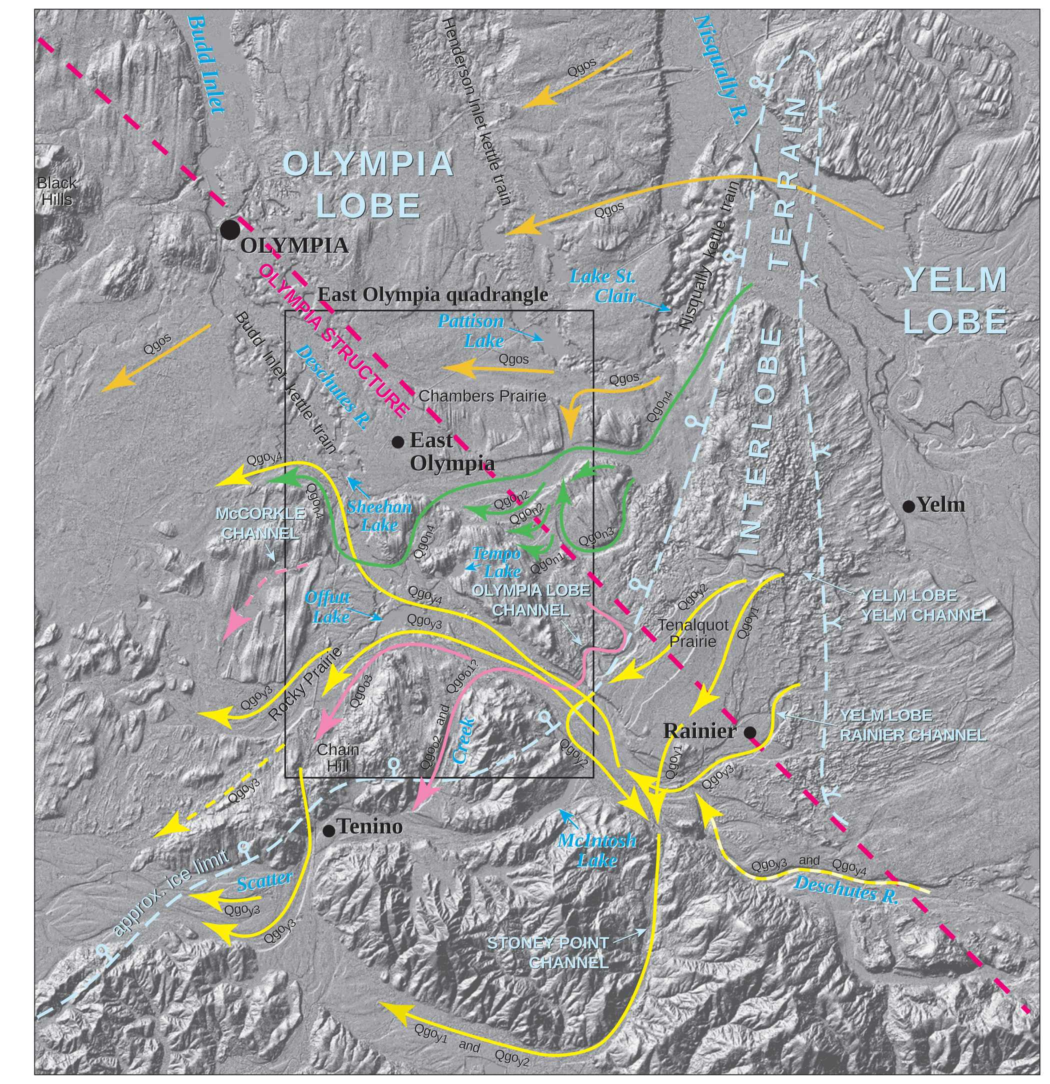

Figure 1. Shaded-relief lidar (airborne laser swath mapping) image of the East Olympia quadrangle and surrounding area. The image has a 6X vertical exaggeration, 315° azimuth illumination, and a 45° look-direction. Notice the area east of Tenalquot Prairie with the nearly west-directed ice-scoured surface caused by the Yelm lobe and the southeast-directed scour of the Olympia lobe in the eastern part of the East Olympia quadrangle. Both lobes converged on the interlobe terrain east of the quadrangle. The Yelm lobe probably reached ice maximum shortly before the Olympia lobe. Arrows labeled with the unit symbol represent the origins, general pathways, and timing of glacial meltwater streams. Dashed arrows indicate possible subglacial channels. Location of the Olympia structure is from the interpretation of an aeromagnetic map of Blakely and others (1999).

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REFERENCES CITED

Blakely, R. J.; Wells, R. E.; Weaver, C. S., 1999, Puget Sound aeromagnetic maps and data: U.S. Geological Survey Open-File Report 99-514, version 1.0 [accessed Oct. 3, 2000 at http://geopubs.wr.usgs.gov/open-file/of99-514/]

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

Easterbrook, D. J.; Crandell, D. R.; Leopold, E. B., 1967, Pre-Olympia Pleistocene stratigraphy and chronology in the central Puget Lowland, Washington: Geological Society of America Bulletin, v. 78, no. 1, p. 13-20.

Gower, H. D., 1978, Possible Quaternary faulting in the Puget Sound region [abstract]: U.S. Geological Survey Professional Paper 1100, p. 79.

Gower, H. D.; Yount, J. C.; Crosson, R. S., 1985, Seismotectonic map of the Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1613, 1 sheet, scale 1:250,000, with 15 p. text.

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.

Logan, R. L., 2003, Geologic map of the Shelton 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-15, 1 sheet, scale 1:100,000. [accessed Aug. 11, 2003 at http://www.dnr.wa.gov/geology/pdf/ofr03-15.pdf]

Logan, R. L.; Walsh, T. J., 2004, Geologic map of the Summit Lake 7.5-minute quadrangle, Thurston and Mason Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2004-10, 1 sheet, scale 1:24,000.

Magsino, Sammantha; Sanger, Elizabeth; Walsh, T. J.; Palmer, S. P.; Blakely, R. J., 2003, The Olympia structure—Ramp or discontinuity? New gravity data provide more information [abstract]: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 479.

Noble, J. B.; Wallace, E. 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.

Phillips, W. M., 1987, Geochemistry and areal extent of the Grays River volcanic rocks, southwest Washington and adjacent Oregon [abstract]: Eos (American Geophysical Union Transactions), v. 68, no. 52, p. 1815.

Phillips, W. M., compiler, 1987, Geologic map of the Mount St. Helens quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-4, 59 p., 1 plate, scale 1:100,000.

Phillips, W. M.; Walsh, T. J.; Hagen, R. A., 1989, Eocene transition from oceanic to arc volcanism, southwest Washington. *In* Muffler, L. J. P.; Weaver, C. S.; Blackwell, D. D., editors, Proceedings of workshop XLIV—Geological, geophysical, and tectonic setting of the Cascade Range: U.S. Geological Survey Open-File Report 89-178, p. 199-256.

Pringle, P. T.; Goldstein, B. S., 2002, Deposits, erosional features, and flow characteristics of the late-glacial Tanwax Creek–Ohop Creek Valley flood—A likely source for sediments composing the Mima mounds, Puget Lowland, Washington [abstract]: Geological Society of America Abstracts with Programs, v. 34, no. 5, p. A-89.

Pringle, P. T.; Goldstein, B. S.; Anderson, N. R., 2000, Tanwax Creek–Ohop Valley late-glacial flood—Evidence that discharge from an ice-dammed lake in the Carbon River Valley was augmented by a temporary landslide dam, Puget Lowland, Washington [abstract]. *In* Washington Department of Ecology; Washington Hydrologic Society; U.S. Geological Survey, Program and abstracts from the 3rd symposium on the hydrogeology of Washington State: Washington Department of Ecology, p. 85.

Sherrod, B. L., 2001, Evidence for earthquake-induced subsidence about 1100 yr ago in coastal marshes of southern Puget Sound, Washington: Geological Society of America Bulletin, v. 113, no. 10, p. 1299-1311.

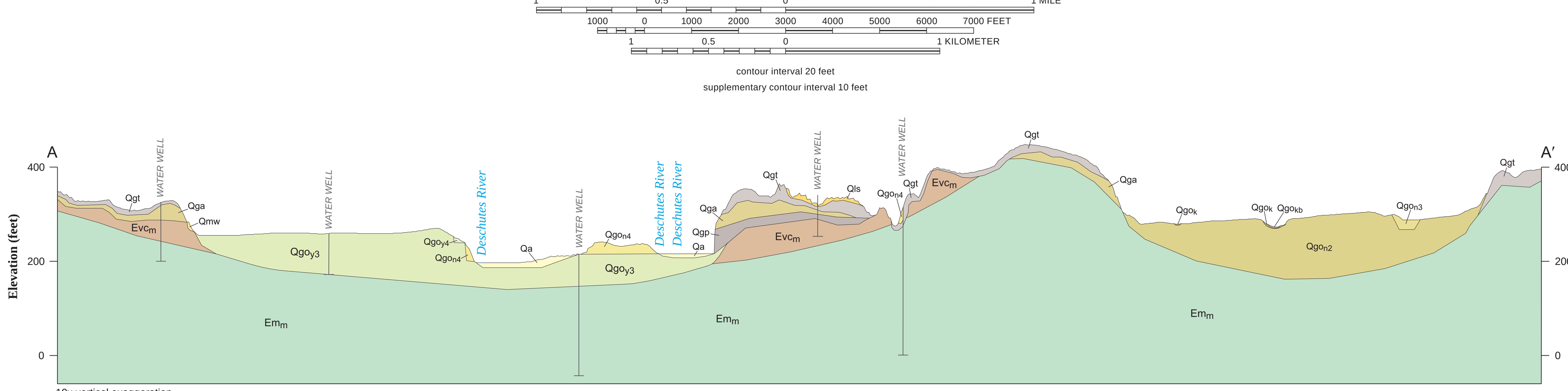
Snavely, P. D., Jr.; Brown, R. D., Jr.; Roberts, A. E.; Rau, W. W., 1958, Geology and coal resources of the Centralia–Chehalis district, Washington, with a section on Microscopical character of Centralia–Chehalis coal, by J. M. Schopf: U.S. Geological Survey Bulletin 1053, 159 p., 6 plates.

Walsh, T. J., compiler, 1987, Geologic map of the Astoria and Ilwaco quadrangles, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-2, 28 p., 1 plate.

Walsh, T. J.; Korosec, 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.

Walsh, T. J.; Logan, R. L.; Polenz, Michael; Schasse, H. W., 2003, Geologic map of the Nisqually 7.5-minute quadrangle, Thurston and Pierce Counties, Washington: Washington Division of Geology and Earth Resources Open File Report 2003-10, 1 sheet, scale 1:24,000. [accessed July 24, 2003 at http://www.dnr.wa.gov/geology/pdf/ofr03-10.pdf]

Washburn, A. L., 1988, Mima mounds—An evaluation of proposed origins with special reference to the Puget Lowlands: Washington Division of Geology and Earth Resources Report of Investigations 29, 53 p.



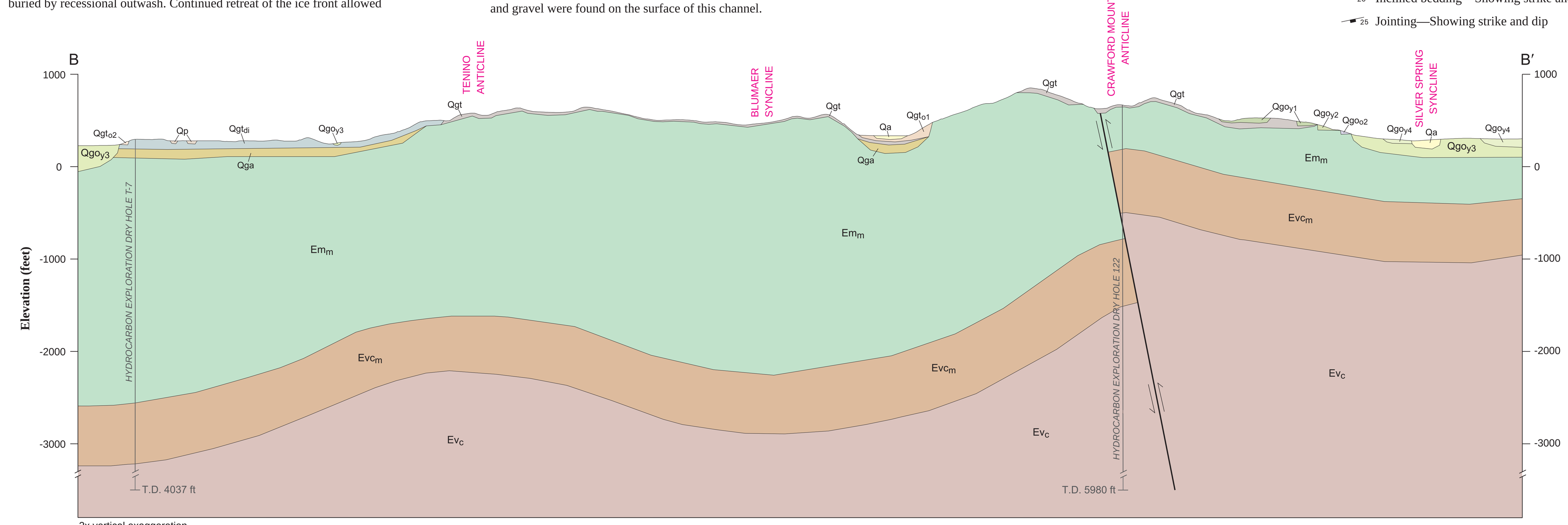


Table 1. Geochemical analyses of units Evc_m (samples 28.77 and 11.81) and Eig (samples 26C +Z and 26C -Z, where Z indicates whether zeolites were included (+) or excluded (–)) performed by x-ray fluorescence at the Washington State University GeoAnalytical Laboratory. Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO. Nd values are preliminary, tests of its quality are still underway

MAJOR ELEMENTS—NORMALIZED (in weight percent)

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
26C +Z	47.50	4.024	15.01	15.04	0.201	5.64	9.02	3.21	0.19	0.165	100.00
26C –Z	47.37	4.081	14.94	15.10	0.201	5.67	9.09	3.22	0.18	0.164	100.00
28.77	66.84	0.658	16.03	3.80	0.050	2.14	4.65	4.55	1.14	0.141	100.00
11.81	67.07	1.279	15.00	4.35	0.069	1.97	5.96	3.33	0.77	0.208	100.00

TRACE ELEMENTS—UNNORMALIZED (in parts per million)

Sample	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th	Nd
26C +Z	101	118	29	390	47	2	387	144	33	8.9	21	438	141	3	0	23	2	23
26C –Z	100	112	30	398	43	3	387	145	34	9.0	20	437	140	1	0	25	1	27
28.77	47	63	10	85	256	18	422	142	15	8.7	20	65	49	3	13	31	3	16
11.81	44	56	19	160	228	9	601	253	44	15.8	18	129	83	3	24	50	4	28