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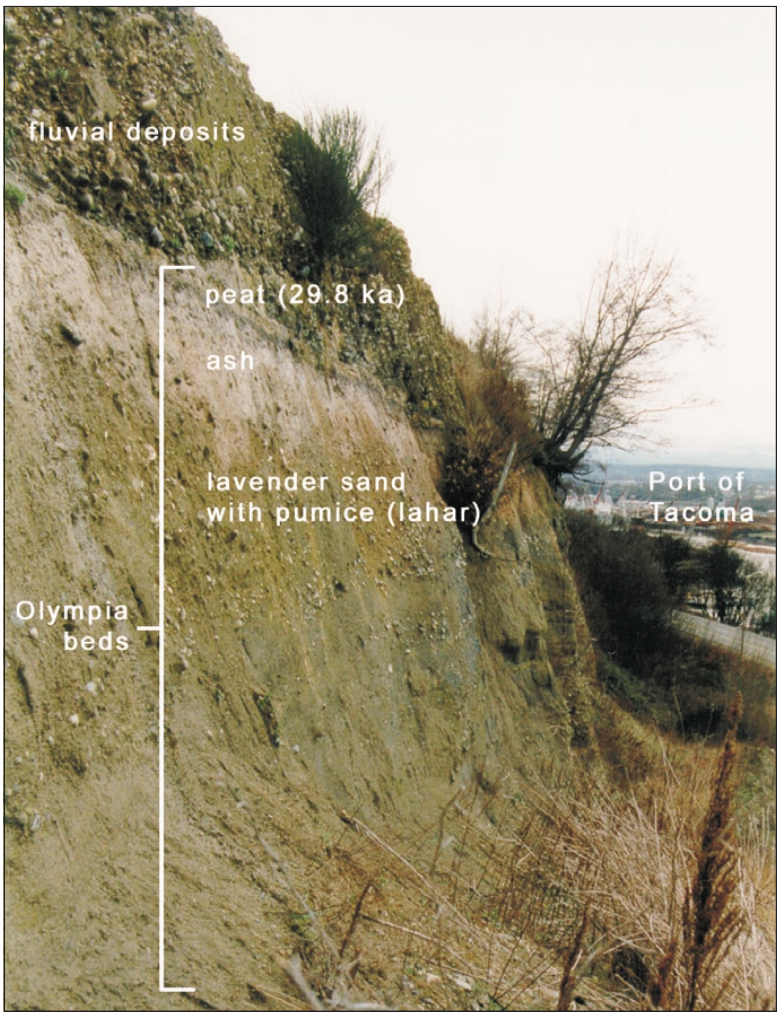
Late Pleistocene Stratigraphy in the South-Central Puget Lowland, Pierce County, Washington



by Richard K. Borden
and Kathy Goetz Troost

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Report of Investigations 33
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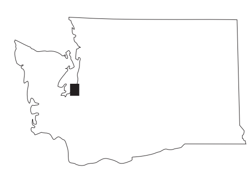

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Front Cover: Former Woodworth quarry on Hylebos Waterway, Tacoma. Photo by K. Troost, 1995.

Back Cover: Abandoned quarry on Hylebos Waterway, Tacoma. Photo by K. Troost, 1999.

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Late Pleistocene Stratigraphy in the South-Central Puget Lowland, Pierce County, Washington

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ABSTRACT

Two distinct sets of late Pleistocene stratigraphic nomenclatures have been developed for the Puget Lowland, Washington: one to the north of the Seattle area and one to the south. The simple sequence that was previously identified in the south-central lowland requires expansion and modification to correlate with the more complex but better-defined northern sequence. We confirm the presence of at least one additional glacial–nonglacial interval within the south-central lowland late-Pleistocene sequence.

Numerous boreholes and detailed measured sections with radiocarbon dates confirm this stratigraphic interpretation. The inferred base of the uppermost unit in the sequence, the Vashon Drift, is sometimes represented by fine-grained glaciolacustrine deposits with an average age of 13,430 yr B.P. This date is about 1,000 years younger than is generally assumed for the inception of the Vashon Stade of the Fraser Glaciation in the southern lowland, but is consistent with Vashon recessional dates reported from elsewhere in the lowland. This implies either (1) that most of the Vashon sediments present in the study area are recessional in age or (2) that Vashon glaciation in the south-central lowland began much later than is commonly believed based upon numerous limiting dates in the northern lowland.

Thin, discontinuous, nonglacial deposits exposed immediately beneath the Vashon Drift have been dated at 17,000 to >46,000 yr B.P. These newly identified nonglacial deposits are termed the "Olympia beds" and are correlative by age and character with sediments deposited during the Olympia climatic interval, which generally corresponds to oxygen isotope stage 3.

The widespread, newly recognized glacial outwash sequence that is immediately below the Olympia beds in the south-central lowland may be correlative with the Possession Drift of the northern lowland. Similarly, many exposures of the second nonglacial interval exposed at or near sea level may correlate with the northern Whidbey Formation or with older, reversely magnetized nonglacial units. The use of the name 'Kitsap Formation' for the second nonglacial sediments and thick fine-grained deposits encountered in the study area is misleading and should be discontinued.

INTRODUCTION

This paper presents stratigraphic and chronologic data from west-central Pierce County in the south-central Puget Lowland (Fig. 1). The study focused on late Pleistocene stratigraphic units that are exposed in outcrop and encountered in boreholes in the Tacoma area. We examined boring logs and subsurface samples from more than 120 boreholes, performed reconnaissance-scale geologic mapping, and made seven detailed measured sections at key outcrops. Sixteen new radiocarbon dates are presented here from both outcrop and subsurface locations.

The new radiocarbon dates confirm the presence of discontinuous but widespread occurrences of nonglacial sediments that are correlative by age and character with the sediments deposited during the Olympia climatic interval. The presence of the Olympia beds also means that the underlying glacial outwash sequence, previously assigned to the Vashon Drift by other workers, is actually an older glacial drift.

Stratigraphic Nomenclature

The late Pleistocene (300,000–10,000 yr B.P.) stratigraphic sequence in the Puget Lowland records repeated advances of the Cordilleran ice sheet into the area (Fig. 1). Numerous workers have studied the glacial and nonglacial stratigraphy and attempted to make regional, basin-wide correlations of stratigraphic units (Table 1). These attempts have been hampered by limited outcrops in much of the lowland, the complexity of the stratigraphic sequence, and until recently, the lack of reliable dating techniques for Pleistocene sediments older than about 45,000 yr B.P.

Willis (1898) and Bretz (1913) established the initial stratigraphic framework for Quaternary sediments in the Puget Lowland. They identified two glacial units separated by a single nonglacial unit. In the southern lowland, the stratigraphic sequence was later modified by Crandell and others (1958), based on measured sections near the town of Sumner, about 10 mi southeast of the Tacoma area. The revised stratigraphic sequence consisted of four glacial units and three intervening nonglacial units:

> Vashon Drift—unnamed nonglacial—Salmon Springs Drift—Puyallup Formation—Stuck Drift—Alderton Formation—Orting Drift

Crandell and others (1958) believed that the erosional contact between the Vashon Drift and the Salmon Springs Drift in their study area was representative of a nonglacial period, but did not apply a name to it.

Sceva (1957) first applied the name "Kitsap Clay Member of the Orting Gravel" to predominantly fine-grained sediments exposed beneath the Vashon Drift in Kitsap County northwest of the study area. He interpreted these deposits to be glacial in origin. Working on the Kitsap Peninsula, Molenaar (Garling and others, 1965) redefined the Kitsap Formation as a nonglacial unit that separates the Vashon Drift from the Salmon Springs Drift and correlated it with the Olympia climatic interval. The study also applied the name "Colvos Sand" to a distinct sand sequence at the base of the Vashon Drift. Walters and Kimmel (1968) adopted this nomenclature while mapping in the Tacoma area and used the following stratigraphic sequence:

> Vashon Drift (with a distinct basal member called the Colvos Sand)—Kitsap Formation—Salmon Springs Drift—Puyallup Formation—Stuck Drift—Alderton Formation—Orting Drift

In the northern lowland, Armstrong and others (1965) defined the "Olympia Interglaciation" as the climatic episode immediately preceding the last major glaciation and lying immediately beneath the Vashon Drift. In British Columbia, the name "Quadra" was already in use to describe these deposits (Armstrong and Brown, 1954). The Vashon Drift in the northern lowland was assigned to one of four stades of the Fraser Glaciation. Armstrong and others (1965) also compiled radiocarbon dates of between 15,000 and 35,000 yr B.P. for the Olympia Interglaciation from throughout the Puget Lowland and proposed the type section at Fort Lawton in Seattle. Mullineaux and others (1965) also identified the nonglacial sediments exposed immediately beneath the Vashon Drift at Fort Lawton as correlative with the Olympia sediments of Armstrong and others (1965) to the north and with the Kitsap Formation of Molenaar (Garling and others, 1965) to the south. Two basal members of the Vashon Drift, the Esperance Sand and the Lawton Clay, were also identified at this exposure. The Lawton Clay Member was defined as glaciolacustrine clay and silt deposited in an ice-dammed lake that formed as the Vashon glacier entered the Seattle area.

In the mid 1960s, based upon the work of numerous researchers, the following sequence was presumed to be valid across the entire Puget Lowland:

> Fraser Glaciation (composed of the Sumas Stade, Everson Interstade, Vashon Stade and Evans Creek Stade)—Olympia Interglaciation—Salmon Springs Glaciation—Puyallup Interglaciation—Stuck Glaciation—Alderton Interglaciation—Orting Glaciation

The Evans Creek Stade of the Fraser Glaciation represents a period of alpine glaciation while the lowland remained free of ice. The Vashon Stade represents the period when the Cordilleran ice sheet invaded the lowland and advanced south of the Tacoma area. Deposits associated with the Sumas Stade and Everson Interstade have been identified only in the northern lowland.

Further work by Easterbrook and others (1967) and Easterbrook (1968, 1969) on Whidbey Island resulted in the naming of additional units within the following sequence:

> Vashon Drift—Quadra Formation (Olympia Interglaciation)—Possession Drift—Whidbey Formation—Double Bluff Drift

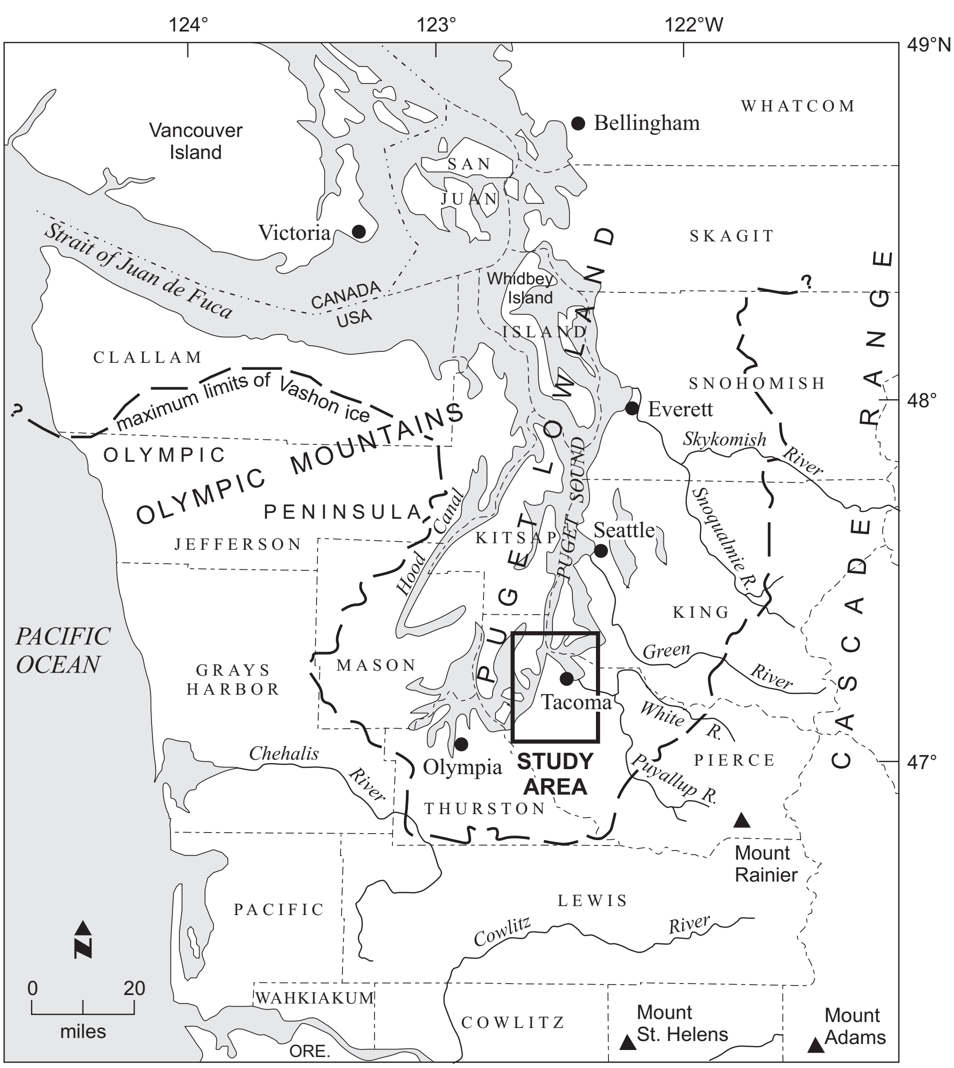


Figure 1. Puget Lowland and study area.

While mapping in Kitsap County to the northwest of Tacoma, Deeter (1979) determined that the sediments previously defined as the Kitsap Formation at their type section actually consisted of three stratigraphic units (Easterbrook's Whidbey Formation, Possession Drift, and Olympia nonglacial sediments). He proposed to continue using the term "Kitsap Formation" but with the strict definition that it only includes sediments deposited during the Olympia climatic interval of Armstrong and others (1965).

Additional radiocarbon dates from the sediments deposited during the Olympia climatic interval indicate that they accumulated between about 15,000 and 60,000 yr B.P. (Deeter, 1979; Hansen and Easterbrook, 1974; Clague, 1981; Troost, 1999). These dates closely approximate the limiting ages for oxygen isotope stage 3 and immediately predate stage 2 (the Fraser Glaciation) (Winograd and others, 1997). Most current researchers do not elevate oxygen isotope stage 3 to full interglaciation status (Winograd and others, 1997; Shackleton, 1969; Clark, 1992). Hansen and Easterbrook (1974) have also identified glacial sediments in portions of the northern lowland that they believed to have been deposited during the same time interval. For these and other reasons, the term "Olympia Interglaciation" has not been used consistently in the literature since it was proposed in 1965. Pessl and others (1989) used the term "Olympia beds" to describe deposits of the Olympia climatic interval, without implying a climatic rank. Their convention is also used in this paper.

Table 1. Puget Lowland stratigraphic nomenclature. *, not to scale

			Puget Lowland Willis (1898), Bretz (1913)	**Southern Puget Lowland** Crandell and others (1958)	**Central and northern Puget Lowland** Armstrong and others (1965), Mullineaux and others (1965)		**Tacoma area** Walters and Kimmel (1968)	**Central and northern Puget Lowland** Easterbrook and others (1967), Easterbrook (1968)	**Puget Lowland** Easterbrook (1986), Blunt and others (1987), Easterbrook (1994), Troost (1999)	
HOLO-CENE		Age* (ka)				^{14}C age (ka)				Age (ka)
PLEISTOCENE	LATE	10			Fraser Glaciation					
					Sumas Stade	9–11				
					Everson Interstade (glaciomarine)	11–13.5				
			Vashon glaciation	Vashon Drift (Vashon till)	Vashon Stade	13.5–25	Vashon Drift	Vashon Drift	Vashon Drift	
							Steilacoom Gravel		Steilacoom Gravel	
					Vashon till		Vashon till		Vashon till	
					Esperance Sand		Colvos Sand		Esperance Sand	
					Lawton Clay				Lawton Clay	
					Evans Creek Stade (alpine)	15–25				
			Puyallup Interglaciation	Unnamed erosional/ nonglacial interval	Olympia Interglaciation	15–35	Kitsap Formation	Quadra Formation	Olympia beds	15–60
								Possession Drift	Possession Drift	60–80
			Admiralty glaciation					Whidbey Formation	Whidbey Formation	~100
		300						Double Bluff Drift	Double Bluff Drift	100–250
	MID	800								
	EARLY			Salmon Springs Drift	Salmon Springs Glaciation		Salmon Springs Drift		Salmon Springs Glaciation	800
				Puyallup Formation	Puyallup Interglaciation		Puyallup Formation		Puyallup Interglaciation	>1000
				Stuck Drift	Stuck Glaciation		Stuck Drift		Stuck Glaciation	~1600
				Alderton Formation	Alderton Interglaciation		Alderton Formation		Alderton Interglaciation	>1600
				Orting Drift	Orting Glaciation		Orting Drift		Orting Glaciation	>1600
		1800								

In the past 20 years, the development of new age-dating techniques, including fission track, laser-argon, thermoluminescence, paleomagnetism, and amino-acid analysis, has allowed early-stage Olympia beds and older units to be dated. Easterbrook and others (1981) determined that the fine-grained sediments in the middle of the Salmon Springs Drift were about one million years old. Subsequent work has shown the Double Bluff Drift to be about 150,000 to 250,000 years old and the Whidbey Formation to be about 100,000 years old (Easterbrook, 1986; Blunt and others, 1987; Easterbrook, 1994). Based upon these studies, the Pleistocene sequence in the Puget Lowland is composed of the following units:

> Vashon Drift (Fraser Drift with multiple stades in the north)—Olympia beds—Possession Drift—Whidbey Formation—Double Bluff Drift—Salmon Springs Drift—Puyallup Formation—Stuck Drift—Alderton Formation – Orting Drift

The Double Bluff Drift marks the base of late Pleistocene sediments in the lowland and is separated from the early Pleistocene fine-grained interbeds in the middle of the Salmon Springs Drift by a data gap of at least 700,000 years.

This complex history has resulted in the use of two sets of late Pleistocene stratigraphic nomenclatures in the Puget Lowland, one based on the younger deposits to the north of Seattle and one based on generally older deposits to the south (Table 1). In the south-central Puget Lowland, only two glacial sequences and a single nonglacial sequence have traditionally been recognized above sea level. The name "Kitsap Formation" has continued to be loosely applied to nonglacial deposits separating the overlying Vashon Drift from the inferred Salmon Springs Drift. The name Salmon Springs Drift has been loosely applied to the iron-oxide-stained drift occurring at around sea level and (or) the next glacial drift below the Vashon.

Recent Investigations in the Study Area

Recent investigators in the Tacoma area have postulated that sediments previously assigned to the base of the Vashon Drift actually represent an additional set of nonglacial and glacial units. The age, character, and extent of these units were not well defined. During a large subsurface study in the Tacoma area, Brown and Caldwell, Inc., and others (1985) identified a discontinuous layer in the subsurface that divided the inferred Vashon Drift in two. This layer, designated as layer A1 by Brown and Caldwell, consisted of clay and sand with abundant organic matter. Based upon a single radiocarbon date collected from a borehole on Fort Lewis, Noble (1990) suggested that layer A1 sediments are correlative with sediments deposited during the Olympia climatic interval of the northern lowland. He proposed the name "Discovery nonglacial unit" for these deposits after the most southerly known surface exposure of confirmed Olympia beds at Discovery Park in the Seattle area (Mullineaux and others, 1965). He also proposed that the underlying glacial drift be named the "Narrows glacial unit" and tentatively correlated it to the Possession Drift of the northern lowland. Another large study conducted for the South King County Groundwater Advisory Committee and others (1991) immediately north of the Tacoma area also identified inferred Olympia beds in the subsurface and an additional glacial drift immediately beneath it. In our earlier work, we first identified outcrops of the Olympia beds in the Tacoma area (Borden and Troost, 1995).

FIELD AND LABORATORY PROCEDURES

Numerous environmental and geotechnical investigations in west-central Pierce County have provided more than 120 deep borehole logs in a nine-square-mile area for use in the present study. Between 1986 and 1996, core samples from approximately 60 of these boreholes were collected and archived during

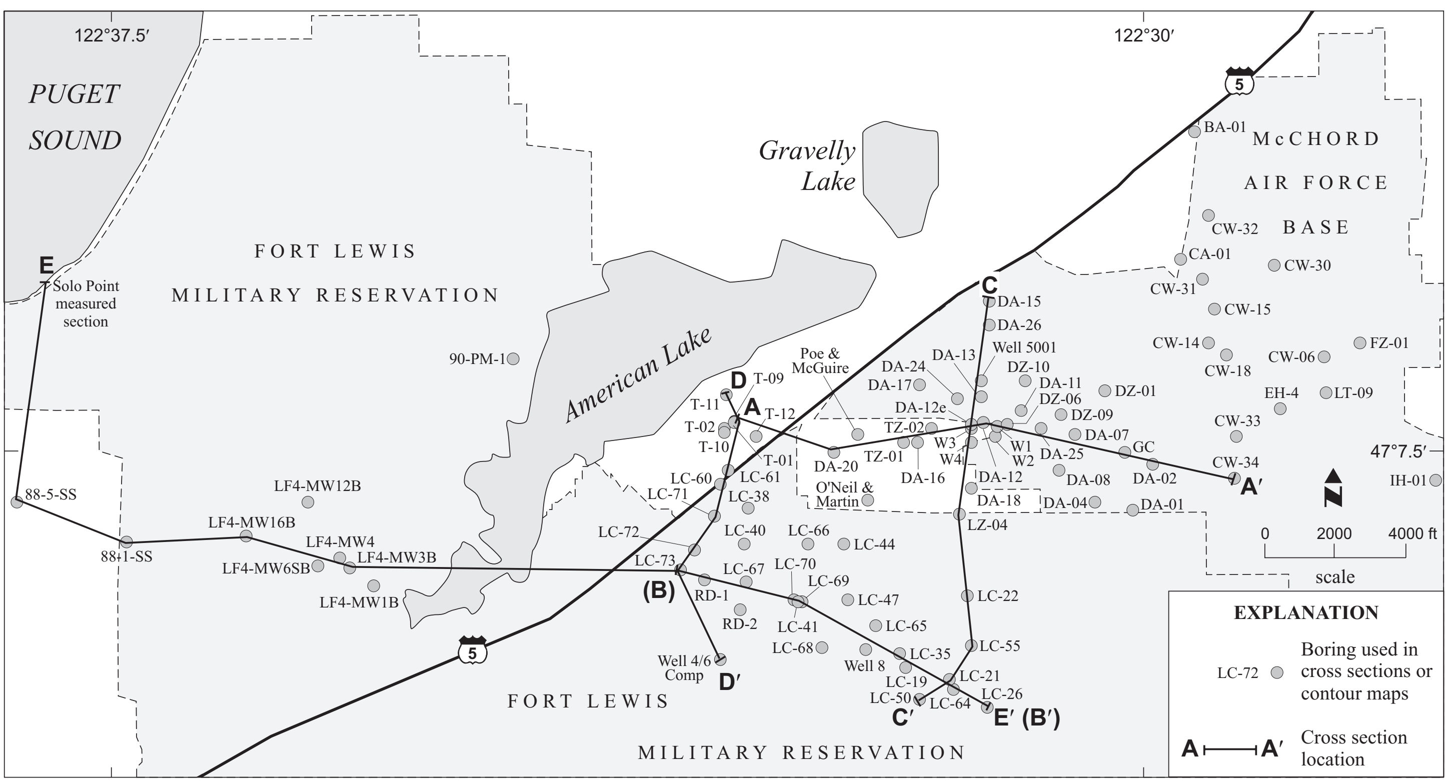


Figure 2. Borehole and cross section location map. See Appendix A for additional borehole information.

field investigations conducted by Shannon & Wilson, Inc., and Foster Wheeler Environmental Corporation. Samples were typically collected on a 5 or 10 ft interval. We originally logged many of these boreholes. These boreholes were used to construct detailed cross sections and paleotopographic maps. Information on boreholes used in the study is summarized in Appendix A, and borehole locations are shown on Figure 2.

We re-examined borehole samples under a binocular microscope. Mineralogic and lithologic point counts were made on sand grains from many samples, as well as descriptions of sand grain iron staining, roundness, angularity, and sorting. We made borehole correlations on the basis of texture, color, mineralogy, organic matter content, oxidation intensity, and stratigraphic position. Being able to directly compare samples from different boreholes, rather than comparing borehole logs alone, allowed us to make correlations with greater certainty than in many previous studies. To aid in the microscope investigation, samples from selected Puget Lowland rivers were also collected and examined.

We conducted reconnaissance-scale outcrop surveys and mapping at selected sites surrounding the subsurface study area. Seven detailed measured sections were made at key outcrops in the west-central Pierce County area. We obtained radiocarbon dates both from outcrops and boreholes during this study and we report three additional dates here from other unpublished sources (Fig. 3; see Table 3 for a summary of radiocarbon data). The radiocarbon analyses were performed by Beta Analytic, Inc., Teledyne Isotopes, and the Illinois State Geological Survey. Paleomagnetic measurements were also made at two of the measured sections as part of the Pacific Northwest Urban Corridor Mapping Project. The paleomagnetic samples were collected and analyzed by Jonathan T. Hagstrum of the U.S. Geological Survey in Menlo Park, California (written commun., 1997; Troost and others, 1997). A single sample was also collected from one of the measured sections and analyzed by fission-track dating (Richard J. Stewart, Univ. of Wash., written commun., 1999).

GLACIAL AND NONGLACIAL DEPOSITION IN THE PUGET LOWLAND

The study area is underlain by a complex, 1300 to 2000 ft thick sequence of alternating glacial and nonglacial Quaternary sediments (Jones, 1996). Previous investigations have suggested at least six advances of the Cordilleran ice sheet into the Puget Lowland during the Pleistocene (Easterbrook, 1994). Glacial sediments represent periods when the lowland was invaded by the Cordilleran ice sheet from the north. Nonglacial sediments represent periods when the lowland was free of ice, although alpine glaciers may, at times, have occupied many of the surrounding mountain ranges. During alpine glacial periods such as the Evans Creek Stade of the Fraser Glaciation, glacial outwash probably reached the study area from the Mount Rainier area, but these sediments are not differentiated from true nonglacial sediments in this study.

This ideal succession of glacial and nonglacial sediments is complicated by the repeated deep erosional events that are likely associated with each glacial period (Bretz, 1913; Crandell and others, 1965; Borden and Troost, 1994; Booth, 1994) and by the poor sedimentary record left by some nonglacial intervals.

Nonglacial Deposits

Lowland sedimentation during nonglacial periods is dominated by relatively low-energy fluvial systems. Lacustrine and marine deposition may be significant towards the center of the lowland, and volcaniclastic deposits such as lahars and tephras may be common nearer volcanoes on the margin of the lowland. Sediment transport by nonglacial rivers is generally from the mountains toward the center of the lowland, subperpendicular to the north-south axis of the Puget trough. Large areas of the lowland may be subjected to erosion or nondeposition and soil development during nonglacial periods. In many places, nonglacial intervals are only marked by paleosols representing a weathering profile or a thin accretionary soil developed on top of a glacial sequence.

The present-day Puget Lowland provides a useful analog for previous nonglacial periods. As shown on Figure 4, most of the present day lowland is dominated by areas of nondeposition, soil formation, or erosion. Significant sediment accumulation is occurring in widely separated river valleys, lake basins, and the Puget Sound. If the present-day lowland were invaded by glacial ice or by outwash deposits related to a Cordilleran ice sheet, a complicated and discontinuous record of nonglacial deposition would be buried by glacial deposits and preserved in the stratigraphic re-

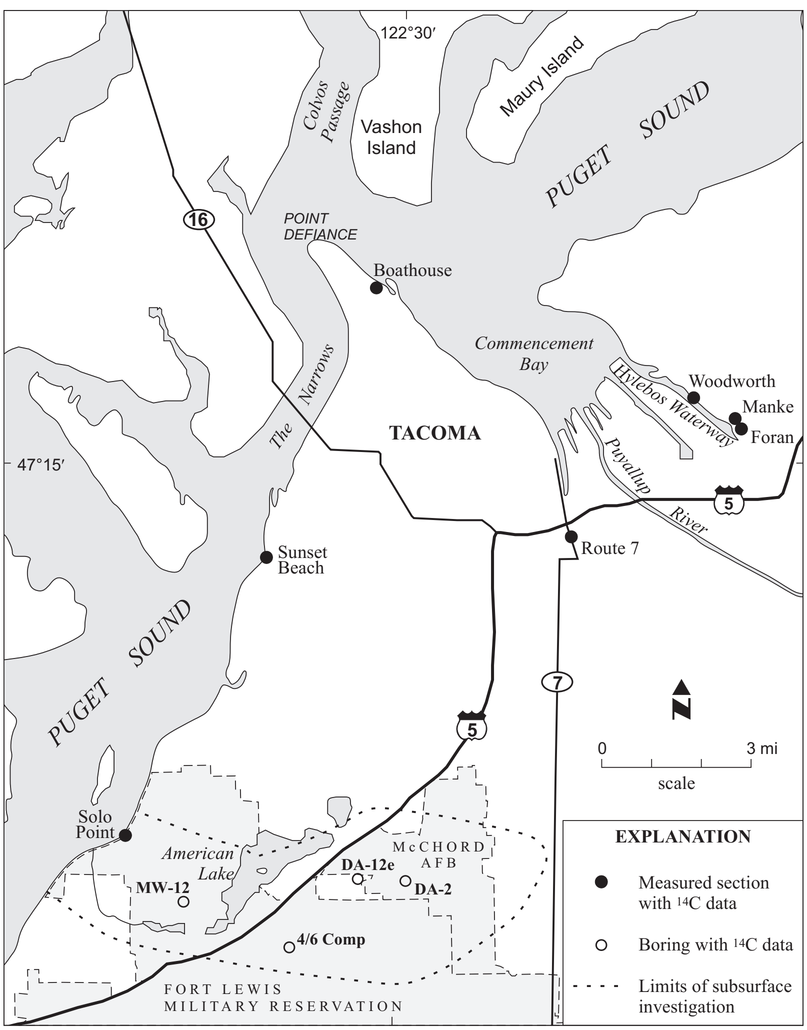


Figure 3. Locations of radiocarbon samples. See Table 3 for radiocarbon data and Appendix B for borehole logs with radiocarbon data.

cord. Thick sedimentary sequences would pinch out abruptly against valley walls. Sediments deposited in river valleys and basins could be several hundred feet lower than time-equivalent sediments or organic-rich paleosols that formed on nearby uplands. The thickness and lateral continuity of nonglacial sediments representing a given nonglacial interval is probably dependent upon several variables, including the duration of the nonglacial interval, subsidence rates in the lowland during the nonglacial interval relative to global sea level, the elevation and surface topography of fill left in the basin by the preceding glacial incursion, and the depth of erosion of the following glacial incursion.

Nonglacial sediments within the study area are largely derived from Mount Rainier, the 14,400 ft volcanic peak located about 40 mi to the east-southeast (Fig. 5) (Crandell and others, 1958; Walters and Kimmel, 1968; Mullineaux, 1970). Mount Rainier sediments are characterized by an abundance of andesitic lithic fragments, a paucity of quartz, and a lavender or reddish gray color (typically 5YR 3/1 on a Munsell color chart). The late Pleistocene nonglacial sediments exposed in the Tacoma area are very similar to sediments being transported by the modern White and Puyallup Rivers (Fig. 5). Unless they contain distinct marker beds such as tephras with unique mineralogies, deposits of different nonglacial intervals generally cannot be differentiated on the basis of sedimentology and sediment source area alone, because similar geologic conditions exist during each nonglacial interval. A study of stratigraphic relationships in conjunction with absolute dating at key locations is required to reliably correlate units.

Glacial Deposits

Glacial sedimentary units are dominated by ice-contact facies such as till, glaciolacustrine facies, and high-energy glaciofluvial facies. The dominant sediment transport direction is from north to south, subparallel to the axis of the Puget trough. Glaciolacustrine sediments commonly mark the base of each glacial sequence. These sediments were deposited in proglacial lakes that formed when the southward advancing ice disrupted the interglacial (northward) drainage network in the lowland, and they represent a transition from nonglacial to glacial sedimentation. In an ideal section, glacial sediments are represented by the following sequence, from bottom to top: (1) fine-grained, glaciolacustrine sediments, (2) coarsening-upward advance outwash, (3) till and poorly sorted ice-contact deposits, and (4) fining-upward recessional outwash locally interbedded with dead-ice deposits. North of the marine limit, this sequence could be capped by glaciomarine drift (near Seattle for the Vashon Stade).

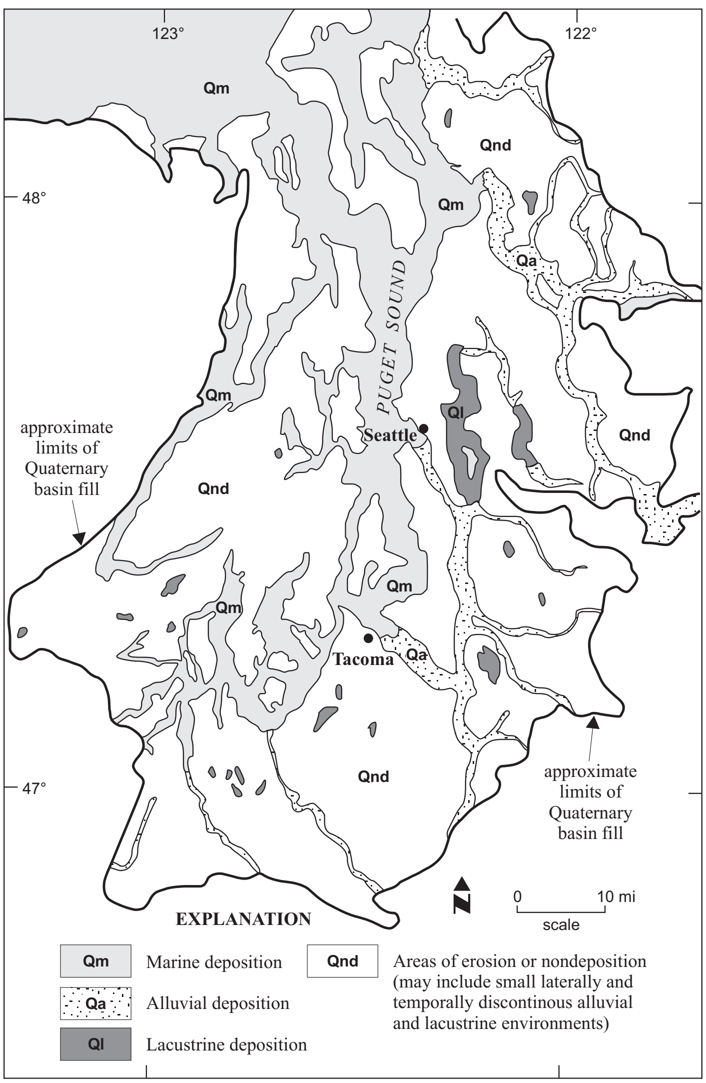


Figure 4. Modern Puget Lowland depositional environments. Source: Huntting and others (1961).

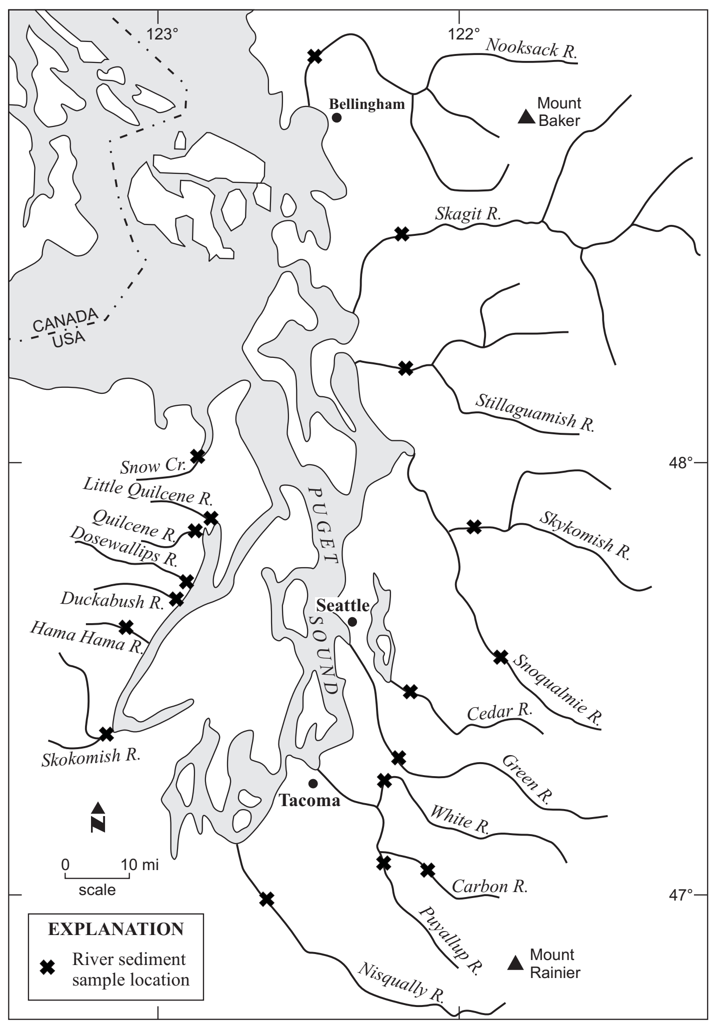


Figure 5. Location map of Puget Lowland river sediment samples.

Glacial sediments within the study area are predominantly derived from the central Cascade Range, with exotic lithologies from the North Cascades and Canada. Glacial outwash sand most closely resembles the sediments being carried into the lowland by the modern-day Snoqualmie and Skykomish Rivers (Fig. 5). These sediments are characterized by an abundance of quartz, mica, granodiorite, and green lithic fragments, and are olive-gray in color (typically 5Y 3/2 on a Munsell color chart). Deposits associated with the various glacial events may look remarkably similar, and at outcrop scale they can commonly be differentiated only by their stratigraphic position or degree of weathering.

Differentiating Glacial and Nonglacial Sediments

Glacial and nonglacial sediments can often be differentiated on the basis of sedimentary facies and sediment source areas.

Till is the most distinctive glacial facies in most drift sequences. Its lack of sorting and bedding, matrix support of the clasts, and dense nature make it easy to distinguish from most types of nonglacial sediments except for lahars. Till can generally be differentiated from lahars on the basis of sediment source area and by a lack of organic material. Unlike till associated with a Cordilleran ice sheet, lahars in the study area are typically composed of sediments from Mount Rainier and contain pockets of organic matter. Glacial outwash sequences tend to be thick, homogeneous, and relatively coarse when compared to nonglacial fluvial sequences, and tend to have a different sediment source area.

The presence of peat or organic-rich sediments is usually indicative of nonglacial depositional environments. Volcanogenic sediments such as tephras and lahars are also more typical of nonglacial units. The lack of volcanogenic sediments in glacial sequences is probably due to the relatively short duration of most glacial periods in the lowland, the rapid rate of sediment accumulation during glacial periods, and the lack of low-energy depositional environments during glacial periods where tephras can accumulate and be preserved.

During glacial periods, the apparent source of sediments is from the north. In the Tacoma area, nonglacial sediments are predominantly derived from Mount Rainier to the southeast. However, glacial sediments are dominated by lithologies with sources from the central Cascades more than 30 miles north of Mount Rainier. Similarly, nonglacial sediments that are exposed along Hood Canal on the western margin of the lowland are predominantly composed of lithologies from the Olympic Mountains (Borden, 1998), but glacial sediments contain a large component derived from the North Cascades. This relationship is probably valid for glacial and nonglacial sediments throughout the lowland, but it may be locally complicated by the reworking of older glacial sediments during interglacial periods and by the incorporation of locally derived rock and sediment into some glacial deposits.

To aid in source area identification during this study, we collected sediment samples from most of the major rivers that drain into the Puget Lowland (Fig. 5). Samples of fine and coarse sand were examined under a binocular microscope and gravel lithologies were determined. Selected lithologic characteristics that are easily identifiable in outcrop and in borehole samples are listed for each river sample in Table 2. Sand from rivers draining Quaternary volcanic peaks such as Mount Rainier or

Table 2. Sediment characteristics of selected Puget Lowland rivers. (1), Munsell color chart designation listed in parentheses; (2), source lithologies listed in order of decreasing exposure surface area in drainage basin

River	Sand color (1)	% Quartz	% Red andesite	% Mica	Source lithologies (2)
Nisqually	dark brown (7.5 YR 3/2)	60	5	trace	andesite, Mount Rainier volcanics
Puyallup	black (5 YR 2.5/1)	40	10	trace	andesite, Mount Rainier volcanics
Carbon	very dark grey to reddish black (5 YR 3/1 to 10 R 2.5/1)	50	10	trace–1%	andesite, Mount Rainier volcanics, granites
White	dark brown to reddish black (7.5 YR 3/2 to 10 R 2.5/1)	40	10	0	andesite, Mount Rainier volcanics
Green	very dark greyish brown (2.5 Y 3/2)	50	trace	trace	andesite
Cedar	very dark greyish brown (2.5 Y 3/2)	45	trace	trace	andesite, granites
Snoqualmie	very dark greyish brown to black (2.5 Y 3/2 to 5 Y 2.5/2)	65	0	trace–2%	granites, greywacke, argillite, andesite
Skykomish	olive grey to dark olive grey (5 Y 3/2 to 5 Y 4/2)	65	0	2–3%	granites, greywacke, argillite, andesite
Stillaguamish	very dark grey to dark olive grey (5 Y 3/1 to 5 Y 3/2)	60	trace	trace–1%	sandstones, argillite, metasediments, granites
Skagit	very dark greyish brown (10 YR 3/2)	70	2	1–2%	metasediments, argillite, gneiss, granites, Mount Baker volcanics
Nooksack	very dark grey (10 YR 3/1)	45	5	trace–1%	sandstones, metasediments, Mount Baker volcanics, granodiorite, dunite
Snow Creek	dark brown (10 YR 3/3)	50	0	0	sandstones, argillite
Little Quilcene	very dark greyish brown (10 YR 3/2)	35	0	0	basalt, sandstones, argillite
Quilcene	black (10 YR 2/1)	15	0	0	basalt
Dosewallips	black (5 Y 2.5/1)	20	0	0	basalt, greywacke, argillite
Duckabush	black (5 Y 2.5/1)	15	0	0	basalt, greywacke, argillite
Hama Hama	dark brown to black (7.5 YR 3.2 to 5 Y 2.5/2)	10	0	0	basalt, greywacke, argillite
Skokomish	very dark greyish brown (2.5 Y 3/2)	10	0	0	basalt, greywacke, argillite

Table 3. Summary of radiocarbon data. The radiocarbon dates have not been converted to calendar years and show a laboratory error of one standard deviation. Sample locations are shown in Figure 3. The Illinois State Geological Survey (ISGS) served as an independent quality assurance laboratory for two samples dated by Beta Analytic, Inc. (Beta). ft MSL, feet above mean sea level; B.P., before present; I, Teledyne Isotopes. *, accelerator mass spectrometry radiocarbon dating corrected for $^{13}C/^{12}C$ ratio, believed to be reworked charcoal from an older stratigraphic unit. All but three samples were collected during this study: †, Timothy J. Walsh, Wash. Div. of Geology and Earth Resources, written commun., 1995; §, date obtained by Shannon & Wilson, Inc., in 1988; #, date obtained by Shannon & Wilson, Inc., in 1989

Site name	Location	Approx. elevation, ft MSL	Sample type	Laboratory sample no.	Conventional ^{14}C age, yr B.P.	Stratigraphic position
Woodworth quarry	SW¼SW¼ sec. 25, T21N R3E	193	charcoal	Beta-95340	>53,480 *	Vashon advance outwash
Borehole DA-12e	SW¼SW¼ sec. 14, T19N R2E	180	wood	Beta-79885	13,510 ±80	Vashon glaciolacustrine sediments
Sunset Beach	SW¼NW¼ sec. 16, T20N R2E	140	flattened wood	ISGS-3343	12,960 ±180	Vashon glaciolacustrine sediments
Sunset Beach	SW¼NW¼ sec. 16, T20N R2E	140	flattened wood	Beta-89876	13,620 ±80	Vashon glaciolacustrine sediments
Borehole MW-12b †	NE¼SW¼ sec. 19, T19N R2E	176	peaty silt	Beta-52222	13,630 ±90	Vashon glaciolacustrine sediments
Route 7	SW¼SE¼ sec. 9, T20N R3E	210	organic sediment	Beta-89256	17,110 ±290	Olympia beds
Borehole 4/6 §	SW¼NE¼ sec. 28, T19N R2E	210	wood	I-15,437	25,100 ±600	Olympia beds
Woodworth quarry	SW¼SW¼ sec. 25, T21N R3E	164	organic sediment	ISGS-3301	27,530 ±390	Olympia beds
Woodworth quarry	SW¼SW¼ sec. 25, T21N R3E	164	organic sediment	Beta-80937	32,040 ±690	Olympia beds
Manke quarry	NE¼SE¼ sec. 36, T21N R3E	137	paleosol	Beta-87981	36,650 ±720	Olympia beds
Solo Point	SW¼NW¼ sec. 13, T19N R1E	80	peat	Beta-120064	41,380 ±1940	Olympia beds
Woodworth quarry	SW¼SW¼ sec. 25, T21N R3E	240	organic sediment, paleosol	Beta-86842	>41,710	Olympia beds
Foran quarry	NW¼SW¼ sec. 31, T21N R4E	130	peat	Beta-89875	>46,450	Olympia beds
Borehole DA-2 #	NW¼NW¼ sec. 24, T19N R2E	204	wood	I-15,705	>40,000	pre-Olympia drift
Borehole DA-12e	SW¼SW¼ sec. 14, T19N R2E	132	wood	Beta-81801	>41,300	pre-Olympia drift
Boathouse	NE¼SW¼ sec. 14, T21N R2E	27	peat	Beta-80938	>46,750	pre-Vashon nonglacial deposits

Mount Baker tend to have a reddish hue and contain distinctive red andesite grains. Sand from rivers elsewhere in the Cascades generally has a greenish or yellowish hue. The presence of muscovite mica and a relatively high quartz content is diagnostic of sand from rivers draining granitic source areas. Rivers draining the Olympic Peninsula have sands that are dominated by black or very dark gray lithic fragments and contain very little quartz. Gravel lithologies tend to reflect the bedrock exposures within the drainage basins with a strong bias towards more resistant lithologies.

RESULTS

Radiocarbon dating information is summarized in Table 3. Detailed descriptions of the geologic setting at each sample site are provided below, along with measured sections and cross sections.

Hylebos Waterway Measured Sections

Radiocarbon dates were obtained from three widely separated exposures on a 400 ft high bluff on the north side of the Hylebos Waterway (Fig. 3). These outcrops were previously mapped as Vashon Drift over Salmon Springs Drift (Waldron, 1961). However, recent field studies and radiocarbon dates show that throughout the area, an upper nonglacial sequence exposed between 130 and 240 ft above mean sea level (ft MSL) separates Vashon Drift from an underlying oxidized outwash sequence. The radiocarbon dates obtained from this nonglacial sequence vary from 27,530 yr B.P. to >46,450 yr B.P. These ages are at least in part correlative with sediments deposited during the Olympia climatic interval. This stratigraphic sequence is laterally continuous for more than 2 mi along the southwest-facing bluff. A lower nonglacial sequence is locally exposed at the foot of the bluff.

The westernmost measured section is from an exposure at Woodworth quarry (Fig. 6). Here, the Olympia beds are about 50 ft thick and consist of two distinct facies: a paleosol developed on a lahar and an underlying andesitic fluvial sand. The lahar and sand are composed mostly of pumice, andesite, and tuffaceous clasts. Locally a thin peat and an ash layer are present above the lahar. The Olympia beds are not present across the entire quarry exposure. Where absent, a sharp contact occurs between an unoxidized outwash sequence above (Vashon outwash) and an oxidized outwash sequence below. A thin paleosol is commonly developed at the contact on top of the oxidized outwash. Organic debris collected from the paleosol at two different locations in the quarry has radiocarbon dates of 27,530 ±390 yr B.P. (ISGS-3301), 32,040 ±690 yr B.P. (Beta-80937) and >41,710 yr B.P. (Beta-86842). A lower nonglacial sequence is exposed immediately above sea level downhill from the quarry. It is composed of andesitic sand and silt with at least four tephra interbeds. These deposits are reversely magnetized and so are likely to be older than 780,000 years B.P. (Troost and others, 1997). This is supported a preliminary fission-track date of 1,100,000 ±150,000 yr B.P. from this lower nonglacial sequence (Richard J. Stewart, Univ. of Wash., written commun., 1999).

The Manke quarry section (Fig. 7) is exposed on the same bluff about one mile southeast of Woodworth quarry. The Olympia beds are intermittently exposed on the bluff between the two quarries. The same stratigraphic sequence is exposed at both quarries except that the basal nonglacial sediments are not visible at Manke quarry. The Olympia beds at Manke quarry are 25 ft thick and consist of interbedded andesitic sand, sandy silt, and tephra. Two peat beds are exposed towards the bottom of the nonglacial sequence. The uppermost peat bed has a radiocarbon date of 36,650 ±720 yr B.P. (Beta-87981). The nonglacial sediments separate Vashon Drift above from an underlying highly oxidized glacial drift.

The Foran quarry section (Fig. 8) is exposed about a quarter of a mile southeast of the Manke quarry. Nonglacial sediments are intermittently exposed on the bluff between the two quarries. At Foran quarry, the nonglacial sediments are about 16 ft thick and separate Vashon Drift above from an underlying highly oxidized glacial drift. The nonglacial sediments are composed of andesitic and tuffaceous sand with two peat beds near the top of the sequence. The lowermost peat bed has a radiocarbon date of >46,450 yr B.P. (Beta-89875). Despite the infinite radiocarbon date, these sediments are believed to correlate with the dated Olympia beds at Manke quarry because they crop out at a comparable elevation and are exposed between the same two drift sequences. The Vashon Drift is in erosional contact with the underlying sediments in Foran quarry. A Vashon erosional channel at least 150 ft deep and filled with coarse gravel cuts through the nonglacial sediments and is deeply incised into the underlying oxidized glacial drift.

Route 7 Measured Section

The Route 7 section (Fig. 9) is exposed on either side of the highway about 2300 ft south of the intersection with Interstate 5 (Fig. 3). The exposure is approximately 4 mi southwest of the Hylebos Waterway sections. This exposure was originally mapped as Vashon Drift by Smith (1977). Our measurements indicate that a 92 ft thick Vashon Drift sequence is underlain by a 46 ft thick Olympia bed sequence at this exposure. An older, highly oxidized glacial outwash is exposed beneath the nonglacial deposit. The Olympia beds consist of a massive basal mudflow with overlying fluvial gravel. The fluvial gravel contains lithologies characteristic of both Mount Rainier and the North Cascades. The gravel is capped by a 2 ft thick gray laminated silt at an elevation of 210 ft MSL. Organic-matter-rich sediments at the base of the silt yield a radiocarbon age of 17,110 ±290 yr B.P. (Beta-89256).

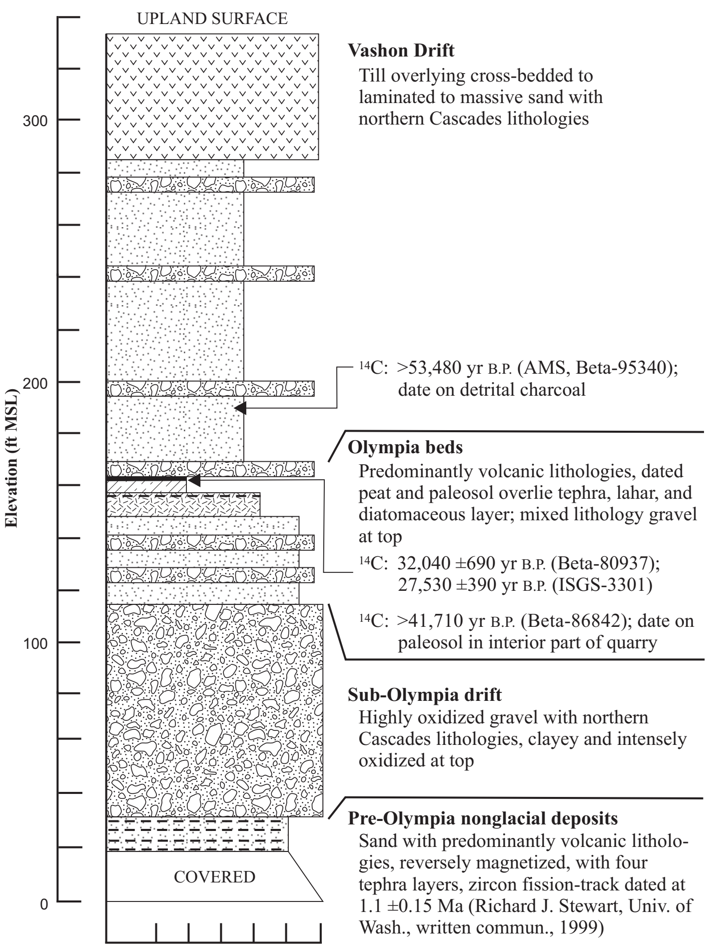


Figure 6. Woodworth quarry composite measured section, Poverty Bay 7.5-minute quadrangle, lat 47.2729 N, long 122.3728 W.

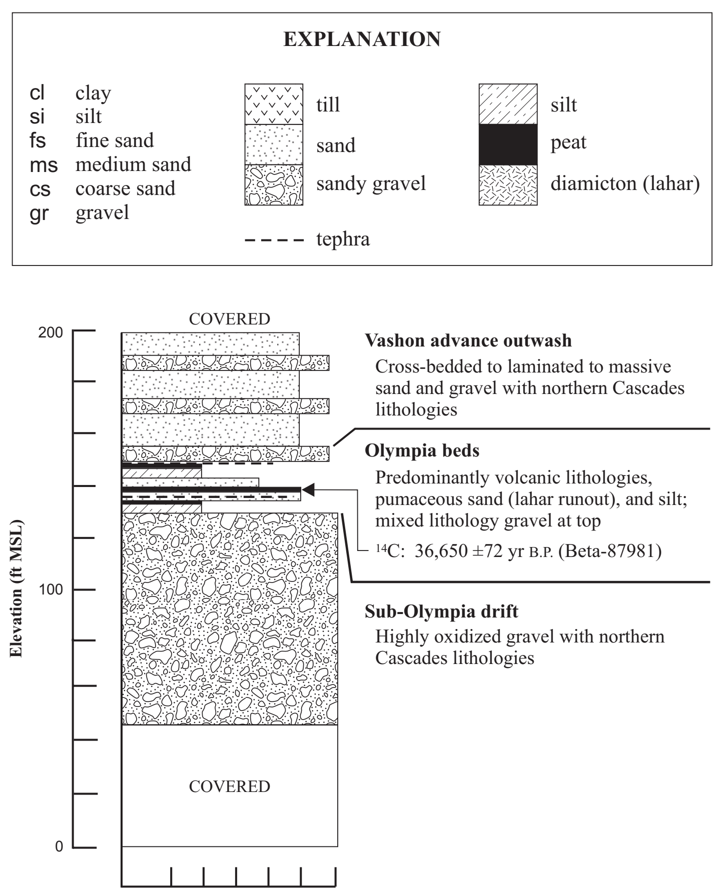


Figure 7. Manke quarry measured section, Poverty Bay 7.5-minute quadrangle, lat 47.2642 N, long 122.3532 W.

The laminated silt also contains a single, 0.5 in. thick tephra layer several inches above the radiocarbon-dated material. The age of this tephra is constrained to a relatively brief period between the underlying date of 17,110 yr B.P. and the inception of Vashon glaciation in the Tacoma area several thousand years later. No tephras have yet been identified within this time frame that originate from Mount Rainier about 40 mi to the east-southeast (Pringle and others, 1994). However, the tephra could be derived from Mount St. Helens about 74 mi to the south. The ash contains cummingtonite (Patrick T. Pringle, Wash. Div. of Geology and Earth Resources, oral commun., 1996), which is unique to Mount St. Helens tephras and is particularly abundant in tephra set S (Mullineaux, 1986). Radiocarbon-dated organic material indicates that much of tephra set S was erupted circa 13,000 yr B.P., but no radiocarbon dates are available for the base of set S at Mount St. Helens and the eruptions that produced the set may have started before 13,650 yr B.P. (Mullineaux, 1996). Other workers have hypothesized that tephra set S could be as old as 16,000 years B.P. or that it may represent several distinct eruptions that spanned several thousand years (Beget and others, 1997).

The tephra identified at the Route 7 exposure in Tacoma may correlate with a tephra identified about 12 mi south in the Ohop Valley (Beget and others, 1997), which is also contained within lacustrine sediments at the base of the Vashon Drift. The Ohop Valley tephra has been positively correlated with Mount St. Helens set S based upon several geochemical and mineralogical criteria, although because of its stratigraphic position it is presumed to be older than 14,500 years B.P. (Beget and others, 1997).

Tacoma Boathouse Measured Section

The Tacoma boathouse section is exposed at the base of an 80 ft high bluff on the northeast side of Point Defiance (Fig. 3). The exposure is located about 7 mi west of the Hylebos Waterway sections. This section was originally mapped as undifferentiated pre-Vashon nonglacial sediments beneath Vashon Drift by Smith (1977). The nonglacial sediments are exposed immediately above sea level and the contact with overlying Vashon Drift is only 52 ft MSL (Fig. 10). A peat bed in the nonglacial sequence yielded a radiocarbon age of >46,750 yr B.P. (Beta-80938). With only an infinite radiocarbon date available, these sediments can not be correlated with any particular nonglacial interval.

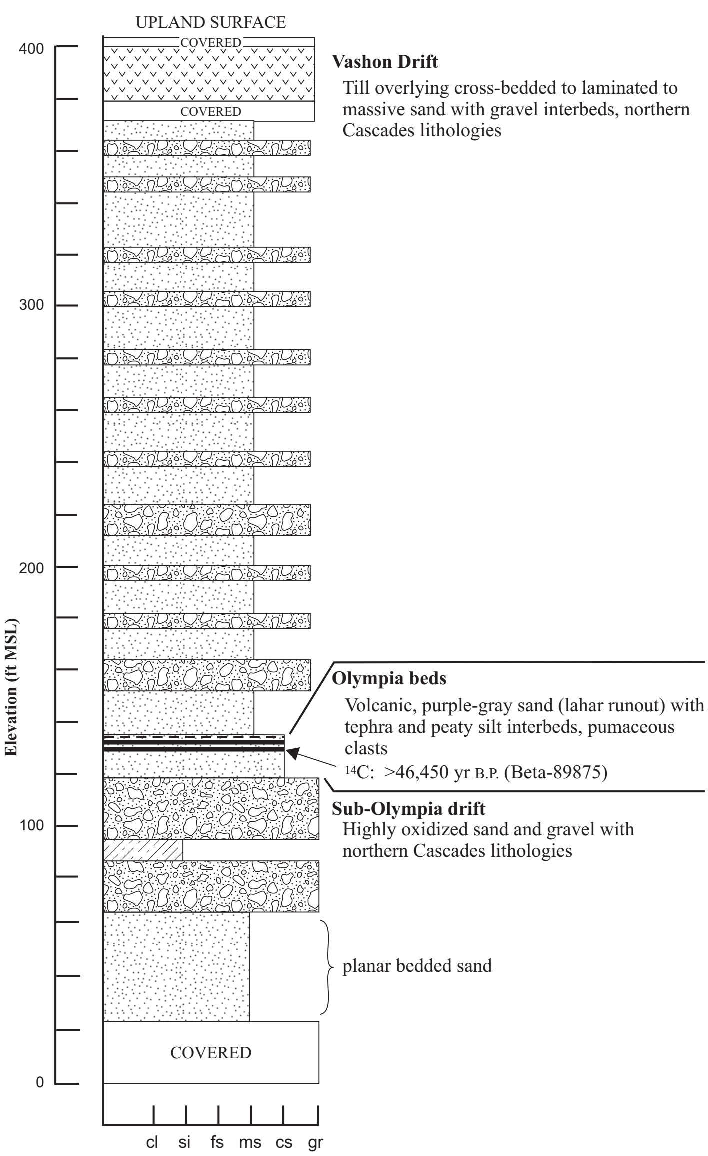


Figure 8. Foran quarry measured section, Poverty Bay 7.5-minute quadrangle, lat 47.2620 N, long 122.3536 W. Explanation on facing page.

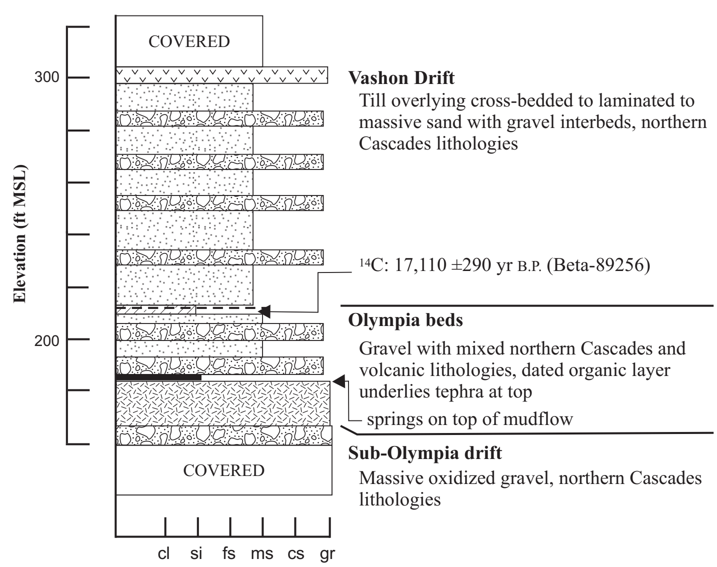


Figure 9. Route 7 measured section, Tacoma South 7.5-minute quadrangle, lat 47.2285 N, long 122.4262 W. Explanation on facing page.

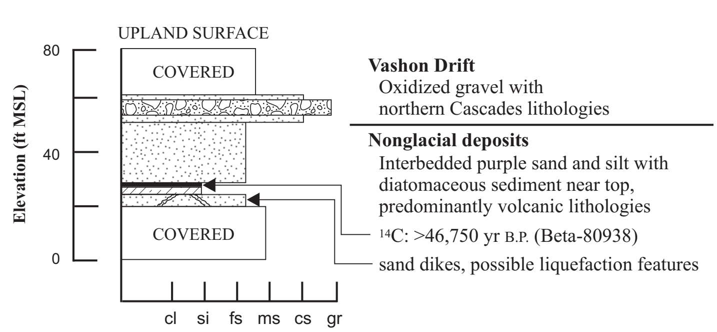


Figure 10. Tacoma boathouse measured section, Gig Harbor 7.5-minute quadrangle, lat 47.3067 N, long 122.5146 W. Explanation on facing page.

Sunset Beach Measured Section

The Sunset Beach section (Fig. 11) is exposed on a 200 ft high bluff on the east side of Puget Sound, 9 mi west-southwest of the Hylebos Waterway sections (Fig. 3). This exposure was originally mapped by Walters and Kimmel (1968) as Vashon Drift. Based on the current study, two and possibly three glacial drift sequences separated by fine-grained glaciolacustrine sediments are exposed in the bluff. Thin Vashon till is present at the top of the bluff and is underlain by a sandy outwash sequence. At 140 ft MSL, near the inferred base of the Vashon Drift, a fine-grained, silty sand that is locally organic-matter-rich is exposed. Two separate samples of wood from this fine-grained unit were radiocarbon dated, yielding ages of 13,620 ±80 yr B.P. (Beta-89876) and 12,960 ±180 yr B.P. (ISGS-3343).

Solo Point Measured Section

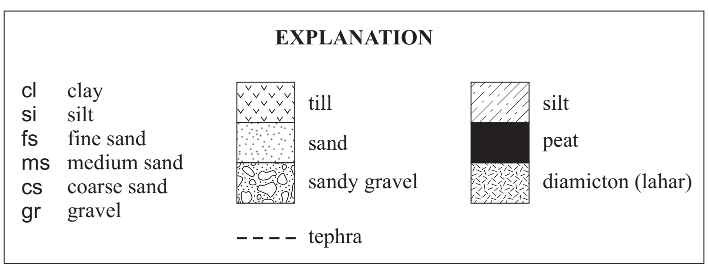
The Solo Point section is exposed on a 300 ft high bluff on the east side of Puget Sound about 14 mi southwest of the Hylebos Waterway sections (Fig. 3). This exposure was originally mapped as Vashon till over the Kitsap Formation by Walters and Kimmel (1968). Vashon till is exposed at the top of the slope at approximately 300 ft MSL (Fig. 12). Much of the underlying slope is covered, but at 122 ft MSL there is a sharp contact between Vashon outwash and a thick nonglacial sequence. The nonglacial sediments are at least 92 ft thick and are composed of interbedded lavender silt, fine-grained tephra, peat, and andesitic sand and gravel. A radiocarbon date obtained from a peat layer at 80 ft MSL yielded an age of 41,380 ±1940 yr B.P. (Beta 120064) (Troost, 1999). The silt is also normally magnetized indicating that the sediments are probably younger than 780,000 years B.P. (Troost and others, 1997). The radiocarbon date is correlative with sediments deposited during the Olympia climatic interval of the northern lowland.

Subsurface Data

Radiocarbon dates were obtained from samples from four boreholes on McChord Air Force Base and the Fort Lewis Military Reservation approximately 12 mi southwest of the Hylebos Waterway sections and 3 mi east of the Solo Point section (Fig. 3). The boreholes span about 5 mi from east to west.

Borehole DA-2 is 320 ft deep and appears to intersect two or three glacial drift sequences (Appendix B, Fig. B-1). The upper 85 ft is a Vashon Drift sequence of, from top to bottom, recessional outwash, till, advance outwash, and glaciolacustrine sediments. Beneath the glaciolacustrine silt, 36 ft of fine to medium glacial sand were encountered. A date from a wood sample found at 96 ft below ground surface (BGS) (204 ft MSL) in the glacial sand was >40,000 yr B.P. (I-15705). Between 121 and 320 ft BGS, interbedded till, outwash, and glaciolacustrine silt of a third outwash sequence may be present.

Borehole DA-12e is 145 ft deep and was drilled about 1 mi west of DA-2 (Appendix B, Fig. B-2). The borehole passes through a Vashon Drift sequence and intersects older glacial sediments. A wood sample collected 92 ft BGS (180 ft MSL) in glaciolacustrine sediments near the inferred base of the Vashon sequence has a date of 13,510 ±80 yr B.P. (Beta-79885). Vashon Drift above the glaciolacustrine sediments is represented by interbedded outwash and till. A second wood sample collected



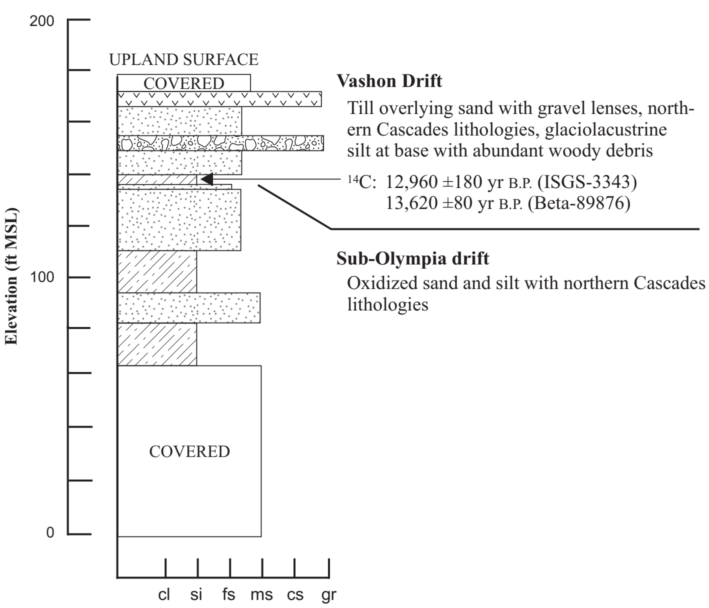


Figure 11. Sunset Beach measured section, Steilacoom 7.5-minute quadrangle, lat 47.2232 N, long 122.5643 W.

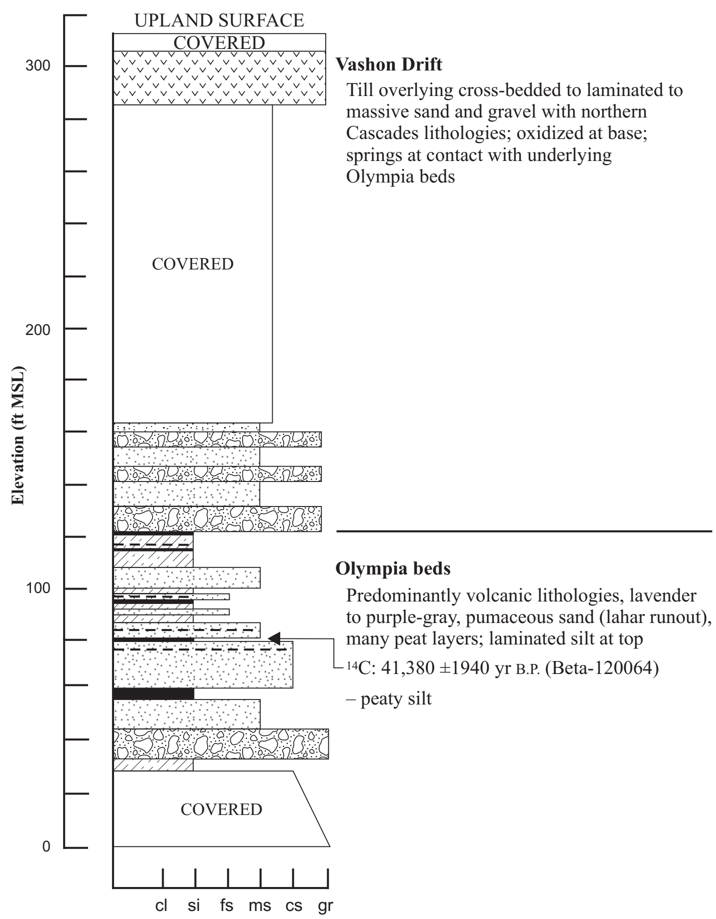


Figure 12. Solo Point measured section, McNeil Island 7.5-minute quadrangle, lat 47.1377 N, long 122.6310 W.

48 ft lower than the first sample (132 ft MSL) in glacial silt and sand has a date of >41,300 yr B.P. (Beta-81801). The contact between Vashon Drift and the older drift sequence is believed to be at 98 ft BGS, where there is a sharp transition from gray clayey silt above to a gray to brown-gray silty sand.

The log for borehole 4/6 is actually a composite of data from two wells that were drilled 1200 ft apart and reported by Noble (1990) (Appendix B, Fig. B-3). The composite borehole is 295 ft deep and is located about 2.5 mi southwest of DA-12e. The borehole intersects three glacial drift sequences and three nonglacial sequences. Our stratigraphic interpretation is similar to that of Noble (1990) except that some of the contacts between units have been adjusted after correlation with surrounding boreholes. A radiocarbon date obtained from an organic-matter-rich gravel with a mudflow texture and Mount Rainier source lithologies at about 60 ft BGS (210 ft MSL) yielded an age of 25,100 ±600 yr B.P. (I-15,437). Based on this date, the gravel most likely correlates with sediments deposited during the Olympia climatic interval.

Borehole MW-12 is 208 ft deep and was drilled about 2.5 mi west of borehole 4/6 (Appendix B, Fig. B-4). This borehole passes through three glacial drift units and one nonglacial sequence. A sample obtained from organic matter in silt at a depth of about 60 ft (176 ft MSL) has a radiocarbon date of 13,630 ±90 yr B.P. (Beta-52222). The organic-matter-rich silt is located near the top of inferred Vashon glaciolacustrine sediments and is overlain by 60 ft of coarse Vashon outwash gravel and sand.

These radiocarbon-dated boreholes are connected with other boreholes by three east–west and two north–south cross sections (Fig. 2 and Figs. 13–17). All of the cross sections have a vertical exaggeration of 20 times in order to emphasize contact relationships and the geometry of paleotopographic surfaces. Four of the cross sections (Figs. 13–16) traverse the part of the study area with the highest borehole density to the east of American Lake. The fifth, cross section E–E′ (Fig. 17), extends 4 mi west to the measured section at Solo Point on Puget Sound.

The east–west cross sections show a relatively uniform stratigraphic section that slopes gently to the west, but is commonly disrupted by thick lenticular-shaped bodies of glaciolacustrine silt (Figs. 13, 14, and 17). Based upon analyses of samples from deep boreholes, these fine-grained sequences contain little organic debris and are devoid of pollen (Estella B. Leopold, Univ. of Wash., written commun., 1996). The lenticular bodies apparently fill glacial erosional troughs cut into the underlying sediments. Outside of these erosional troughs, the glacial drift sequences are laterally continuous and of relatively uniform thickness. This more uniform stratigraphy is particularly evident on the north–south cross sections that do not intersect the deep erosional features (Figs. 15 and 16). In contrast to the drift sequences, nonglacial units are relatively thin and discontinuous as shown in cross section.

DISCUSSION

At least three glacial and three nonglacial units can be identified in the sediments that occur above sea level in the study area. Previous mapping and borehole stratigraphic interpretations in the study area generally identified only three or four units. The thickness, distribution, and age relationships of each of these units is discussed in the following sections. For some units, we present isopach and paleotopographic maps based upon the borehole correlations described in Field and Laboratory Procedures (p. 4).

Vashon Drift (Qv)

Vashon Drift covers the surface of most of the study area. The drift sequence varies between 40 and 260 ft thick in the bore-

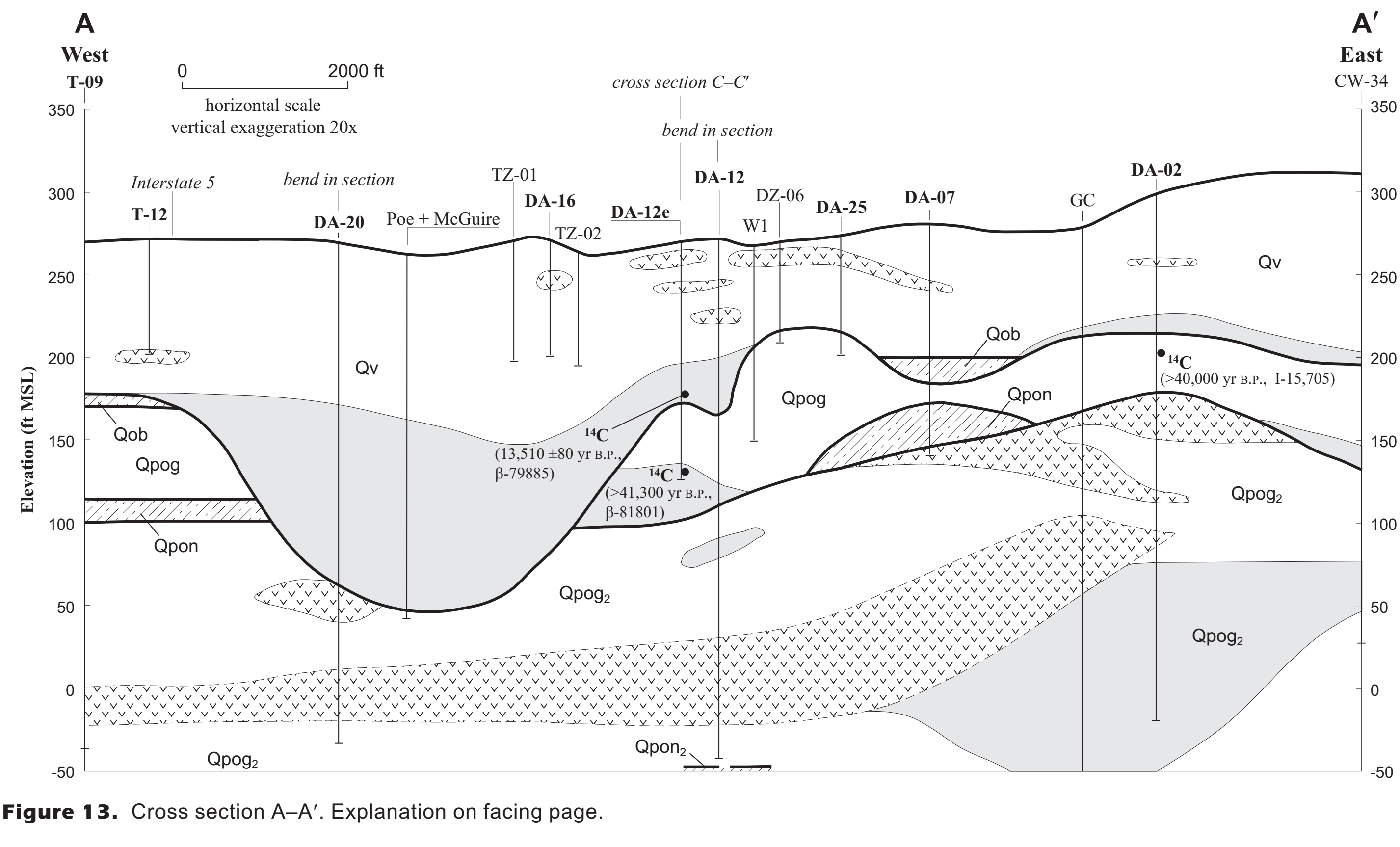
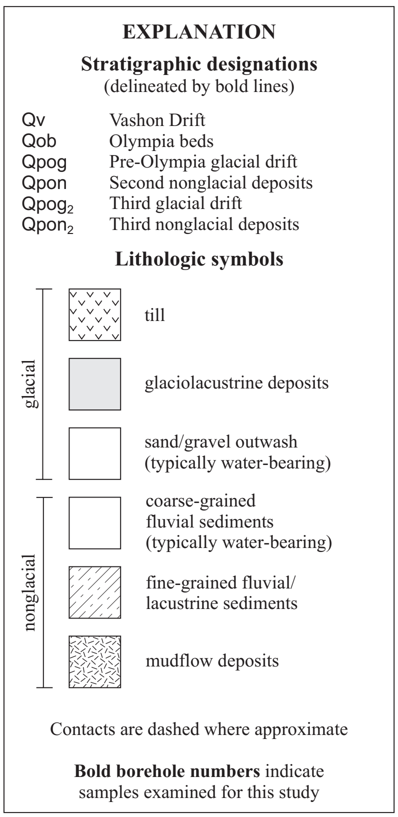


Figure 13. Cross section A–A′. Explanation on facing page.

holes and measured sections. Older stratigraphic units crop out only in cliffs along Puget Sound and in deeply incised river valleys and gullies. Vashon Drift is dominated by advance and recessional outwash with discontinuous glaciolacustrine sediments at the base and discontinuous till towards the top of the sequence. Basal glaciolacustrine sediments were encountered in about 20 percent of the boreholes and in one of the measured sections. Many of these glaciolacustrine sediments are herein correlated with the Lawton Clay, whose type section is in the Seattle area (Mullineaux and others, 1965).

Beneath most of the subsurface study area (Fig. 3), the base of the Vashon Drift slopes gently to the north and west, and is in contact with either the Olympia beds or an older glacial drift sequence. This relatively uniform surface is disrupted by at least



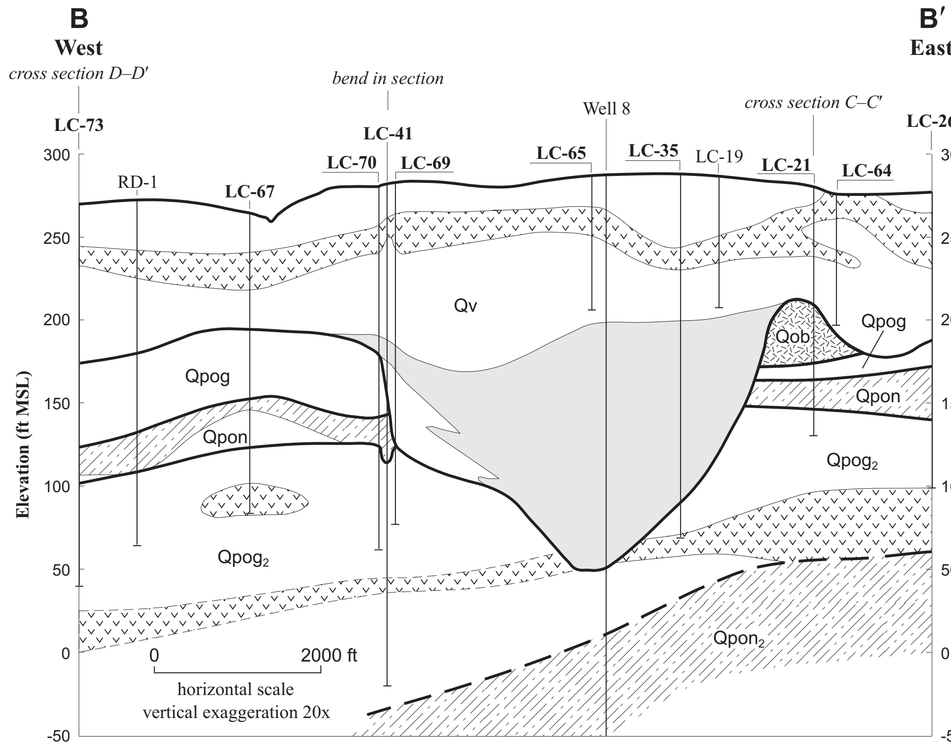


Figure 14. Cross section B–B′.

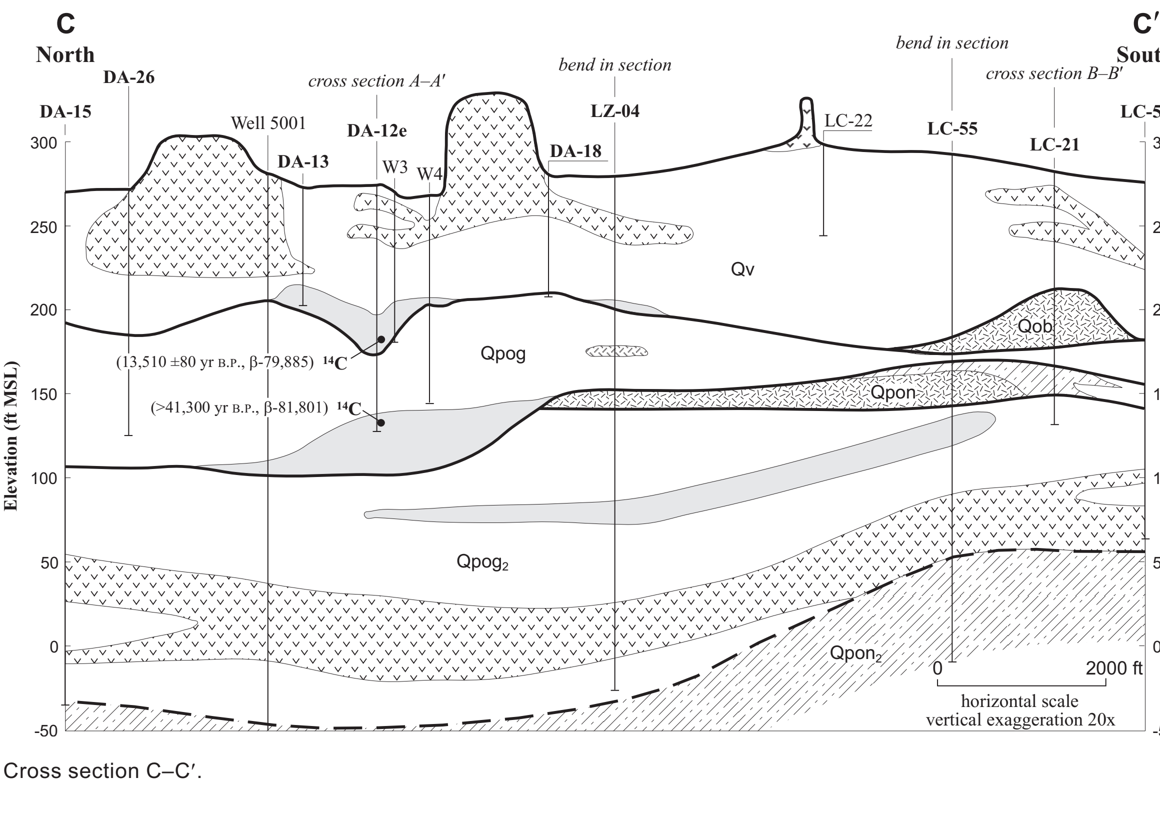


Figure 15. Cross section C–C′.

one deep trough that is oriented north–south and is traceable for over a mile in the subsurface (Fig. 18). The base of the trough cuts downsection all the way to the third glacial drift unit. The Vashon Drift sequence is typically 100 ft thick in the subsurface study area, but thickens to as much as 230 ft in the center of the trough. Based upon crosscutting relationships, the vertical continuity of glacial sediments in the trough, and a single radiocarbon date of 13,510 ±80 yr B.P. (Beta-79885) (borehole DA-12e), the trough is thought to have been cut and filled during Vashon time.

Four radiocarbon dates are reported herein from glaciolacustrine sediments near the inferred base of the Vashon Drift (Table 3). These samples were obtained from three widely spaced locations. Vashon outwash overlies the sampling points at all three locations and Vashon diamicton has been identified above the sampling points at Sunset Beach and in borehole DA-12e (Troost and Borden, 1996). The four radiocarbon dates yield an average age of 13,430 yr B.P., which is about 1,000 years younger than is generally assumed for the advance of Vashon ice into the south-central lowland. This seeming anomaly requires that either (1) all four samples had been contaminated with younger organic matter, (2) few Vashon advance sediments are preserved in the study area and the radiocarbon samples were collected from recessional glaciolacustrine sediments, or (3) the samples were collected from Vashon advance sediments and Vashon glaciation began much later in the south-central lowland than is commonly believed.

It is unlikely that all four samples were contaminated with younger organic matter. Three of the samples, collected from three different locations and analyzed in three different years, have ages within 120 years of each other and an average age of 13,590 yr B.P. (Table 3, samples Beta-79885, Beta-89876, and

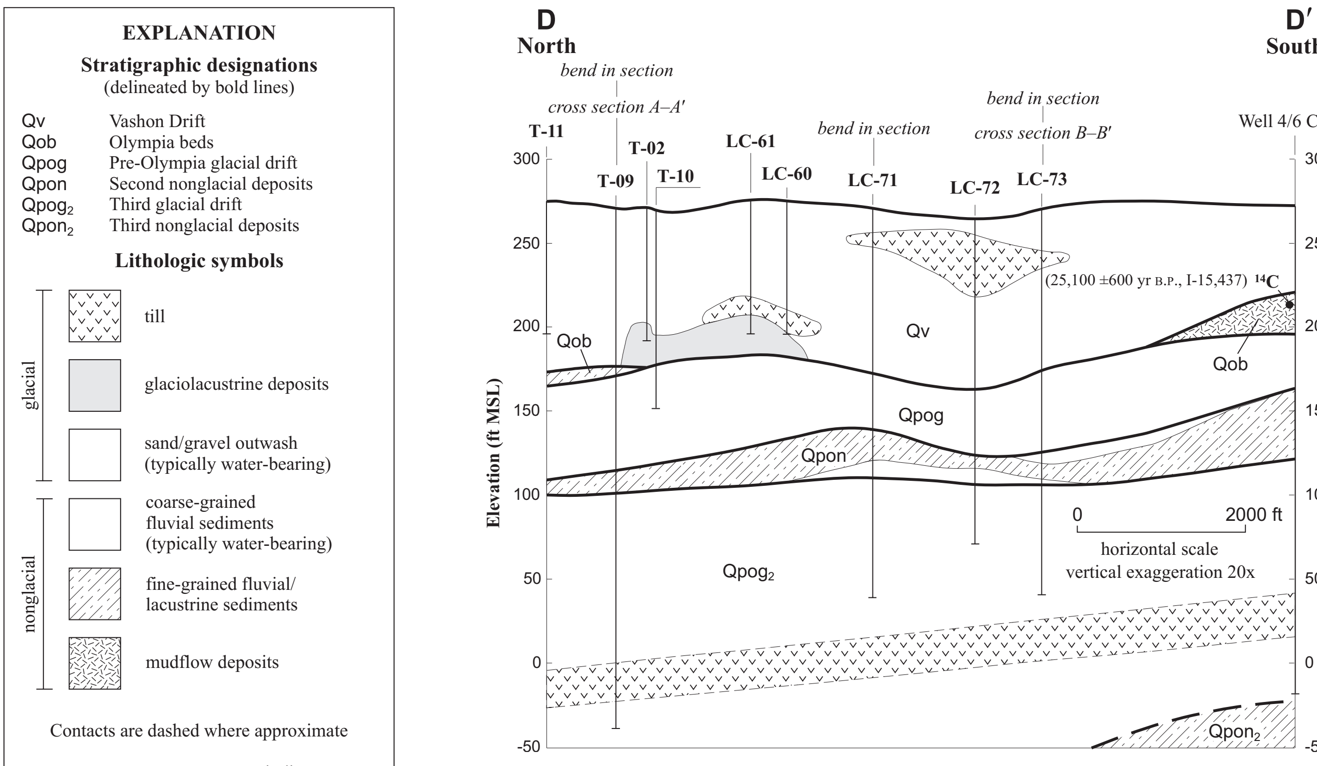


Figure 16. Cross section D–D′.

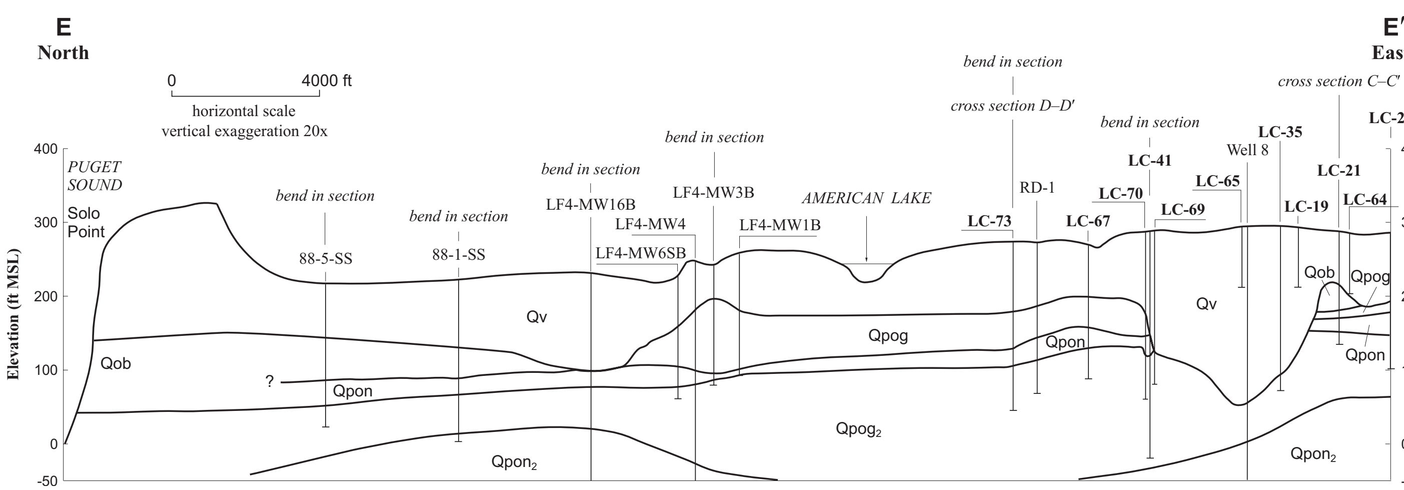


Figure 17. Cross section E–E′.

Beta-52222). If these anomalously young dates were a result of contamination, it would require that all three samples contain about the same percentage of younger organic material, which is unlikely. Two of these three samples were collected from more than 60 ft below the ground surface, so there would have been little opportunity for contamination by younger material. The fourth date, obtained from a wood fragment that was collected at the Sunset Beach exposure to confirm a date previously obtained from the same exposure, was about 600 years younger than the other three (Table 3, sample ISGS-3343).

The dates reported here are consistent with Vashon recessional dates obtained from several locations in the north and central lowland (Rigg and Gould, 1957; Yount and others, 1980; Leopold and others, 1982; Easterbrook, 1986; Anundsen and others, 1994; Dethier and others, 1995). The dates presented by these authors were generally derived from peat bog, lacustrine, or glaciomarine sediments deposited during or shortly after the recession of the Vashon ice sheet. If the samples in the current study were also collected from recessional sediments, it would require that at three widely separated locations in the Tacoma area, (1) little or no Vashon advance sediments are present, (2) vegetation was growing nearby during the recessional period, and (3) the radiocarbon-dated material was buried beneath 60 to 90 ft of Vashon recessional sediments after it was deposited. It would also require that the till capping the bluff at Sunset Beach (Fig. 11) is an ablation till underlain by 85 ft of Vashon recessional outwash. Porter and Carson (1971) noted that younger organic matter may be incorporated into older recessional glacial sediments when drift-mantled stagnant ice melts away and causes material to collapse into underlying voids. Kovanen and Easterbrook (2001) cited the same process to explain the presence of organic matter beneath pure diatomite at the base of kettle-fill deposits in the Nooksack drainage in the northern Puget Lowland. However, the limited size of the Sunset Beach exposure makes it difficult to determine if it is part of a larger kettle complex, and it is unclear if this mechanism can explain the presence of anomalously young organic debris beneath thick well-sorted outwash sediments.

There are few constraining dates available south of Seattle to document the advance of the Vashon ice sheet (Booth, 1987). Early radiocarbon dates from the Seattle area, 25 mi north of the present study area, indicated that the Vashon ice front arrived there sometime after 15,000 years B.P. (Mullineaux and others, 1965; Deeter, 1979). Seven recently published dates from Vashon advance outwash in the Seattle area average 14,546 ±28 ^{14}C yr B.P. (Porter and Swanson, 1998). If the young dates reported in the current study are from Vashon advance sediments, this would imply that the ice front required about 1,000 years to move from the Seattle to the Tacoma area. Previous workers have postulated a more rapid rate of advance because of the constraining ages obtained from post-Vashon sediments throughout the lowland. Rigg and Gould (1957) published a commonly referenced date of 13,650 yr B.P. (their sample number L-346a) for post-Vashon sediments in Lake Washington near Seattle. Many subsequent studies have yielded maximum constraining dates of around 13,500 yr B.P. for the retreat of Vashon ice from the lowland (Yount and others, 1980; Leopold and others, 1982; Easterbrook, 1986; Anundsen and others, 1994; Dethier and others, 1995). Clearly, an age of 13,500 yr B.P. for the Vashon retreat is not compatible with the new radiocarbon dates provided by this study if they were actually collected from Vashon advance sediments. For both sets of dates and interpretations to be cor-

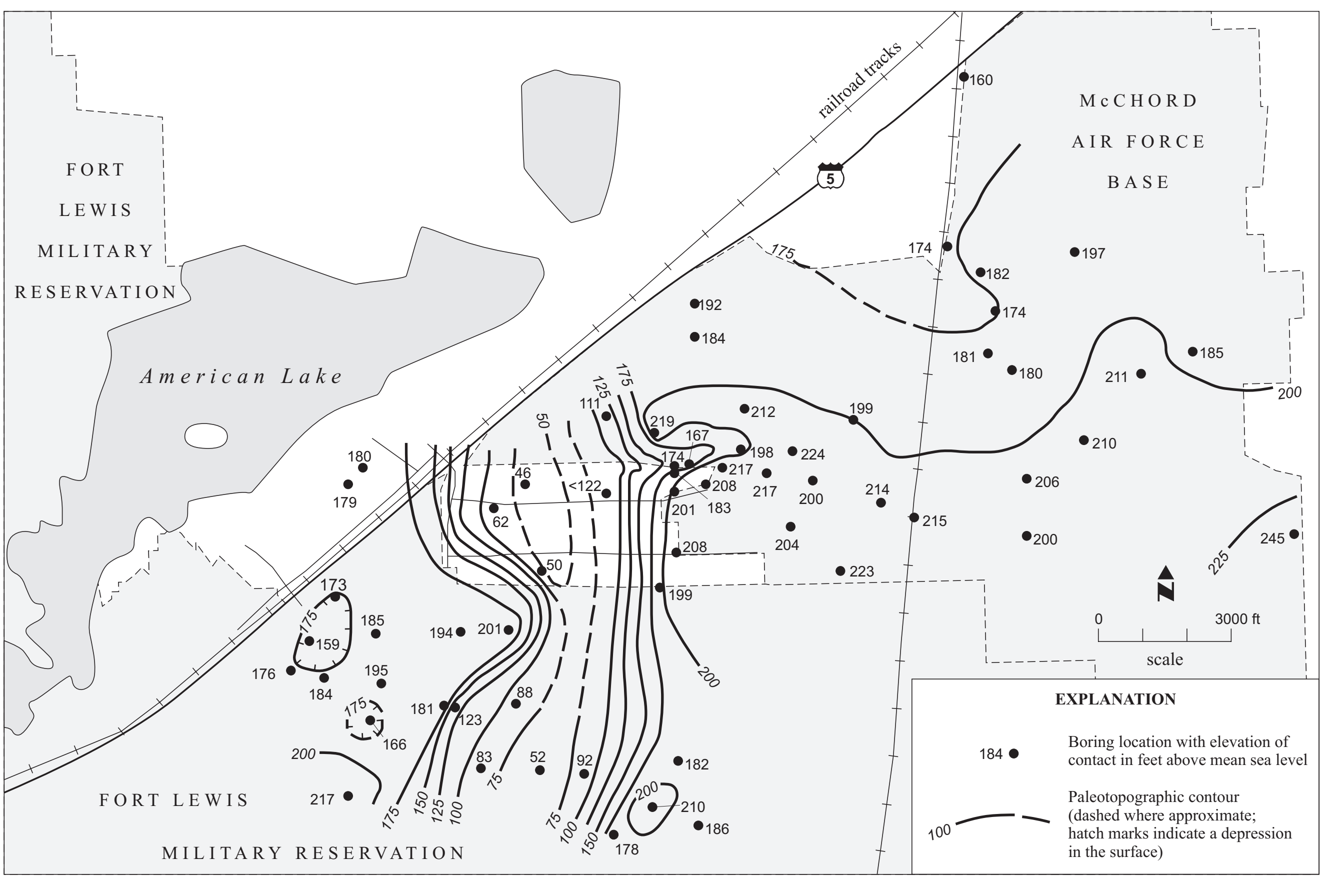


Figure 18. Paleotopographic map of the base of the Vashon Drift (unit Qv).

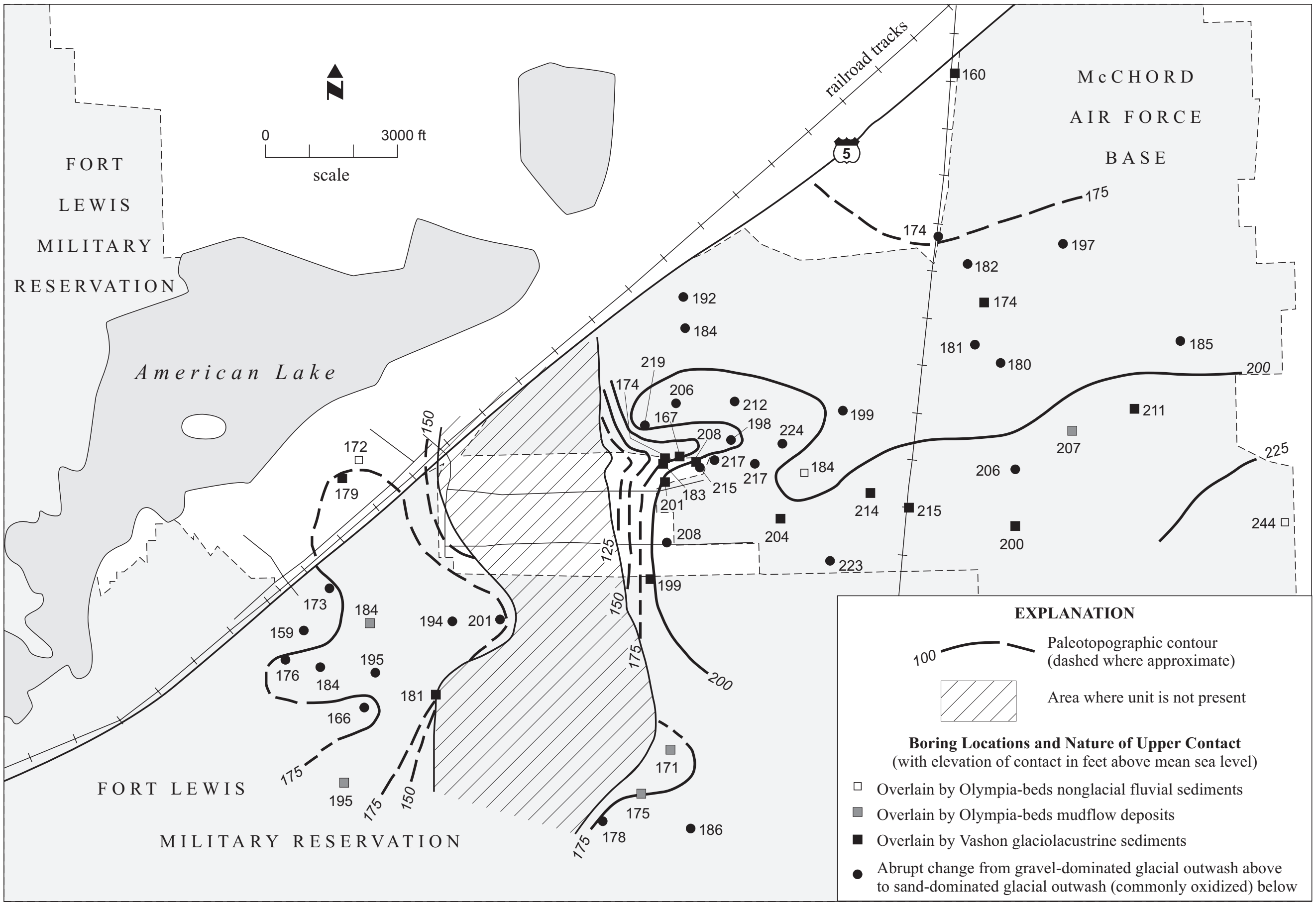


Figure 19. Paleotopographic map of the top of the pre-Olympia drift (unit Qpog).

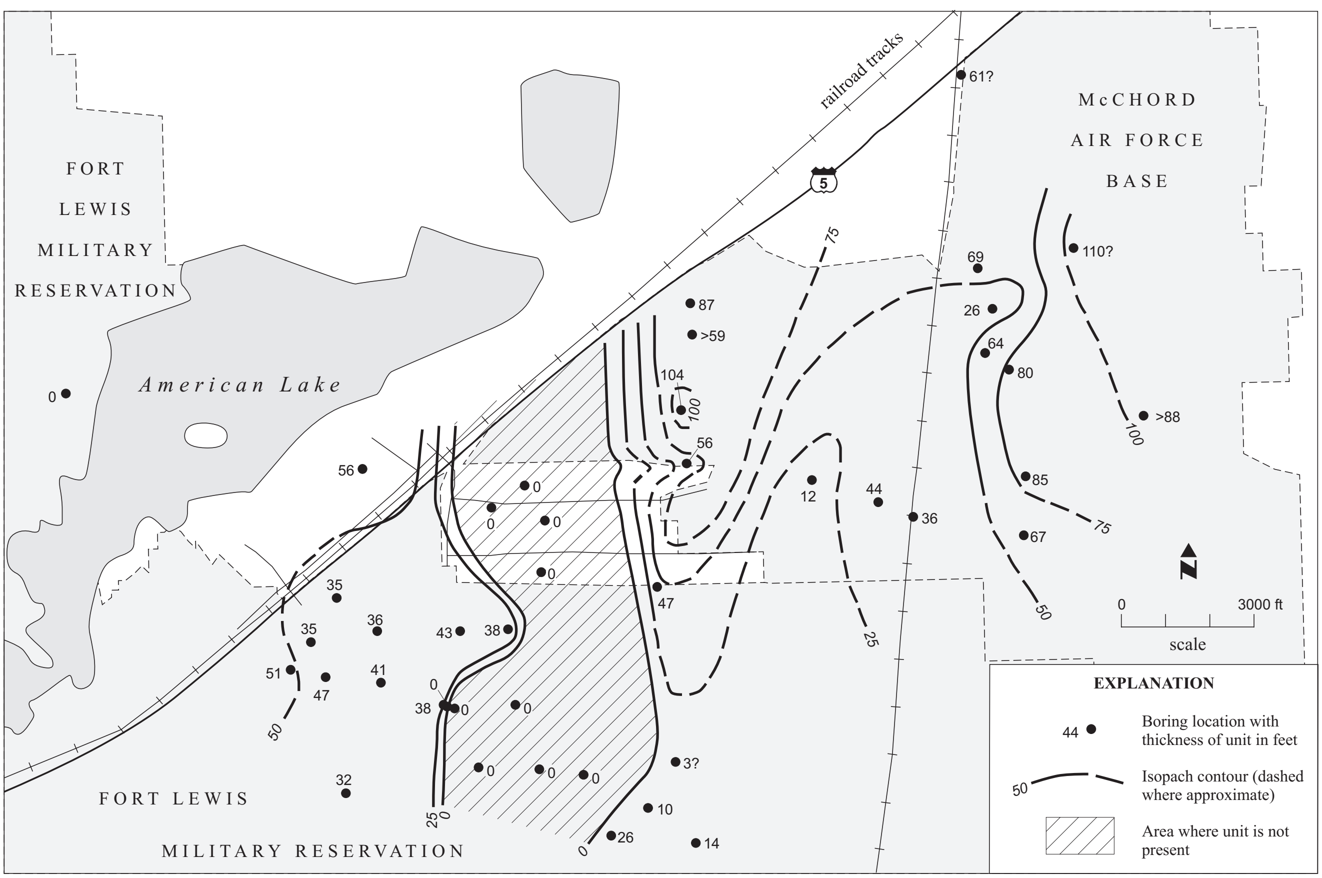


Figure 20. Isopach map of the pre-Olympia drift (unit Qpog).

rect it would require the Vashon ice sheet to be advancing to its terminus in the southern lowland at the same time that post-glacial sediments were beginning to accumulate in the north and central lowland. We do not feel that this issue will be fully resolved until additional constraining age dates for the Vashon advance have been obtained from the southern Puget Lowland.

Olympia Beds (Qob)

Nonglacial sediments deposited during the Olympia climatic interval are locally present throughout the study area but have variable thickness and are discontinuous. They are generally represented by lahars, ashes, and fine-grained fluvial sediments. The Olympia beds were identified at the Hylebos Waterway, Route 7, and Solo Point measured sections, and in the subsurface study area. Probable Olympia beds were identified in about 10 percent of the boreholes that were examined (see Fig. 19). In the boreholes, Olympia beds were encountered between 170 and 220 ft MSL. In the measured sections, the Olympia beds were exposed as high as 240 ft MSL at Hylebos Waterway in the north to perhaps as low as sea level at Solo Point in the south.

Finite radiocarbon dates obtained from the Olympia beds in the study area range from 17,000 to 41,000 yr B.P. (Troost and Borden, 1996). Several samples from inferred Olympia sediments have infinite radiocarbon ages of up to >46,000 yr B.P. Previously published radiocarbon dates from Olympia sediments elsewhere in the lowland and in southwestern British Columbia are consistent with these dates. Finite dates ranging from 15,000 to 40,500 yr B.P. and perhaps as old as 58,800 yr B.P. have been reported (Deeter, 1979; Mullineaux and others, 1965; Hansen and Easterbrook, 1974; Armstrong and others, 1965; Clague, 1981).

Pre-Olympia Drift (Qpog)

A thick and laterally continuous fine-grained glacial outwash sequence underlies the Olympia beds throughout the subsurface study area, but may not be present beneath the Olympia beds at the Hylebos Waterway and Route 7 measured sections to the north. No associated till was identified in any of the boreholes or measured sections examined during this study, although till has been encountered in outcrops of inferred pre-Olympia drift elsewhere in the Tacoma area (Troost and others, 1997).

Two radiocarbon-dated samples from inferred pre-Olympia drift yielded ages of >40,000 yr B.P. and >41,300 yr B.P. (Table 3, samples I-15705 and Beta-81801). These dates are at least 25,000 years older than the Vashon Drift.

In the subsurface, this outwash was differentiated from overlying Vashon advance outwash by one or more of the following: (1) the presence of intervening Olympia beds, (2) the presence of intervening glaciolacustrine sediments, (3) an abrupt change from a gravel-dominated glacial outwash above to a sand-dominated glacial outwash below, and (4) the presence of a thin, moderately to intensely oxidized zone at the top of the sand-dominated sequence. The transition between the overlying gravelly Vashon outwash and the underlying sand-dominated glacial sequence is typically very sharp. A paleotopographic map of the top of the pre-Olympia drift was generated according to the above criteria (Fig. 19). The top surface of the drift slopes gently to the north and west. Elevations vary between 160 and 240 ft MSL except on the margins of the Vashon erosional trough. No pre-Olympia drift occurs within this erosional feature, but outside the trough, drift sequences more than 100 ft thick were encountered in some boreholes (Fig. 20).

Based upon its character and stratigraphic position directly beneath the Olympia beds, this unit may correlate with the Possession Drift. The Possession Drift in the northern lowland has been dated at about 80,000 yr B.P. by amino-acid analysis of marine shells (Easterbrook, 1994). The older outwash sequence in the Tacoma area has seldom been differentiated from the overlying Vashon advance outwash because: (1) Olympia and Lawton Clay marker beds are rarely present in the section and are difficult to recognize where they are present, (2) as a glacial drift it generally resembles the overlying Vashon advance outwash, and (3) in the study area, it does not contain an associated glacial till. If the Possession glacial maximum was located at or north of the Tacoma area, this would explain both the scarcity of till and the relatively low-energy outwash sediments that dominate the inferred Possession sequence in the subsurface study area immediately to the south of that glacial maximum.

The characteristics and stratigraphic relationships of the pre-Olympia drift are very similar to the description of the Colvos Sand made by Garling and others (1965). The Colvos Sand is described as a laterally continuous sandy outwash sequence immediately beneath and in sharp, sometimes unconformable contact with the overlying gravelly Vashon advance outwash. Garling and others (1965) assumed that the Colvos Sand was an early phase of Vashon glaciation, but many of the outwash sequences designated as Colvos Sand in the Tacoma area may actually be correlative with the pre-Olympia drift or an older glacial drift.

Second Nonglacial Deposits (Qpon)

A second nonglacial interval is commonly present in the subsurface study area beneath the pre-Olympia drift, but was not positively identified in any of the measured sections. In general, the second nonglacial deposits are present only in the southern half of the subsurface study area (Fig. 21). In the northern half, they tend to be missing in areas where the overlying pre-Olympia drift is thickest. The nonglacial sediments are also missing within the Vashon erosional trough. Where present, the top of the second nonglacial deposits slopes gently to the west. In the south, the surface elevations vary between about 120 and 170 ft MSL. In the north, a single isolated occurrence of the second nonglacial deposits has a surface elevation of only 100 ft MSL. Outside of the erosional areas, the second nonglacial sediments vary between about 10 and 40 ft in thickness (Fig. 22).

Based upon their character and stratigraphic position as the next oldest nonglacial sequence beneath the Olympia beds, many of the second nonglacial deposits encountered during this study may correlate with the Whidbey Formation of the northern lowland. In the northern lowland, the Whidbey Formation is thick, laterally continuous, and separated from the Olympia beds by a single glacial drift unit, the Possession Drift (Easterbrook and others, 1967). The Whidbey Formation has been dated to about 100,000 yr B.P. in the northern lowland by amino-acid analyses and thermoluminescence (Easterbrook, 1994).

Other studies have correlated the second nonglacial sediments of the subsurface study area with the nonglacial sediments that crop out at sea level over much of the Tacoma area (Brown and Caldwell, Inc., and others, 1985; Noble, 1990). In the past, these exposures were identified as the Kitsap Clay or the Kitsap Formation and were assumed to be related to the Olympia climatic interval (Sceva, 1957; Garling and others, 1965; Walters and Kimmel, 1968). However, at different locations the sea-level nonglacial exposures may actually correlate to the Olympia beds (as at Solo Point), the Whidbey Formation, or an older nonglacial interval (as at Woodworth quarry) (Troost

Figure 21. Paleotopographic map of the top of the second nonglacial deposits (unit Qpon).

Figure 22. Isopach map of the second nonglacial deposits (unit Qpon).

and others, 1997; Booth and Waldron, in press). Correlation between the subsurface study area and the sea cliff exposures is difficult under these circumstances and the use of the term "Kitsap Formation" would be misleading.

Third Glacial Drift (Qpog$_2$)

The third glacial drift encountered in the subsurface study area is characterized by an oxidized drift sequence whose upper surface is near sea level. In the subsurface study area, this drift underlies the second nonglacial deposits, but at the Hylebos Waterway measured sections it may directly underlie the Olympia beds.

In the subsurface, the third glacial drift is a 150 ft thick sequence of advance and recessional outwash with interbedded till deposits. In boreholes, these glacial deposits were distinguished from younger drift sequences by one or more of the following: (1) the presence of intervening second nonglacial sediments, (2) the presence of intervening glaciolacustrine sediments, and (3) the presence of a thick, intensely oxidized zone at the top of the third glacial recessional outwash. In one location, till occurs at the top of the third glacial drift sequence (Fig. 13, eastern end of cross section A–A′). This point is also a topographic high on the paleosurface and may represent a buried drumlin-like feature (Fig. 23). Outside of the Vashon erosional trough, the upper surface of the drift slopes gently to the north and west with elevations ranging from as high as 179 ft to as low as 102 ft MSL. The Vashon erosional trough is incised almost 100 ft through the original paleotopographic surface on top of the third glacial drift.

The stratigraphic position and character of the third glacial drift is similar to highly oxidized drift sequences noted at the upper Salmon Springs type section to the east (Crandell and others, 1958), at Penultimate drift exposures to the south (Lea, 1984), and at Qc3 drift exposures in King County immediately north of the study area (South King County Groundwater Advisory Committee and others, 1991). Some of these drift sequences may correlate with the Double Bluff Drift of the northern lowland. The Double Bluff Drift has been dated to between 150,000 and 250,000 years B.P. in the northern lowland (Easterbrook, 1994). In the north, the Double Bluff Drift, like our third glacial drift, is the third glacial drift in the sequence, is commonly oxidized, and is exposed at sea level (Easterbrook and others, 1967).

Third Nonglacial Deposits (Qpon$_2$)

A third set of nonglacial sediments was encountered in several of the deep boreholes in the subsurface study area. The upper surface of these nonglacial sediments slopes moderately to the northwest and varies between about 50 and -40 ft MSL (Fig. 24). The thickness of this unit is not known because its lower contact was not identified in any of the boreholes.

Based upon their stratigraphic position in the subsurface study area, these sediments are assumed to be older than the Whidbey Formation and to be pre–late Pleistocene in age. The reversely magnetized nonglacial sediments exposed at the base of the Woodworth quarry measured section on Hylebos Waterway are likely older than 780,000 years and so are also probably older than the Whidbey Formation. Recent work at this outcrop has yielded a preliminary fission track date of 1,100,000 ±150,000 yr B.P. (Richard J. Stewart, Univ. of Wash., written commun., 1999).

Figure 23. Paleotopographic map of the top of the third glacial drift (unit Qpog$_2$).

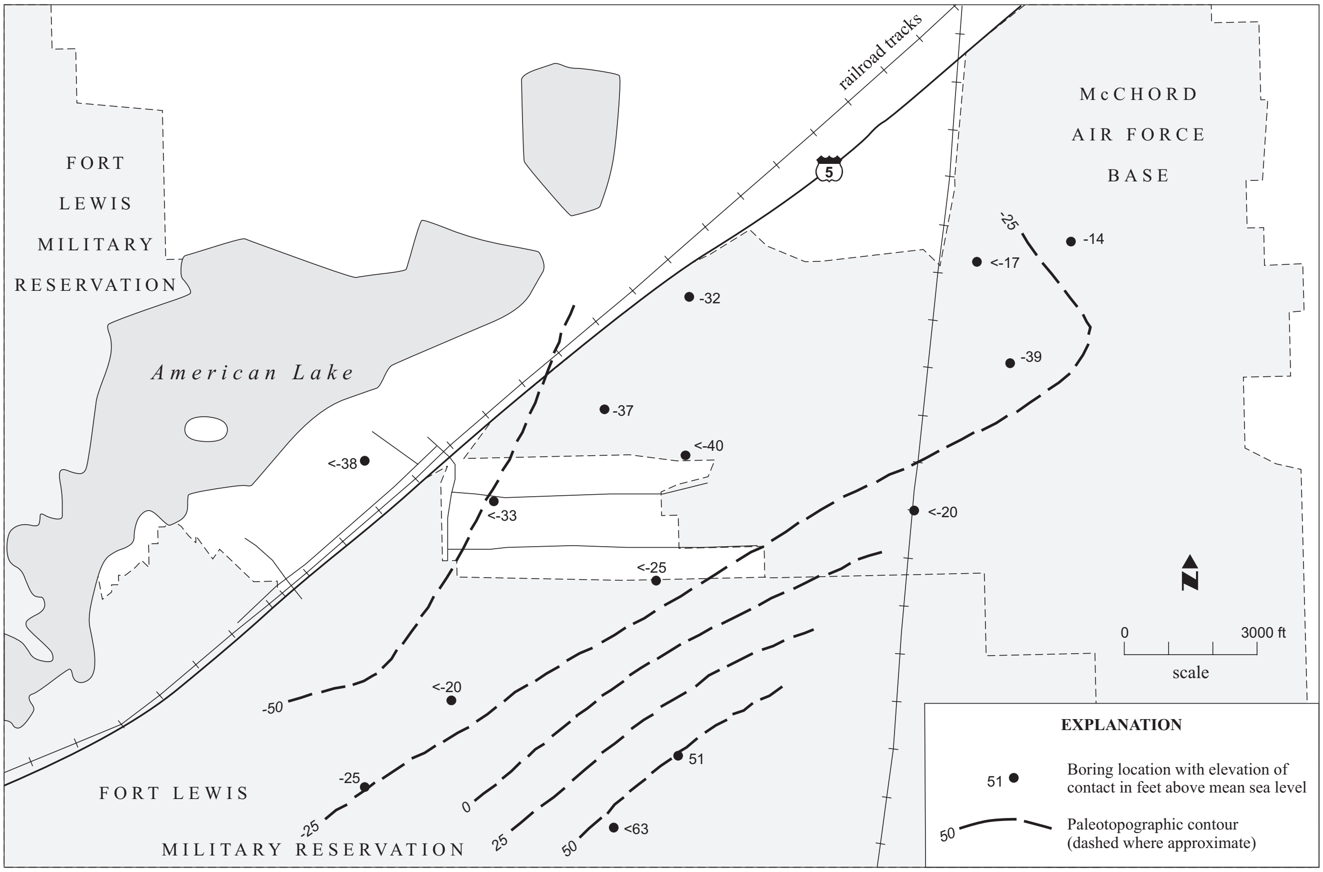


Figure 24. Paleotopographic map of the top of the third nonglacial deposits (unit Qpon$_2$).

Vashon recessional outwash, unit Qv	Interbedded, brown to gray sandy gravel and sand with minor silt interbeds		Vashon unconfined aquifer
Vashon till and ice contact deposits, unit Qv	Dense, gray, silty sandy gravel and gravelly sandy silt, generally matrix supported	Discontinuous aquitard	
Vashon advance outwash, unit Qv	Interbedded, brown to gray sandy gravel and sand with minor silt interbeds		
Glaciolacustrine silt/clay (Lawton Clay), unit Qv	Gray, laminated to massive silt and clayey silt with minor fine sand interbeds	Discontinuous aquitard	
Olympia beds, unit Qob	Mottled, massive, organic-rich, clayey, sandy gravel (mudflows) or lavender silt, peat, sand, and gravelly sand (fluvial and overbank deposits) (17,110 to >46,450 yr B.P.)	Discontinuous aquitard	
Pre-Olympia drift, unit Qpog	Gray-brown, fine to medium-grained sand with minor sandy gravel interbeds, oxidized at top; common silt interbeds at base, rare and discontinuous till		
Second nonglacial deposits, unit Qpon	Mottled, massive, organic-rich, clayey, sandy gravel (mudflows) or lavender silt, peat, sand, and gravelly sand (fluvial and overbank deposits)	Aquitard (locally breached by unit Qv and Qpog erosional features)	
Third glacial drift, unit Qpog$_2$	Interbedded, orange to dark gray sandy gravel and sand with minor silt interbeds, intensely iron-oxide stained at top		Sea level aquifer
	Dense, gray, silty, sandy gravel and gravelly, sandy silt, generally matrix supported (till)	Discontinuous aquitard	
	Interbedded, gray-brown to dark gray sandy gravel and sand with minor silt interbeds		
Third nonglacial deposits, unit Qpon$_2$	Lavender silt, peat, sand, and gravelly sand (fluvial and overbank deposits)	Aquitard	

Figure 25. Generalized stratigraphic and hydrostratigraphic column for west-central Pierce County. Shaded units generally act as aquitards.

Hydrogeologic Implications

The nature and distribution of these glacial and nonglacial units has a profound influence on ground-water flow and contaminant movement in the Quaternary sequence beneath the study area. As shown on Figure 25, glacial drift sequences tend to act as aquifers because they are dominated by sand and gravel outwash deposits. Conversely, nonglacial sediments tend to act as aquitards because of their generally fine-grained nature. However, these generalizations are not everywhere correct. Glacial drift units locally contain discontinuous aquitards such as till and glaciolacustrine sediments, and nonglacial sediments locally contain permeable alluvial sand and gravel layers.

The sediment package generally considered to comprise the Vashon unconfined aquifer by hydrogeologists working in the Tacoma area actually contains two distinct glacial intervals and one nonglacial interval. Discontinuous aquitards associated with the Vashon till, Lawton Clay, and Olympia beds are all contained within the unconfined aquifer. Regionally, all of the sediments above the second nonglacial deposits probably do act as a single aquifer system, but locally these discontinuous aquitards may impede the vertical movement of water and contaminants. These aquitards may also perch groundwater above the regional water table and locally influence the rate and direction of horizontal groundwater flow.

The second nonglacial sediments are relatively continuous beneath the Tacoma area and are typically thought to isolate the upper unconfined aquifer from a confined aquifer that is present near sea level. However, in some areas the aquitard is breached by deep erosional features associated with younger glacial events. In these areas there may be little to impede the vertical movement of water and contaminants between the two aquifer systems. Figure 14 shows the erosional feature that truncates the second nonglacial deposits in the subsurface study area. Most of the trough is filled with fine-grained glaciolacustrine sediments, so it generally maintains the laterally continuity of the aquitard. However, a sandy sequence on the western side of the trough provides a pathway for water movement between the unconfined and confined aquifers. This permeable sequence may also have provided a conduit for trichloroethylene contamination that is widespread in the upper aquifer to enter the lower aquifer (Borden and Troost, 1994).

CONCLUSIONS

The identification of widespread sediments deposited during the Olympia climatic interval and an additional underlying glacial outwash sequence in the Tacoma area allows the late Pleistocene stratigraphic nomenclature in the northern and south-central Puget Lowlands to be tentatively reconciled. The proposed youngest to oldest late Pleistocene sequence in the south-central lowland is Vashon Drift (with Lawton Clay as its basal unit), Olympia beds, pre-Olympia drift (possibly Possession Drift), and a second nonglacial unit (possibly Whidbey Formation). At some locations, an oxidized third glacial drift may also be late Pleistocene in age if it is correlative with the Double Bluff Drift. The third nonglacial deposits are likely pre–late Pleistocene in age. All of these units are present in the Tacoma area, although at any given location one or more may be missing. The use of the term "Kitsap Formation" for the first and (or) second nonglacial sediments should be discontinued because throughout the history of its usage, it has been applied to nonglacial sediments of nearly all ages. The stratigraphic framework in the Tacoma area is thus much more complicated than previously described. This complexity has significant implications for regional hydrogeologic models, structural interpretation, and evaluation of geologic hazards.

The inferred base of the Vashon Drift in the study area is sometimes represented by fine-grained glaciolacustrine sediments with an average age of 13,430 years B.P. This is about 1,000 years younger than is generally assumed for the inception of Vashon glaciation in the south-central lowland but is consistent with Vashon recessional dates reported by other workers. This implies that either 1) almost all of the Vashon sediments in the study area are recessional in age or 2) Vashon glaciation in the south-central lowland began much later than is commonly believed.

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Appendix A. Borehole summary

[1] Only boreholes used in cross sections and contour maps or that provided a radiocarbon sample are included; [2] State Plane Cooordinates; [3] complete citation for each borehole is given in references following the table; [4] 'yes' indicates that samples from that borehole were examined as part of this study.

Borehole[1]	East[2]	North[2]	Ground elev. (ft)	Depth (ft)	Reference[3]	Samples[4]
BA-01	1504004	669307	272.7	235	JRB Associates (1983)	no
CA-01	1503555	665504	291.5	250	JRB Associates (1983)	no
CW-06	1507876	662451	301.6	51.5	Enserch (1994)	no
CW-14	1504381	662970	306.0	276.0	Enserch (1994)	yes
CW-15	1504574	663982	293.0	266.0	Enserch (1994)	yes
CW-18	1504919	662559	310.2	363.0	Enserch (1994)	yes
CW-30	1506425	665308	279.9	280.5	Ebasco (1992)	yes
CW-31	1504247	664889	296.6	311.0	Ebasco (1992)	yes
CW-32	1504429	666768	276.9	372.5	Ebasco (1992)	yes
CW-33	1505229	660076	303.0	288.0	Foster Wheeler (1995)	yes
CW-34	1505171	658775	311.1	288.0	Foster Wheeler (1995)	no
DA-01	1502074	657820	299.3	70.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-02	1502672	659250	300.2	320.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-04	1500926	658044	283.0	68.5	Ebasco and Shannon & Wilson (1991c)	yes
DA-07	1500344	660135	281.3	140.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-08	1499776	659091	275.7	76.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-11	1498687	660912	271.1	76.5	Ebasco and Shannon & Wilson (1991c)	yes
DA-12	1497486	660600	273.4	313.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-12e	1497151	660550	272.0	145.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-13	1497417	661372	272.3	69.5	Ebasco and Shannon & Wilson (1991c)	yes
DA-15	1497688	664272	268.5	305.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-16	1495541	659968	271.8	150.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-17	1495595	661732	272.5	313.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-18	1497141	658562	278.7	73.0	Ebasco and Shannon & Wilson (1991c)	yes
DA-20	1492975	659706	271.8	304.5	Ebasco and Shannon & Wilson (1991c)	yes
DA-24	1496692	661312	270.1	62.5	Ebasco and Shannon & Wilson (1991c)	yes
DA-25	1499246	660324	275.2	72.5	Ebasco and Shannon & Wilson (1991c)	yes
DA-26	1497677	663535	271.4	146.0	Ebasco and Shannon & Wilson (1991c)	yes
DZ-01	1501278	661521	285.4	108	JRB Associates (1983)	no
DZ-06	1498243	660491	271.8	63	Greiling and Peshkin (1986)	no
DZ-09	1499879	660824	271.1	63	Greiling and Peshkin (1985)	no
DZ-10	1498799	661820	265.9	68	Greiling and Peshkin (1985)	no
EH-4	1506538	660931	296.8	118	Ebasco and Shannon & Wilson (1991a)	yes
FZ-01	1509024	662935	279.5	103	JRB Associates (1983)	no
GC	1501870	659610	280.0	634	Washington Department of Ecology	no
IH-01	1511307	658675	330.7	103	Ebasco and Shannon & Wilson (1991b)	yes
IH-03	1509683	659845	326.0	101	Ebasco and Shannon & Wilson (1991b)	yes
LC-19	1495138	653099	289.2	78.7	Shannon & Wilson (1986)	no
LC-21	1496426	652743	279.7	150.2	Envirosphere and Shannon & Wilson (1988)	yes

Borehole[1]	East[2]	North[2]	Ground elev. (ft)	Depth (ft)	Reference[3]	Samples[4]
LC-22	1497011	655282	296.1	52.5	Greiling and Peshkin (1985)	no
LC-26	1497564	651917	276.9	179.0	Ebasco and Shannon & Wilson (1993)	yes
LC-35	1494905	653530	288.0	219.0	Ebasco and Shannon & Wilson (1993)	yes
LC-38	1490375	657970	271.0	83.0	Shannon & Wilson (1986)	yes
LC-40	1490263	656927	277.3	179.0	Ebasco and Shannon & Wilson (1994)	yes
LC-41	1491859	655154	281.8	302.0	Envirosphere and Shannon & Wilson (1988)	yes
LC-44	1493259	656849	271.2	149.8	Envirosphere and Shannon & Wilson (1988)	yes
LC-47	1493403	655176	280.6	269.0	Ebasco and Shannon & Wilson (1993)	yes
LC-50	1495547	652150	271.7	208.0	Ebasco and Shannon & Wilson (1993)	yes
LC-55	1497114	653766	289.6	300.0	Envirosphere and Shannon & Wilson (1988)	yes
LC-60	1489536	658736	276.3	73.0	Envirosphere and Shannon & Wilson (1988)	yes
LC-61	1489769	659151	277.2	80.0	Envirosphere and Shannon & Wilson (1988)	yes
LC-64	1496580	652424	276.5	79.0	Envirosphere and Shannon & Wilson (1988)	yes
LC-65	1494223	654393	286.5	80.0	Envirosphere and Shannon & Wilson (1988)	yes
LC-66	1492176	656900	281.2	189.0	Ebasco and Shannon & Wilson (1994)	yes
LC-67	1490344	655739	263.7	179.0	Ebasco and Shannon & Wilson (1993)	yes
LC-68	1492566	653737	281.0	259.0	Ebasco and Shannon & Wilson (1993)	yes
LC-69	1491985	655128	282.2	205.0	Ebasco and Shannon & Wilson (1993)	yes
LC-70	1491765	655182	280.7	219.0	Ebasco and Shannon & Wilson (1993)	yes
LC-71	1489355	657746	269.5	230.0	Ebasco and Shannon & Wilson (1994)	yes
LC-72	1488749	656736	263.9	194.0	Ebasco and Shannon & Wilson (1994)	yes
LC-73	1488280	656095	269.6	230.0	Ebasco and Shannon & Wilson (1994)	yes
LF4-MW1	1478994	655689	255.6	166.5	Applied Geotechnology (1993)	no
LF4-MW3	1478313	656247	241.0	166.5	Applied Geotechnology (1993)	no
LF4-MW4	1477961	656547	245.8	336.5	Applied Geotechnology (1993)	no
LF4-MW6	1477333	656287	223.2	165.0	Applied Geotechnology (1993)	no
LF4-MW12B	1477005	658234	236.0	208	Applied Geotechnology (1993)	no
LF4-MW16	1475180	657238	232.6	306.0	Applied Geotechnology (1993)	no
LT-09	1507958	661401	311.7	189.0	Enserch (1994)	no
LZ-04	1496741	657756	277.4	302.0	Ebasco and Shannon & Wilson (1991c)	yes
O'Neil & Martin	1494040	658208	278.0	320.0	Washington Department of Ecology	no
Poe & McGuire	1493712	660200	265.0	222.0	Washington Department of Ecology	no
RD-1	1489009	655799	272.3	206.9	U.S. Army Corps of Engineers (1982)	no
RD-2	1490076	654908	274.5	140.5	U.S. Army Corps of Engineers (1982)	no
T-01	1490023	660701	272.5	79.0	Ecology and Environment (1986)	no
T-02	1489711	660410	272.8	80.0	Ecology and Environment (1986)	no
T-09	1490036	660709	272.1	310.0	Envirosphere and Shannon & Wilson (1988)	yes
T-10	1489689	660316	270.5	118.0	Ecology and Environment (1986)	no
T-11	1489736	661502	277.0	80.0	Envirosphere and Shannon & Wilson (1988)	yes
T-12	1490605	660206	274.4	70.0	Envirosphere and Shannon & Wilson (1988)	yes
TZ-01	1495090	659956	272.7	73.0	Greiling and Peshkin (1985)	no
TZ-02	1495903	660395	264.7	68	Greiling and Peshkin (1985)	no
W1	1497905	660451	269.8	120	Ecology and Environment (1984)	no
W2	1497878	660136	268.2	77	Ecology and Environment (1984)	no
W3	1497130	660406	269.3	88	Ecology and Environment (1984)	no

Borehole[1]	East[2]	North[2]	Ground elev. (ft)	Depth (ft)	Reference[3]	Samples[4]
W4	1497137	659961	266.2	122	Ecology and Environment (1984)	no
88-1-SS	1471543	657079	220.0	215.8	Woodward-Clyde Consultants (1989)	no
88-5-SS	1468231	658349	215.0	191	Woodward-Clyde Consultants (1989)	no
90-PM-1	1483260	662620	250.5	140	Shannon & Wilson (1990)	yes
Well 5001	1497420	661820	280.0	435	Washington Department of Ecology	no
Well 4/6 Comp	1489500	653500	270.0	295	Noble (1990)	no
Well 8	1493920	653680	287.0	1008.0	Washington Department of Ecology	no

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[1] Ebasco Environmental, Ebasco Services Incorporated, Enserch Environmental, and Envirosphere Company are now Foster Wheeler Environmental Corporation.

Appendix B. Boreholes with radiocarbon data

The original published logs for these boreholes are reproduced on the following pages (Figs. B-1 through B-4). See Appendix A for complete borehole log references. BGS, below ground surface; MSL, above mean sea level.

Borehole DA-2c,d
(Ebasco and Shannon & Wilson, 1991c)

See Figure B-1 for original published log

Radiocarbon date:

96 ft BGS	>40,000 yr B.P. (I-15,705)

Inferred stratigraphic units:

0 – 40 ft BGS	Vashon recessional outwash
40 – 45 ft BGS	Vashon till
45 – 75 ft BGS	Vashon advance outwash
75 – 85 ft BGS	Vashon glaciolacustrine sediments
85 – 121 ft BGS	Pre-Olympia drift
121 – 320 ft BGS	Third glacial drift

Borehole DA-12e
(Ebasco and Shannon & Wilson, 1991c)

See Figure B-2 for original published log

Modifications to geologic log (based upon re-examination of archived borehole samples):

5 – 15 ft BGS	dense gray silty sandy gravel (till)
15 – 25 ft BGS	brown-gray slightly silty to silty sandy gravel
25 – 35 ft BGS	dense gray silty sandy gravel (till)
65 – 74 ft BGS	gray silty fine sand; wet

Radiocarbon dates:

92 ft BGS	13,510 ±80 yr B.P. (Beta-79885)
140 ft BGS	>41,300 yr B.P. (Beta-81801)

Inferred stratigraphic units:

0 – 35 ft BGS	Interbedded Vashon till and outwash
35 – 74 ft BGS	Vashon outwash
74 – 98 ft BGS	Vashon glaciolacustrine sediments
98 – 145 ft BGS	Pre-Olympia drift

Borehole 4/6 Composite
(Noble, 1990)

See Figure B-3 for original published log

Radiocarbon date:

60 ft BGS	25,100 ±600 yr B.P. (I-15,437)

Inferred stratigraphic units:

217 – 270 ft MSL	Vashon Drift
195 – 217 ft MSL	Olympia nonglacial sediments
163 – 195 ft MSL	Pre-Olympia drift
119 – 163 ft MSL	Second nonglacial deposits
-22 – 119 ft MSL	Third glacial drift
-25 – -22 ft MSL	Third nonglacial deposits

Borehole LF4-MW12B
(Applied Geotechnology, 1993)

See Figure B-4 for original published log

Radiocarbon date:

60 ft BGS	13,630 ±90 yr B.P. (Beta-52222)

Inferred stratigraphic units:

0 – 58 ft BGS	Vashon Drift
58 – 101 ft BGS	Vashon glaciolacustrine sediments
101 – 134 ft BGS	Pre-Olympia drift
134 – 153 ft BGS	Second nonglacial deposits
153 – 208 ft BGS	Third glacial drift

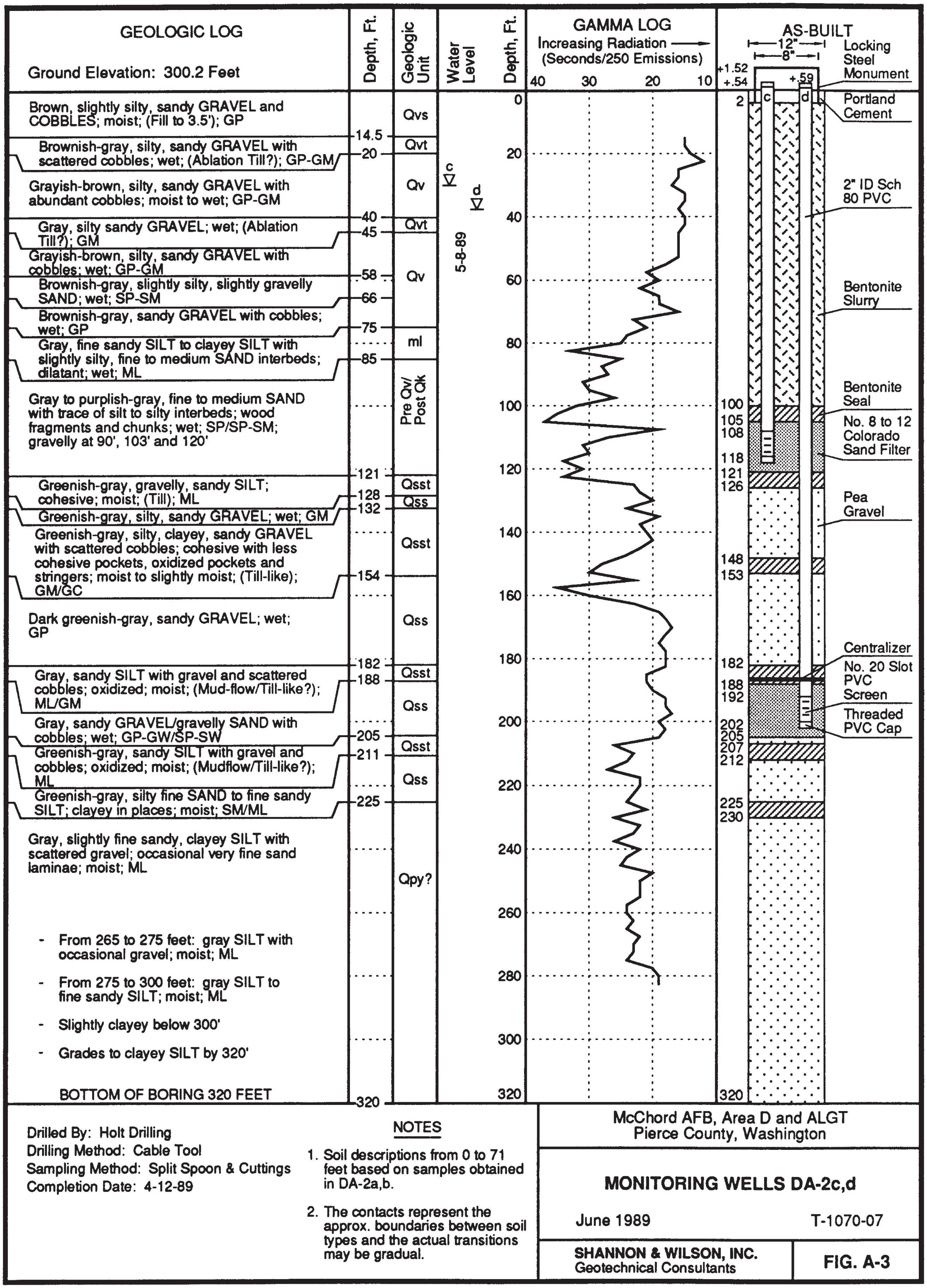


Figure B-1. Borehole DA-2c,d (Ebasco and Shannon & Wilson, 1991c)

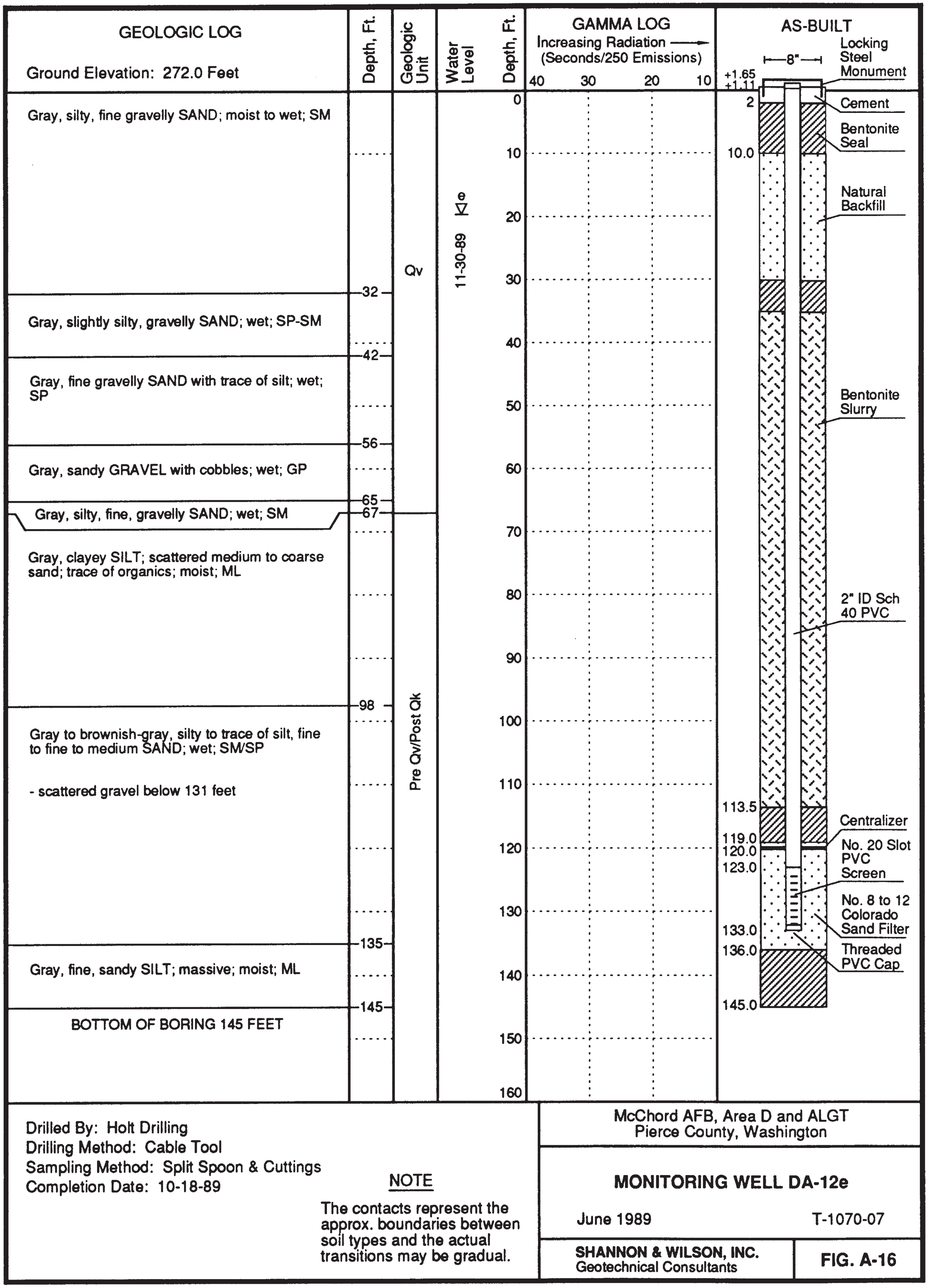


Figure B-2. Borehole DA-12e (Ebasco and Shannon & Wilson, 1991c)

BASIC DATA LOG R-2

Composite Logs for Wells 4 and 6, New Madigan Hospital (19/2E-28H) Wells are 1,200 feet apart, altitude at surface is 270 feet.

Altitude of base (ft)		Thickness (ft)
	Vashon Drift, Steilacoom Gravel Member	
230	Brown-gray cobbly gravel (to 10-in. diameter) with some sand and silt.	40
	Discovery nonglacial unit	
217	Brown medium sand, silty; some gravel;some thin silt layers.	13
203	Brown sandy, silty gravel, with cobbles to 10-in. diameter and embedded wood and peat. Has mudflow texture. Mt. Rainier clast types predominant. Wood radiocarbon dated at 25,100 +/- 600 yr (D. K. Balmer, oral commun., 1989).	14
195	Brown, fine to medium, silty sand.	8
	Narrows glacial unit	
186	Red-brown sand.	9
177	Brown sand-gravel diamicton (till?).	9
168	Brown, small gravel and coarse sand.	9
163	Brown, sandy, silty gravel.	5
	Kitsap Formation	
126	Brown, silty sand, silty clay, some gravel. Laminations noted.	37
119	Brown silt and sand with ash partings.	7
67	Brown, iron-stained and iron-cemented sand and gravel with wood pieces.	52
	Flett Creek glacial unit	
63	Gray gravel, sand, silt, clay (till).	4
40	Gray silt, sandy, clayey gravel with boulders.	23
14	Brown and gray (layered) silty sand and gravel.	26
3	As in overlying interval, but with notable coal detritus.	11
-20	“Clean” well-sorted sand and gravel with notable coal detritus.	23
-22	Brown gravelly coarse sand.	2
	Clover Park nonglacial unit(?)	
-25	Brown, fine to medium sand.	3
	(Base not penetrated.)	

Figure B-3. Borehole 4/6 Composite (Noble, 1990)

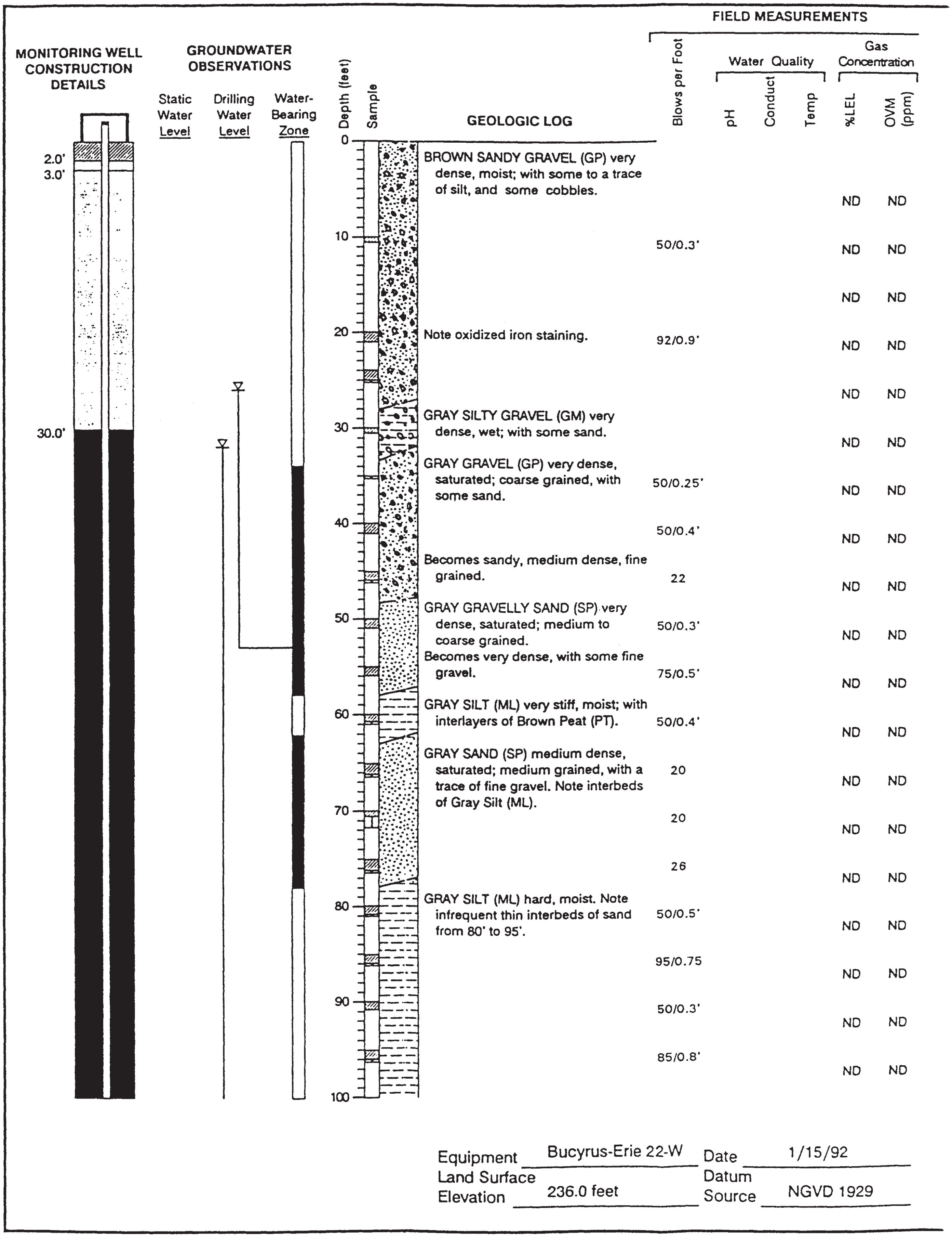


Figure B-4. Borehole LF4-MW12B (Applied Geotechnology, 1993)

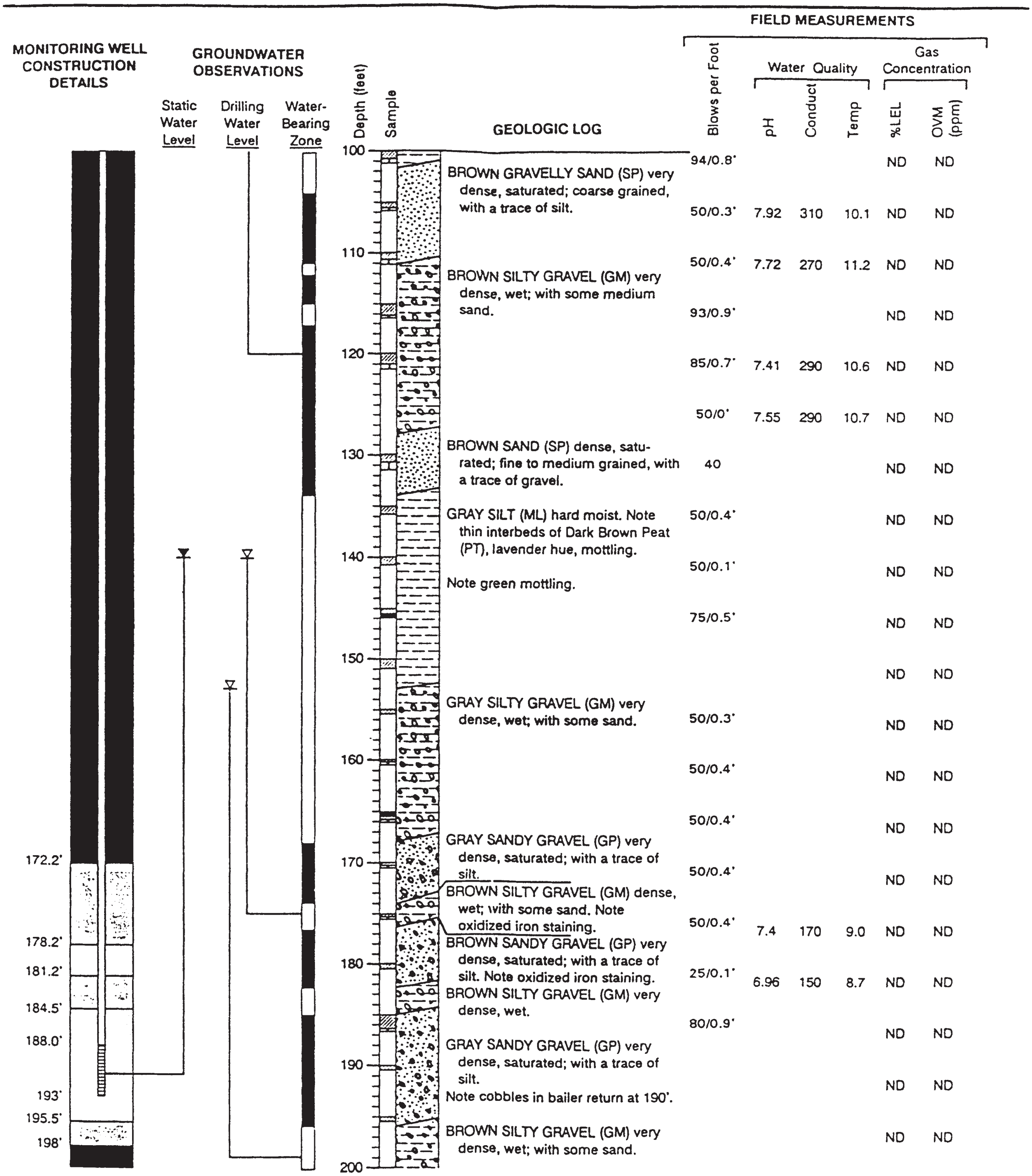


Figure B-4. Borehole LF4-MW12B (Applied Geotechnology, 1993) *(continued)*

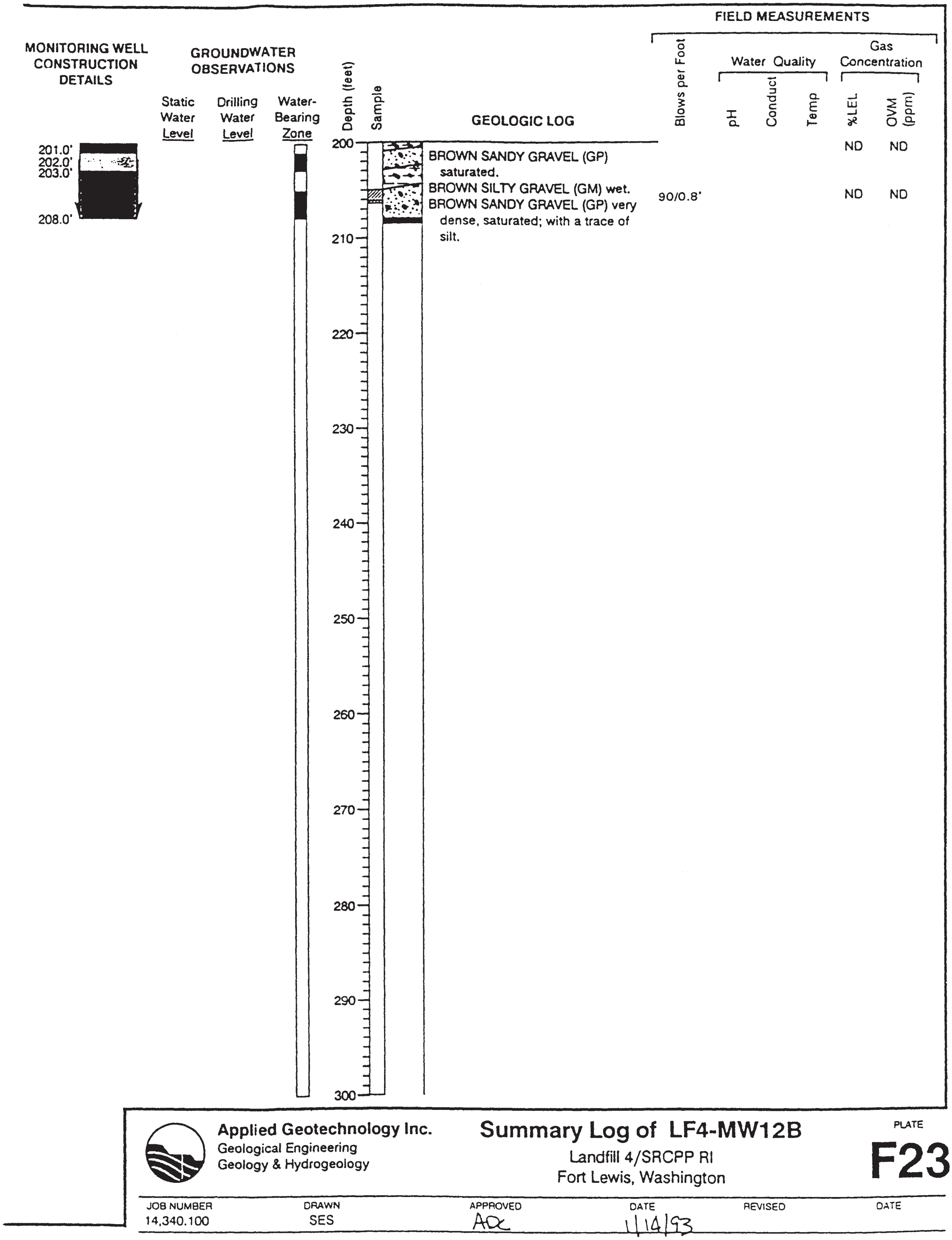
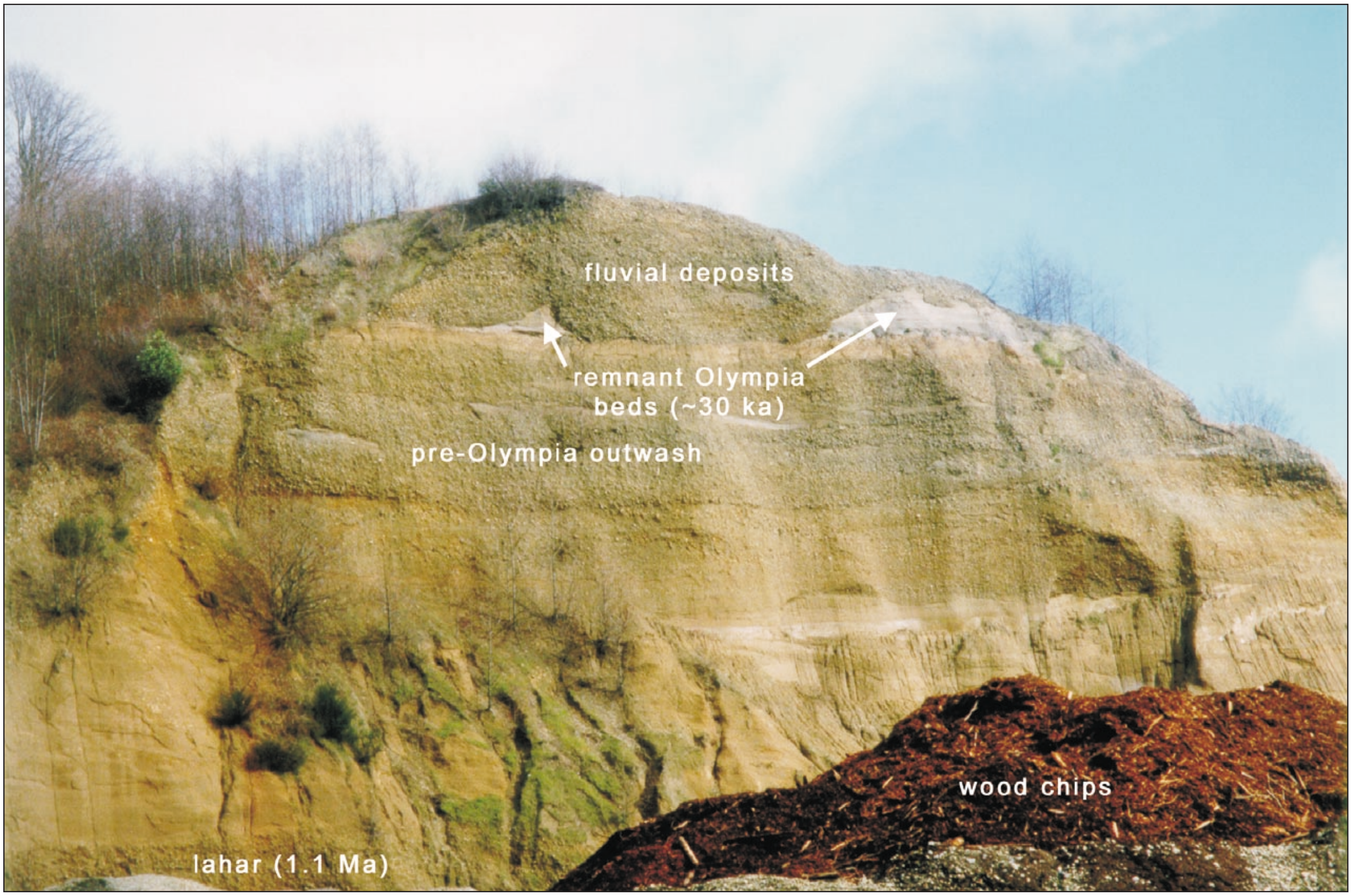


Figure B-4. Borehole LF4-MW12B (Applied Geotechnology, 1993) *(continued)*


fluvial deposits
remnant Olympia
beds (~30 ka)
pre-Olympia outwash
wood chips
lahar (1.1 Ma)