Chronology, Lithology and Paleoenvironmental Interpretations of the Penultimate Ice-Sheet Advance into the Puget Lowland, Washington State

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Abstract

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Stratigraphic nomenclature and chronology has been a problem for geologists seeking to understand the Quaternary history of the Puget Lowland of Washington State for over one hundred years. Accurate identification of deposits, and accurate age assignments for those deposits, can help us to better understand the paleoclimate of the region, the physical characteristics of deposits encountered during infrastructure projects, the timing of tectonic deformation and recent seismicity, and our geological history. Each of these has profound consequences on our daily lives. In this dissertation I have established a stratigraphic framework for the last million years of geologic history in the Puget Lowland, based on global climate patterns, abundant new absolute dates, and detailed mapping that synthesizes my work and the work of others over the last century.

Two decades of detailed field mapping, absolute and relative dating, and analyses have identified new geologic units and clarified and expanded our understanding of many others that had been

previously identified but imprecisely described or understood. The techniques I have made use of include luminescence dating, paleomagnetic correlations, radiocarbon dating, fission-track and Ar/Ar dating, palynology, macrofossil identification, provenance, and field-measured sections. My data suggest that the Vashon stade (representing the regional advance of the Marine Isotope Stage 2 ice sheet) ended quite abruptly, nearly simultaneously in the north and south Lowland. The prior MIS 4 ice sheet advance, named the "Possession glaciation," was of similar extent to that of the Vashon stade, extending to within about 25 km of the Vashon limit. MIS 4 fine-grained glacial deposits are abundant in the Puget Lowland. The Whidbey Formation (MIS 5) and Double Bluff Drift (MIS 6), previously recognized only north of Seattle, have now been newly identified in the southern Puget Lowland, over 60 km from their type section on Whidbey Island. Newly identified stratigraphic units include deposits from the MIS 7 interglacial period, informally named the "Hamm Creek formation" for 200-ka pumice deposits in Seattle; deposits from the MIS 8 glacial period, collectively named the "Defiance drift"; and the "Gig Harbor gravel," which may be part of MIS 8 or even older. In addition, reversely magnetized deposits, assumed to be older than 780 ka based on limiting luminescence ages, have been identified in multiple locations along the Tacoma and Gig Harbor coastline.

Many unconformities exist in the Pleistocene record of the Puget Lowland, making stratigraphic correlation difficult even with absolute dating. Each time-stratigraphic unit is an unconformity-bounded sequence with widely distributed but discontinuous deposits. Glaciotectonic and tectonic discontinuities further confound correlations. With diligence and knowledge, however, we can continue to improve our geologic understanding. Society's future economic progress and human well-being in the Puget Lowland region depends in large measure on our ability to predict and plan for global climate changes, geologic hazards, and the complexity of the ground beneath us. Understanding the relatively recent geologic history of the region, of which this dissertation is a contribution, is a necessary step in that process.

Acknowledgements

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Chapter 1 - Introduction

1.1 Significance

The purpose of this dissertation is to synthesize two decades' worth of study, data collection, and interpretation of key elements of the Quaternary stratigraphy and lithology of the Puget Lowland of western Washington State. Those elements focus on the continental ice-sheet advance in the Puget Lowland during Marine Isotope Stage (MIS) 4, locally known as the "Possession glaciation," and more specifically on data related to geographic distribution, chronology, and lithology of this ice advance and its deposits. The synthesis and data compilation are parts of my PhD research project and geological quadrangle mapping completed for the United States Geological Survey (USGS). During this mapping, evidence for multiple ice advances having overridden Seattle was encountered and partly inspired this study (Troost et al., 2003; Mahan et al., 2003).

For many decades, practitioners assumed that the Possession-age ice sheet did not advance as far south as Seattle (Lea, 1984; Walsh et al., 2003; Dr. Stephen Porter, University of Washington, 2003, personal communication). However, my research shows that the Possession ice sheet advanced not only south of Seattle but also beyond Tacoma, leaving a discontinuous record of glaciomarine drift, till, outwash, and glaciolacustrine deposits. This dissertation presents a compilation of the data that demonstrates a variety of well-dated deposits documenting the minimal extent, and likely near-terminal position, of the MIS 4 ice sheet in the Puget Lowland.

In addition to the Possession-age ice sheet, evidence for new cycles of interglaciation and glaciations from the last 1 Ma emphasizes the need for updates of, and further refinement to, the Quaternary stratigraphy of the central Puget Lowland.

1.2 Research Goals

The poorly defined history and extent of pre-Fraser glaciations in the Puget Lowland, coupled with their importance for interpreting the global distribution of glaciation and more local applications to geologic hazards and groundwater resources, have motivated the following research questions that have guided my research for the past two decades:

How far did the Possession-age ice sheet extend into the Puget Lowland?

The maximum extent, suite of deposits, and geomorphology of the Possession glaciation is not known. Prior to my research, deposits at only three locations had been positively identified with the Possession glaciation on the basis of absolute ages (Easterbrook, 1994). It is likely that any end moraines of the Possession glaciation were obliterated by the larger, subsequent Vashon-age glacier; in contrast, remnant moraines 1.2 km south of the southern Vashon ice margin are attributed to the Double Bluff glaciation, associated with an ice-sheet advance during MIS 6, by Lea (1984) based on weathering, placing the Double Bluff glacier advance 2 to 12 km beyond the extent of Vashon glacier. Thus, preservation of older moraines is likely only for the largest ice sheets in the Puget Lowland (Gibbons et al., 1984). Determining the extent of lesser advances has proven much more problematic, given limited surface exposures of concordant age and loss of evidence from subsequent overriding by the larger MIS 2 (Vashon) ice advance.

Beyond the dated exposures around Whidbey Island, what Possession-age glacial facies are present in other parts of the Puget Lowland? What can we learn from the pattern of their deposition and preservation?

Till and outwash had previously been positively attributed to MIS 4 at only three locations, none of which are at the type section of the Possession-age deposits on Whidbey Island (Easterbrook et al., 1967). In many locales, however, deposits representing multiple glacial advances are present and are separated by interglacial deposition and weathering or by unconformities. Thick outwash, glaciomarine drift, glaciolacustrine units, and tills are common facies in these exposures and in subsurface explorations. However, they have been heretofore uncorrelated with any named (or unnamed) glacial or interglacial period, and because the Quaternary geologic units all share many of the same sedimentary facies and are discontinuous across the Puget Lowland, many of the usual tools of stratigraphic identification or correlation are not useful.

How much topographic relief existed in the Puget Lowland before and after the Possession-age glaciation, and what are the geologic hazards and implications for groundwater resources and contamination of that relief?

The modern Puget Lowland landscape is largely the result of deposition and erosion during the Fraser glaciation (MIS 2; Armstrong et al., 1965). Modern topographic relief is about 500 m, with surface elevations ranging from a high of about 200 m on the uplands down to -300 m in deep basins of Puget Sound. Deep erosion and thick deposition are attributed to this most recent glaciation, but such processes surely would have been active during prior ice-sheet advances as well. Unconformities are common due to this cycling of deep erosion and result in numerous angular unconformities, which can complicate efforts to identify structural deformation as evidence for past seismic activity. Furthermore, deep erosion, if also present in the Possession-age deposits, would have provided basins for subsequent infilling of either fine or coarse-grained material that can have profound impacts on groundwater flow and consequently on the development and use of groundwater resources and the distribution of earth materials.

What were the climatic conditions in the Puget Lowland during MIS 4 and how do they compare to global conditions during this period and to the much better-known conditions in the Puget Lowland during MIS 2?

Climatic conditions in the Puget Lowland during MIS 2 are relatively well-constrained by pollen records (Whitlock et al., 2000; Whitlock and Bartlein, 1997; Heusser, 1977; Heusser et al., 1980) and ice-sheet reconstruction (e.g., Thorson, 1981; Booth, 1986). Pollen records indicate that at the beginning of MIS 2 the region experienced a cold and dry period (Grigg and Whitlock, 2002) with an average July temperature 2 to 7 degrees C colder than today (Heusser, 1977; Grigg and Whitlock, 2002). The dry period was followed by a cool wet period, with precipitation comparable to modern values, during which the Cordilleran ice sheet expanded to its maximum extent (Grigg and Whitlock, 2002; Whitlock and Bartlein, 1997; Hicock et al., 1999; Hansen and Mackin, 1949). Proxy climate records during MIS 4 are not nearly as common or well documented as for MIS 2, particularly in the Pacific Northwest.

1.3 Funding

The data presented herein are the result of many projects all with a common goal: to unravel the Quaternary history and stratigraphy of the Puget Lowland to support tectonic, groundwater, and geologic hazards efforts. Much of the work was funded by the Geologic Division of the USGS, and some of the dating was the result of in-kind services from the Geologic Division as well.

For the USGS, this work has been primarily supported by two projects: the Pacific Northwest Urban Corridor Mapping Project, managed by Dr. Ray Wells; and the National Earthquake Hazards Reduction Program (NEHRP) for the Pacific Northwest formerly managed by Dr. Craig Weaver and more recently by Dr. Thomas Pratt. Additional funding has been provided by research grants and scholarships from the Geological Society of America, the Association of Environmental and Engineering Geologists, the Association for Women Geoscientists, and the Earth and Space Sciences Department at the University of Washington.

1.4 Geographic Setting

The Puget Lowland in Western Washington is an elongate structural and topographic basin bordered by the Cascade Mountains to the east and the Olympic Mountains to the west. The Lowland is part of a larger topographic low occupied by the Salish Sea, which extends from the Strait of Georgia in British Columbia (B.C.), Canada into Puget Sound in Washington (Figure 1-1).

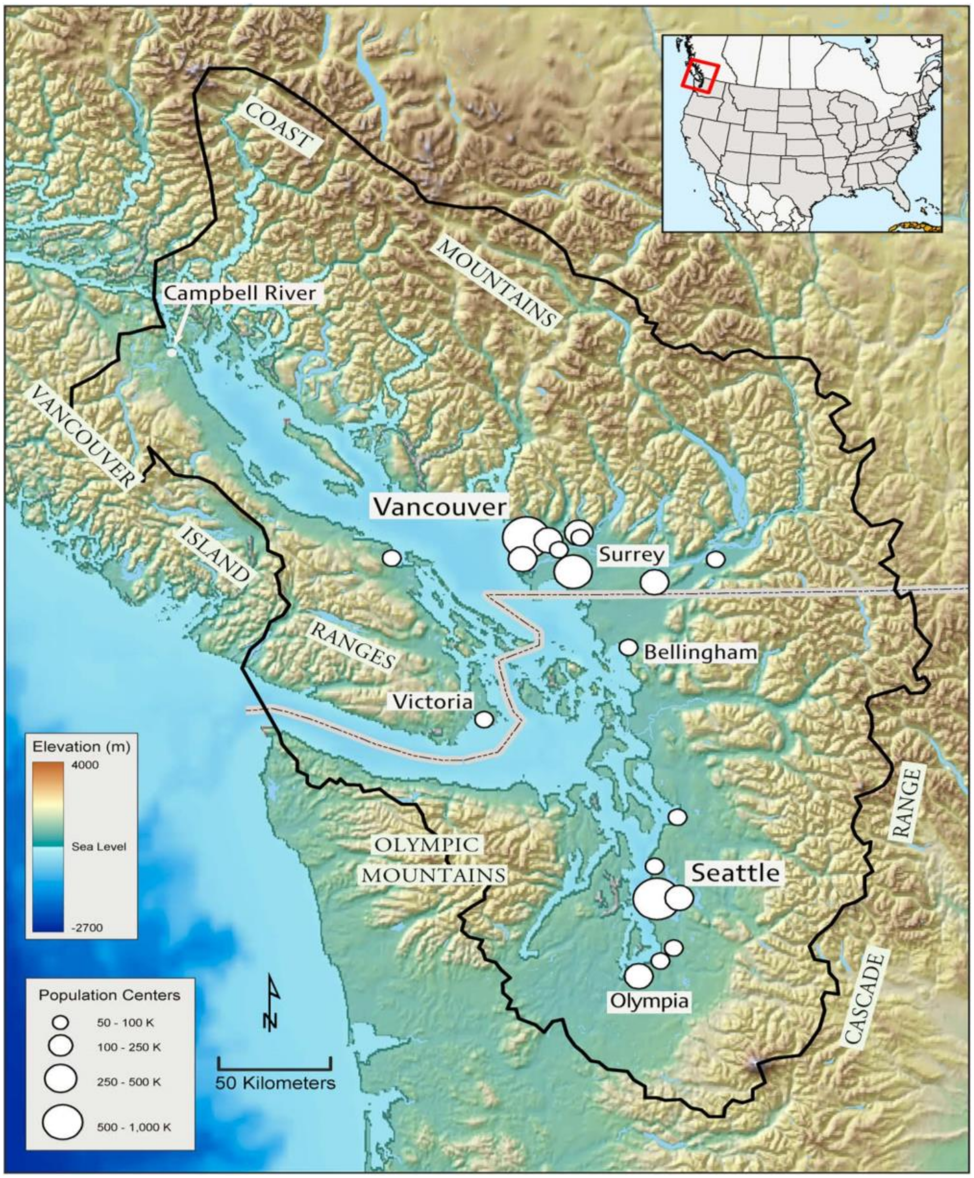

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Figure 1-1. Map showing the Salish Sea region and associated waterways (outlined in black), Georgia Strait, Puget Sound, and major cities. From the Encyclopedia of Puget Sound, UW Tacoma Center for Urban Waters.

1.5 Geologic Setting

The geology of the Puget Lowland is dominated by a complex, alternating, and incomplete sequence of glacial and interglacial deposits that unconformably rests on a deformed bedrock surface. That bedrock surface elevation varies from above-ground outcrops to several kilometers below the ground. Bedrock crops out in an east-west band across the center of the Puget Lowland at the latitude of south Seattle and also around the perimeter of the Puget Lowland.

1.6 Glacial Setting

Glaciers of the Cordilleran Ice Sheet, coalescing from the northern Cascade Ranges in British Columbia, have advanced down the Strait and into the Puget Lowland likely more than a dozen times, based on the marine isotope record of global ice volumes (Booth et al., 2004a; Troost et al., 2005) (Figure 1-2).

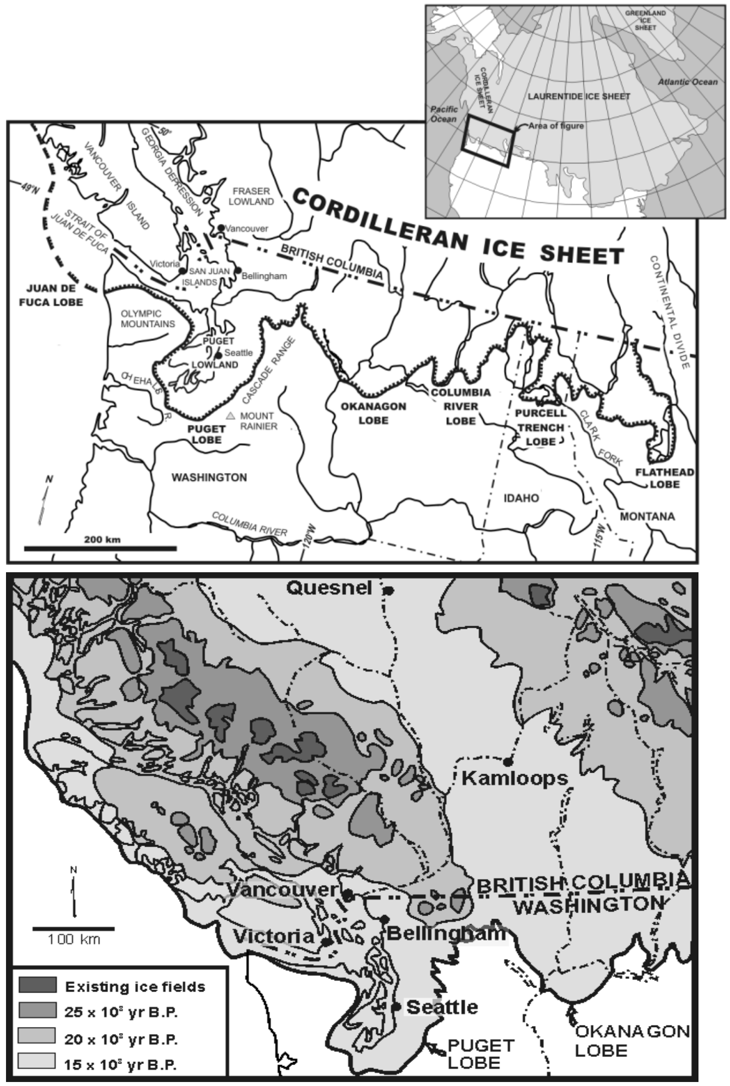


Figure 1-2. Maps showing (top) the extent and (bottom) growth of the Cordilleran ice during the last glaciation. From Booth et al., 2004a.

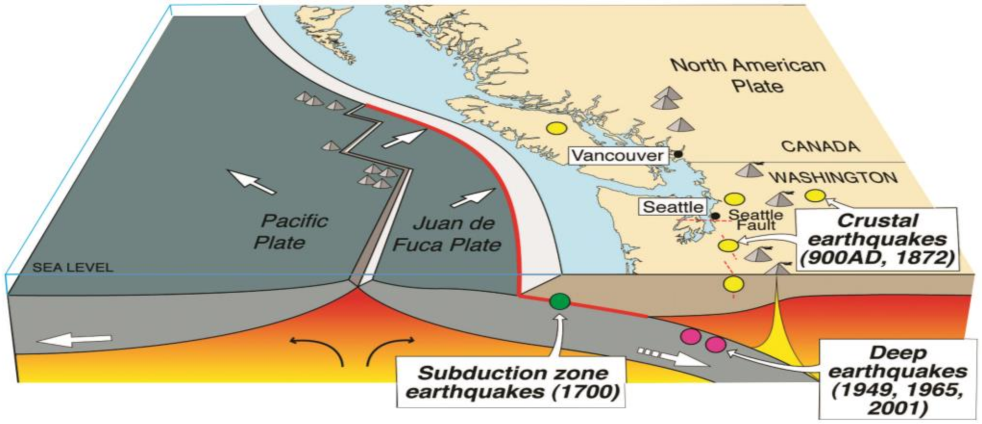
The Cordilleran Ice Sheet terminated in several lobes, locally named the Juan de Fuca, Puget, Okanagan, Columbia River, Purcell Trench, and Flathead lobes. Alpine glaciers originating from the Cascade Range and Olympic Mountains also advanced multiple times into the Puget Lowland, and toward the WA coast and eastern WA (Thackray, 2001; Porter, 1977). The last such advance of the Cordilleran Ice Sheet, during what has been named the Vashon stade of the Fraser glaciation

(Armstrong et al., 1965), reached the central Puget Sound region about 17,600 cal yr BP and retreated past this area by 16,570 cal yr BP (Troost, 2011; Porter and Swanson, 1998).

The modern landscape is largely a result of repeated cycles of glacial scouring and deposition, and recent processes such as landsliding and river action. The north-south ridges and deep troughs of the Puget Lowland are the result of glacial scouring and subglacial stream erosion. Troughs, now occupied by marine water, extend the length of the Puget Lowland, consistent with the most recent glaciation (Booth, 1994).

1.7 Tectonic Setting

The Puget Lowland is tectonically active with an offshore subduction zone (Figure 1-3), associated volcanoes, north-south compression within the continental plate, multiple sources of earthquakes, and at least 15 active shallow faults (Figure 1-4; Nelson et al., 2014). Numerous Tertiary to Holocene faults and folds have deformed both the bedrock and overlying Quaternary sediments (Figure 1-4). Active faults crossing the Puget Lowland include the Seattle fault zone, the Southern Whidbey Island fault zone, the Tacoma fault, and the Olympia fault. Progressive folding and faulting have accommodated approximately 5 mm per year of shortening within the last 7000 yr in the Lowland (Figure 1-5; Pratt et al., 2015). These thrust faults create a series of basins and uplifts, separated by active faults, within the Puget Lowland. In general, the older Quaternary stratigraphic units in the Lowland are exposed at or above sea level only in the areas of greatest uplift (Booth et al., 2004b). Most recently, an earthquake on the Seattle fault zone around 1040-910 cal yr BP resulted in 8m of vertical offset (Atwater and Moore, 1992; Nelson et al., 2014). At least 5 surface-rupturing earthquakes have occurred in the past 3500 yr based on trenching and analyses by Nelson et al. (2014) and Pratt et al. (2015).



Source	Affected Area	Max. Size	Recurrence
Subduction Zone	W. WA, OR, CA	M9	500-600 yr
Deep JdF plate	W. WA, OR	M7	30-50 yr
Crustal faults	WA, OR, CA	M7?	?

Figure 1-3. Diagram showing the 3 sources for earthquakes in Washington.
Modified from USGS Pacific Northwest Geologic Mapping and Urban Hazards website, accessed December 2016.

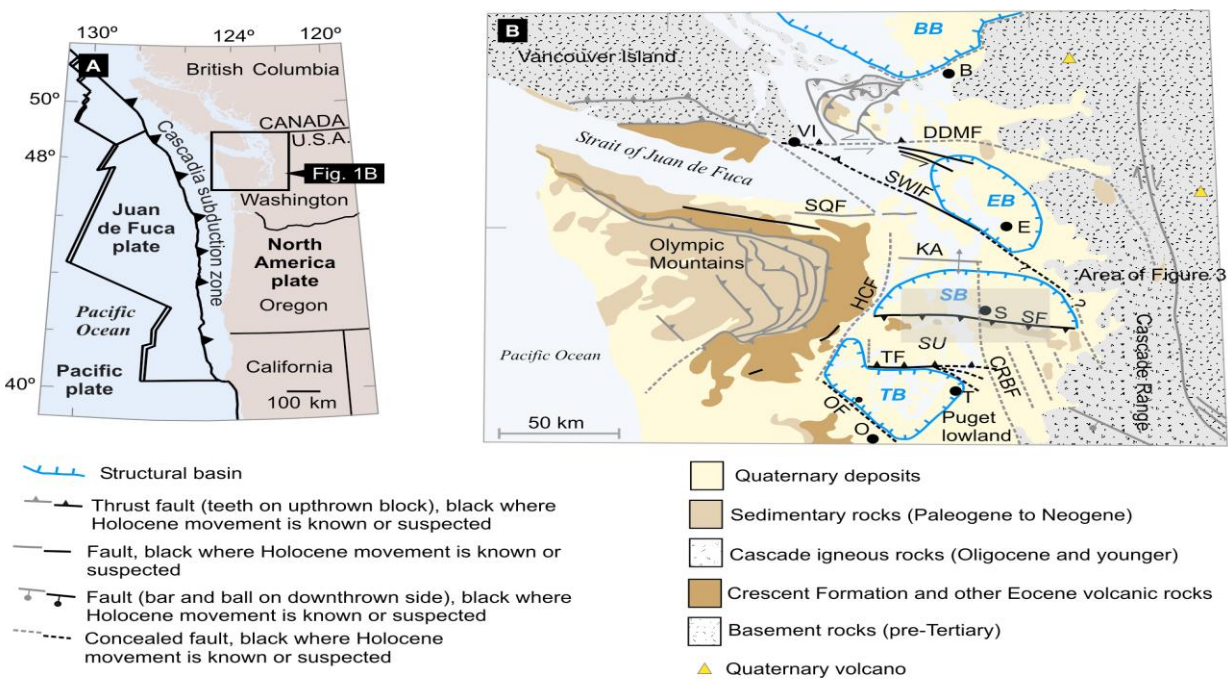


Figure 1-4. Map of Holocene tectonic features in Western Washington.
Map A shows the relationship of the Cascadia subduction zone to the coast of Washington. Map B shows the active faults, basins, and uplifts within the Puget Lowland; south to north: O-Olympia, OF-Olympia Fault Zone, T-Tacoma, TB-Tacoma Basin, TF-Tacoma Fault Zone, CRBF-Coast Range Boundary Fault, SU-Seattle Uplift, S-Seattle, SF-Seattle Fault Zone, SB-Seattle Basin, HCF-Hood Canal Fault, KA-Kingston Arch, E-Everett, EB-Everett Basin, SQF-Sequim Fault, SWIF-Southern Whidbey Island Fault Zone, VI-Vancouver Island, DDMF-Darrington/Devils Mountain Fault Zone, B-Bellingham, BB-Bellingham Basin. From Dr. Brian Sherrod, USGS.

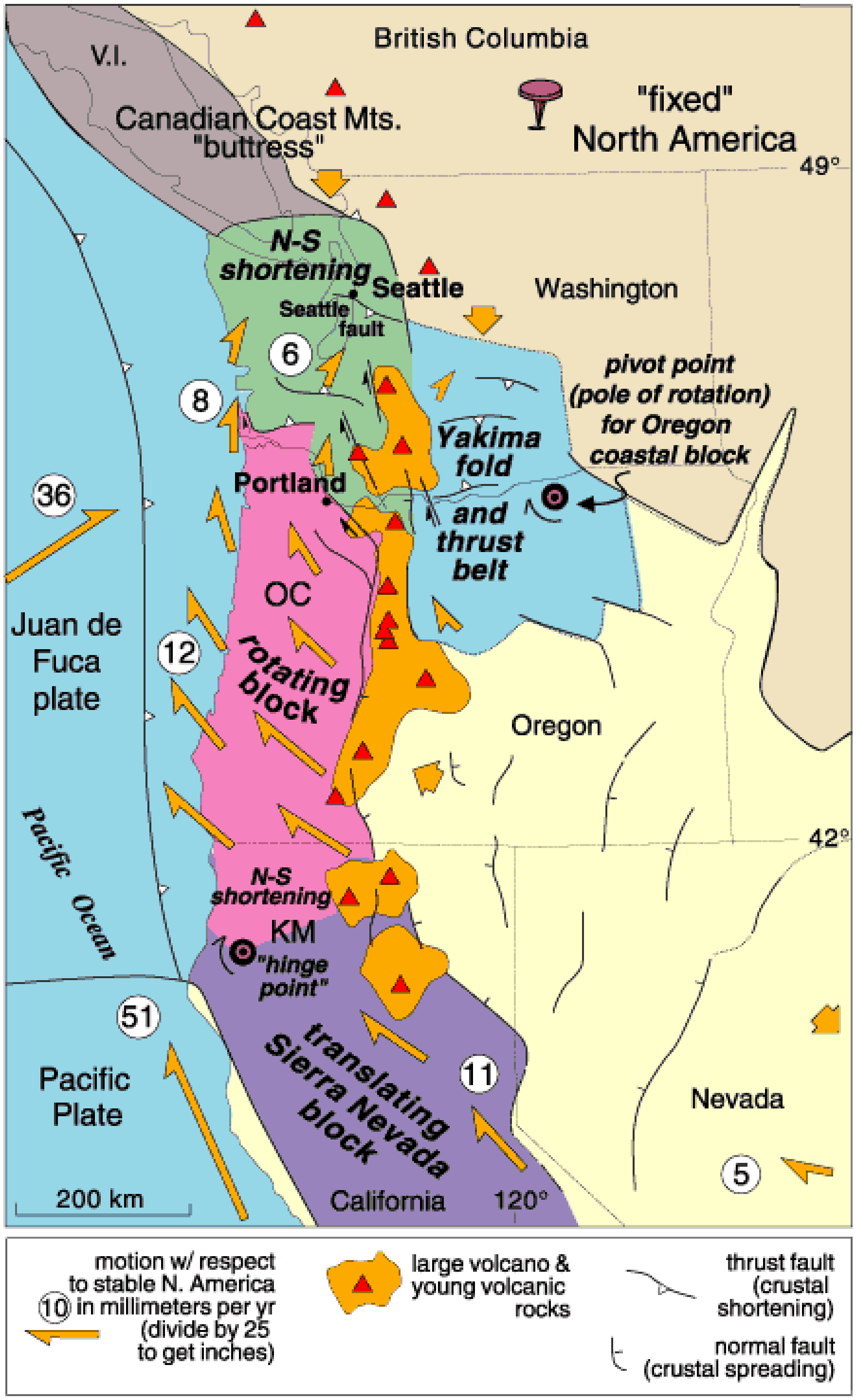


Figure 1-5. Map showing rotation and crustal shortening in the Pacific Northwest. From USGS Pacific Northwest Geologic Mapping and Urban Hazards website, accessed December 2016.

Chapter 2 - Summary of Geochronological Studies in the Puget Lowland

2.1 History of Stratigraphic Efforts

Little is known about Quaternary ice-sheet glaciations in the Puget Lowland of WA except for the most recent, the Fraser glaciation, defined by Armstrong et al. (1965), that culminated about 16,850 cal yr BP (Troost, 2011) during MIS 2. Oxygen isotope records (Shackleton and Opdyke, 1973), however, indicate that global climate patterns likely induced a dozen or more glacial periods, both world-wide and regionally (Booth et al., 2004a) in the last one million years.

Bailey Willis (1898) was among the first to document glacial deposits in the Puget Lowland, particularly the most widespread of these deposits, which he named the Vashon till of the Fraser glaciation. By the mid to late 20th century, essentially three separate stratigraphic sequences had been proposed to depict the known glacial advances into the Puget Lowland: one developed in the north Puget Lowland, one in the Seattle area of the central Puget Lowland, and one in the southeast Lowland (Table 2-1). The ice-sheet stratigraphy in the southeastern Puget Sound area was the first to be described (Crandell et al., 1958), identifying four glacial advances: from oldest to youngest they were named the Orting, the Stuck, the Salmon Springs, and the Vashon. Intervening interglaciations in this region were defined from oldest to youngest by deposits named the Alderton, Puyallup, and Kitsap Formations (Crandell et al., 1958; Walters and Kimmel, 1968). Farther north in Seattle, Stark and Mullineaux (1950) had previously described 3 till sheets based on exposures in clay and gravel pits: from oldest to youngest, they named them the Beacon till, Klinker till, and Vashon till. Intervening interglacial units were named the Duwamish Formation and the lower part of the Lawton Clay (Stark and Mullineaux, 1950).

Stark and Mullineaux (1950) was not a formal publication, however, and its nomenclature was never fully adopted in the published literature.

Early and important palynology work by Leopold and Crandell (1958), Hansen and Mackin (1949), and Hansen (1938) documented the climatic transitions within the interglacial deposits and used pollen to confirm glacial/interglacial conditions and transitions.

Table 2-1. Early Stratigraphy for the Northern, Central, and Southeastern Puget Lowland

Northern Puget Lowland Stratigraphy[1]	Seattle Area[2]	Southeastern Puget Lowland Stratigraphy[3]
• Vashon Drift • Quadra Sand/Olympia Interglaciation deposits* • Possession Drift • Whidbey Formation • Double Bluff Drift	• Vashon Till • Lawton Formation • Klinker Till or "Mid-Cliff Till" • Duwamish Formation • Beacon Till or "Sea Level Till"	• Vashon Drift • Kitsap Formation • Salmon Springs Drift with Lake Tapps Tephra • Puyallup Formation • Stuck Drift • Alderton Formation • Orting Drift

[1]Easterbrook et al., 1967; Armstrong et al., 1965*
[2]Stark and Mullineaux, 1950
[3]Crandell et al., 1958

In the northern Puget Sound area, Easterbrook et al. (1967) identified three glacial advances on Whidbey Island: from oldest to youngest, they named them the Double Bluff, the Possession, and the Vashon. Intervening interglacial periods consisted of the Whidbey and Quadra Formations (Easterbrook et al., 1967; Table 2-1). Correlation with the previously defined "southern" stratigraphy of Crandell et al. (1958) using absolute dating did not exist, but many subsequent investigators used superposition to correlate the Possession and Double Bluff glacial advances with the Salmon Springs and Stuck drifts. In the absence of absolute dating, correlation with the previously defined "southern" stratigraphy of Crandell et al. (1958) was only possible using superposition, which many subsequent investigators employed

The bulk of the absolute ages available for the northern Puget Lowland were produced by Easterbrook and colleagues through the 1980's and 1990's (Easterbrook, 1986; Easterbrook, 1994; Easterbrook and Briggs, 1979; Easterbrook and Rutter, 1981, 1982; Easterbrook et al., 1988, 1992; Kovanen and Easterbrook, 2001). Additional chronology data for the northern Puget Lowland were produced by Armstrong et al. (1965), Westgate et al. (1987), Blunt et al. (1987), Clague (1981), Clague et al. (1997), Kovanen (2002), Dethier et al. (1995), Hicock and Armstrong (1981), and Hicock and Armstrong (1985). This work, particularly on Whidbey Island defined a "northern Puget Lowland" stratigraphy and type sections.

Most of the region's published age control information appeared after Rigg and Gould (1957) had already determined a limiting age for the end of the Vashon stade. The "Olympia Interglaciation" was defined by Armstrong et al. (1965) with only a few limiting radiocarbon ages recognizing it as the pre-Vashon interglacial stage; later Troost (1999) and Troost et al. (2005) provided clarification of the characteristics and far more extensive radiocarbon age control on the Olympia interglacial period, recognizing that the lower boundary of such deposits lies beyond the range of radiocarbon dating. Mullineaux et al. (1965) defined stratigraphic members of the Vashon stade in the Seattle area and provided limited radiocarbon age control. Porter and Swanson (1998) utilized new and existing radiocarbon ages to constrain the dates of advance and retreat of the Vashon ice sheet. Several geological consultants working in the Seattle and South Snohomish County area have subsequently contributed many 14C ages on Vashon-age and Olympia-age deposits during the past two decades.

Newly developed amino-acid dating was used in 1981 and 1987 (Easterbrook and Rutter; Blunt et al.) to date the Double Bluff Drift, Whidbey Formation, and Possession Drift.

Thermoluminescence was used in the early 1990's (Easterbrook et al., 1992; and Easterbrook, 1994) to provide ages for the Double Bluff Drift and Whidbey Formation.

In the southeastern Puget Lowland, Crandell et al. (1958) developed a stratigraphy parallel to that of the four glaciations identified in the Midwestern US (Nebraskan, Kansan, Illinoian, Wisconsinan) of the mid-20th century. Crandell et al. (1958) also created type sections for this region. Additional age control in the Southern Puget Lowland was subsequently added by Easterbrook (1994), Easterbrook and Briggs (1979), Westgate et al. (1987), Easterbrook et al. (1992), Easterbrook (1986), Easterbrook et al. (1988), Troost (1999), and Borden and Troost (2001). Chronology techniques included 14C, fission track, laser-argon, paleomagnetism, infrared-stimulated luminescence (IRSL), and ash chemistry. In particular, several of these studies demonstrated that the Salmon Springs Drift and older units were deposited during the Matuyama reversed polarity chron and so older than 780 ka. These included laser-argon techniques on ash and pumice in the Alderton and Puyallup Formations (Easterbrook et al., 1992; Easterbrook, 1994), fission-track dating of the Lake Tapps Tephra (Easterbrook and Briggs, 1979; Easterbrook et al., 1981; Westgate et al., 1987), and magnetostratigraphy (Easterbrook, 1986). These findings contradicted an earlier publication that asserted a relatively young age to this stratigraphic sequence, based on an apparently erroneous radiocarbon age (78 ka; Stuiver et al., 1978).

By the end of the 1990's a few of the oldest stratigraphic units exposed in the Puget Lowland had at most one or two absolute dates, young units (Vashon and Olympia) had multiple dates, and some units still had no age control at all and so were identified and mapped based solely on the principles of superposition. Uncertainty ranges in excess of 100,000 years were common for some of the dates obtained on the pre-Vashon units. This compilation of previously published ages included a data gap in the known ages of exposed Quaternary deposits—between the 200 ka Double Bluff Formation and the reversely magnetized deposits identified in the southern Puget Lowland and so area presumed to be older than 780 ka.

From the previous publications, till and outwash deposits throughout the Puget Lowland were positively attributed to the Possession-age glacier at only three locations, none of which are at the type section on Whidbey Island. In many locales, however, deposits that appear to represent multiple glacial advances are present and separated by interglacial deposition and weathering or by unconformities. Thick outwash, glaciomarine drift, glaciolacustrine units, and tills are common facies in these exposures and in subsurface explorations. Despite this evidence of multiple glacial advances and intervening nonglacial periods, none of these pre-Vashon-age deposits have heretofore been correlated with any named (or unnamed) glacial or interglacial period.

2.2 Problems with the early correlations of Quaternary deposits

One of the reasons for ambiguities in the stratigraphic nomenclature in the Puget Lowland is the assumption of consistent time-stratigraphic units, whereas many time-transgressive units are present in reality. For example, depositional transitions occur with the onset of glacial climate and with the ending of glacial climate. Over time in response to an advancing ice sheet and associated isostatic response, a fresh-water lake deposit could transition to a glaciomarine unit and then to a glaciolacustrine unit, undergoing gradual changes in grain size, pollen content, other fossil content, and chemical composition. Other problems in stratigraphic nomenclature and its assignment to particular outcrops include the abundance of unrecognized unconformities and the general absence of absolute age dating. Errors in correlation have contributed to the confusion.

Several different correlation charts that endeavored to display the relationship between Quaternary stratigraphic units in the northern and southern Puget Lowland were published between the 1950s and 1980s. The chart published by Woodward et al. (1995), for example, shows some of the correlation problems resulting from incomplete stratigraphic information and inadequate age control (Table 2-2). Many errors came from workers assigning nomenclature by counting down from the top of a stratigraphic section, potentially unaware of the abundance of unconformities in the stratigraphic record.

Two of the most widely confused and mis-correlated units are the “Salmon Springs Drift” and “Kitsap Formation” (Table 2-2). For decades, the Salmon Springs deposits at the type section were thought to represent the penultimate glaciation in the southern Lowland (Crandell et al., 1958 and Luzier, 1969). Subsequent dating, however, proved that the Salmon Springs Drift was on the order of 1 Ma (Easterbrook, 1994; Westgate et al., 1987), making this a very unlikely candidate for the penultimate ice advance into the region. Salmon Springs Drift was also considered the “sea level” drift by many workers, and so (for example) glacial drift exposed at sea level around Tacoma was automatically labeled thusly in numerous geological maps from the mid-1900s (i.e., Waldron, 1962; Molenaar, 1965; Walters and Kimmel, 1968; Noble, 1990).

Table 2-2. Correlation Chart from Woodward et al., 1995

	Climate units & approximate Age[1]	Island County[3]	Snohomish County[4]	N.W. King County[5]	S.W. King County[6]	Pierce County[7]	Kitsap Peninsula[8]	Mason County[9]	Thurston County[10]	Jefferson County[11]	Seattle[12]
	HOLOCENE		Younger and Older Alluviums	Sedimentary Deposit, Peat	Peat, Alluvium	Alluvium Peat	Alluvium	Alluvium	Alluvium		
PLEISTOCENE	10,000										
	FRASER GLACIATION	Glacial-marine Drift, Recessional Outwash Till Advance Outwash [2]Esperance Sand	Marysville Sand; Arlington Gravel; Stillaguamish Sand Members of Vashon Drift Till Advance & Esperance Sand	Recessional and Delta Outwash Till Advance Outwash ?	Recessional Outwash Till Ice-marginal Deposits Advance Outwash	All phases of Vashon Drift (Recessional & Advance Outwash, Till)	Recessional Outwash Till [2]Esperance Sand Advance Outwash	Recessional Outwash Till Advance Outwash	Recessional Outwash [1,2] Till Advance Outwash	Recessional Outwash Till Advance Outwash	Till Advance Outwash
	23,000										
	OLYMPIA INTER-GLACIATION	Quada Formation	Pilchuck Clay Member	Unnamed Sand Upper Clay	Salmon Springs Drift		Colvos Sand	Kitsap Formation	Kitsap Formation	Undiffer-entiated	Lawton Formation
	60,000										
	POSSESSION GLACIATION	Possession Drift	Undifferentiated Till	Unnamed Gravel		Colvos Sand, Salmon Springs Drift					Klinker Till, Beacon Till, Duwamish Formation
	80,000										
	WHIDBEY INTER-GLACIATION	Whidbey Formation	Admiralty Clay	Lower Clay	Puyallup Formation	Kitsap Formation Puyallup Formation	Kitsap Formation				
	>100,000										
	DOUBLE-BLUFF GLACIATION	Double Bluffs Drift			Intermediate Drift	Stuck Drift?	Salmon Springs Drift	Salmon Springs Drift	Salmon Springs Drift[1,2]		

[1] Based on Marine Isotope Curve of Martinson and Others (1987) and dating work of Easterbrook (1982)
[2] Esperance Sand – Member
[3] Easterbrook, 1968
[4] Newcomb, 1952
[5] Liesch and Others 1963
[6] Luzier, 1969
[7] Walters and Kimmel, 1968
[8] Garling, Molenaar, et al., 1965
[9] Molenaar, and Noble, 1970
[10] Grimstad and Carson, 1981
[11] Grimstad and Carson, 1981

The Kitsap Formation was named by Sceva in 1957, defined by a type section at Maplewood near the Pierce/Kitsap County line, but without any age control. Deeter (1979) described this formation as having two glacial drifts separated by an interglacial unit, inconsistent with the time-stratigraphic nomenclature used by his contemporaries in the Puget Lowland naming individual glacial drifts or interglacial packages. The term, Kitsap Formation, was subsequently loosely applied to interglacial deposits and fine-grained deposits below the Vashon drift throughout the central and southern Puget Lowland. Subsequently, Deeter (1989, personal communication) stated that the term "Kitsap Formation" should be abandoned due to the grouping of different stratigraphic units, and later mapping has uniformly abandoned this term (including that encompassing the original type section; Booth and Troost, 2005).

Deposits assigned to the Olympia interglaciation of Armstrong et al. (1965) have also been plagued by inconsistent nomenclature. Various authors have advocated for various names and a consensus had not been reached even as late as the early 2000's, with such alternatives as the Olympia beds (Minard and Booth, 1988), Olympia Formation, Olympia nonglacial deposits, Olympia interglacial deposits, Quadra Formation, Pilchuck Clay Member, Transition beds, and Discovery interglacial unit (see Noble, 1990 for a comprehensive overview). The type section for the Olympia interglaciation is at South Beach at Fort Lawton in Discovery Park (Mullineaux et al., 1965). Curiously, however, the name was derived from thick deposits on the west valley wall above the Nisqually River near Olympia, WA (as reported by Noble, 1990). Radiocarbon ages acquired at this and other localities throughout the Puget Lowland have demonstrated that these deposits are correlative in age with MIS 3, and represent interglacial conditions in the Puget Lowland. They are herein renamed the Olympia Formation (Chapter 5).

Yet another challenge with the Quaternary nomenclature in the Puget Lowland is the abundance of local names for undated deposits that have been identified at many outcrops on the basis of lateral continuity, lithology and weathering characteristics within a given map area. While this is an appropriate mapping method when absolute age control is absent, it confounds regional correlation efforts; it runs the risk of spurious local correlations as well.

2.3 Review of Existing Data

Hundreds of publications in combination from previous workers present a rich but ambiguous description of the Quaternary stratigraphy of the Puget Lowland. The work is summarized as shown on Table 2-3 and as described below. The type sections for these geologic units are shown on Figure 2-1.

Table 2-3. Simplified Stratigraphic Column from Prior Studies

Geologic Unit	Reference	Age (ka)	Age Method
Vashon Drift	Armstrong et al., 1965	25-13.5	^{14}C
Olympia Interglacial Deposits	Armstrong et al., 1965 Troost, 1999	35-15 > 45-15	^{14}C
Possession Drift	Easterbrook and Rutter, 1981	~80	Amino Acid
Whidbey Formation	Easterbrook and Rutter, 1981; Easterbrook, 1994	107-96 151-102	Amino Acid Thermoluminescence
Double Bluff Drift	Easterbrook and Rutter, 1982; Blunt et al., 1987; Easterbrook et al., 1992	250-150 178-111 291-177	Amino Acid Amino Acid Thermoluminescence
Salmon Springs Drift	Easterbrook, 1994	1000	Inferred from Tephra
Lake Tapps Tephra	Easterbrook and Briggs, 1979; Westgate et al., 1987	840 1000	Fission Track Fission Track
Puyallup Formation	Easterbrook et al., 1992	1690-1640	Laser Argon, Reversely Magnetized
Stuck Drift	Easterbrook, 1994	~1600 >1000	Reversely Magnetized
Alderton Formation	Easterbrook, 1994	2400-1000	Laser Argon
Orting Drift	Easterbrook, 1986	2000?	Reversely Magnetized

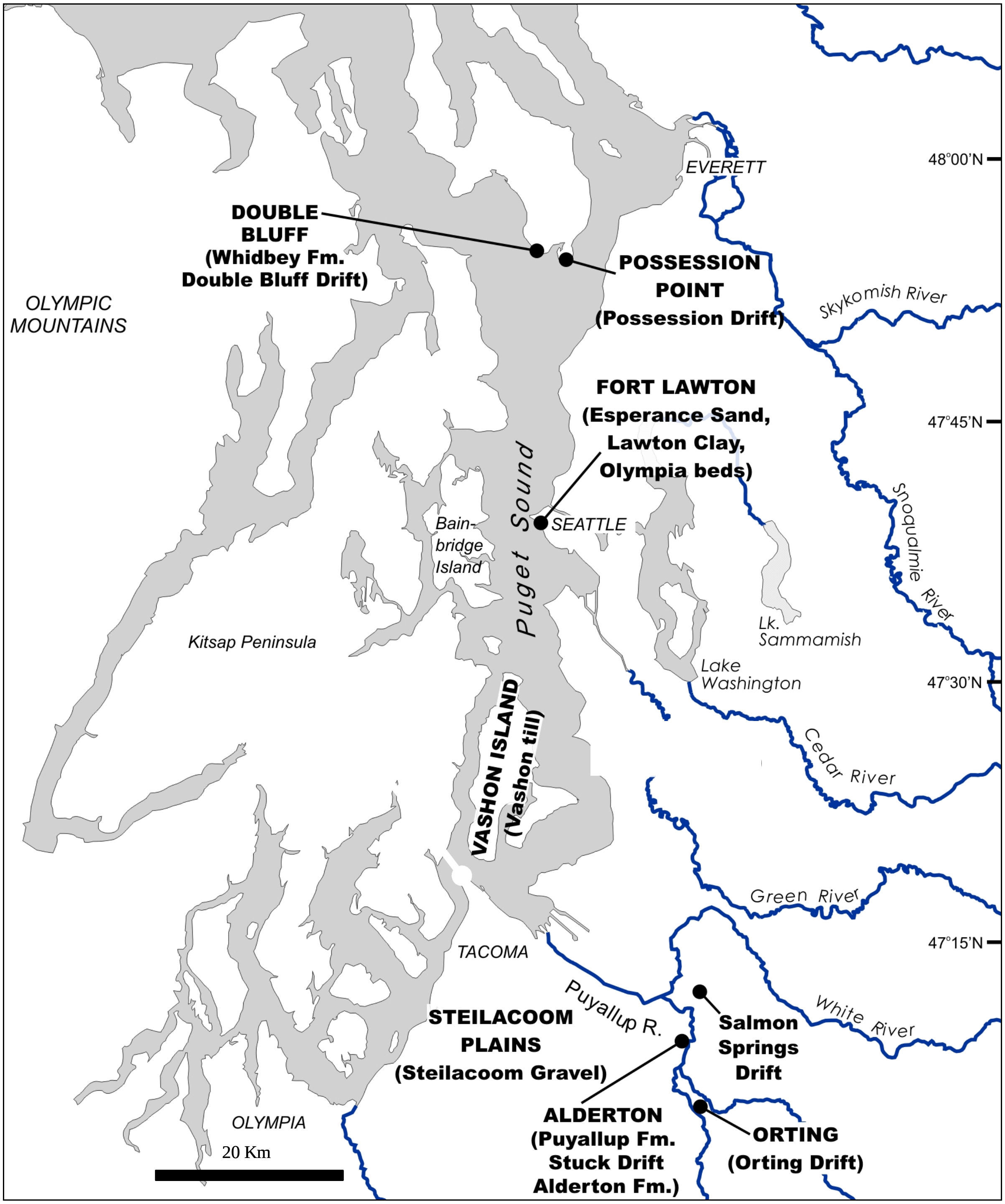


Figure 2-1. Type section locations for stratigraphic units identified from 1898 through 1968. Table 2-4 contains the reference information for the type sections.

Early radiocarbon dates placed the age of the Possession Drift at 34,980 and 47,600 ^{14}C yr BP (Easterbrook, 1969; Hansen and Easterbrook, 1974) and correlated the Possession Drift in the northern Puget Lowland with the Salmon Springs Glaciation in the southern Puget Lowland (Easterbrook et al., 1967). Subsequent amino acid dating on shells in Possession glaciomarine drift at Blowers Bluff, Port Williams, and Stillaguamish (Easterbrook and Rutter, 1981 and 1982; Blunt et al., 1987) produced an average age of 80 ± 22 ka.

Age determinations on the Whidbey Formation on Whidbey Island include amino-acid dates on shells of 96 ± 35 ka, 97 ± 35 ka, and 107 ± 9 ka (Blunt et al., 1987); and four thermoluminescence ages ranging from 102 ± 38 ka to 151 ± 43 ka (Berger and Easterbrook, 1993; Easterbrook, 1994).

A broad range of ages have been obtained in the Double Bluff Drift: thermoluminesence dating of clay beneath Double Bluff glaciomarine drift yielded ages of 289 ± 74 ka and 291 ± 86 ka, an age of 320 ±100 ka was obtained on clay in the Double Bluff Drift, and amino acid dating of shells in the glaciomarine drift range from 111 to 178 ka (Easterbrook and Rutter, 1981; Easterbrook and Rutter, 1982; Blunt et al, 1987; Easterbrook et al., 1992).

Based on these dates and additional dating during my research, tentative correlations can be made between the third-oldest glaciation on Whidbey Island, the “Double Bluff” glaciation, with MIS 6; the overlying Whidbey Formation with MIS 5; the Possession Drift with MIS 4; and deposits of the Olympia nonglacial interval with MIS 3 (Figure 2-2).

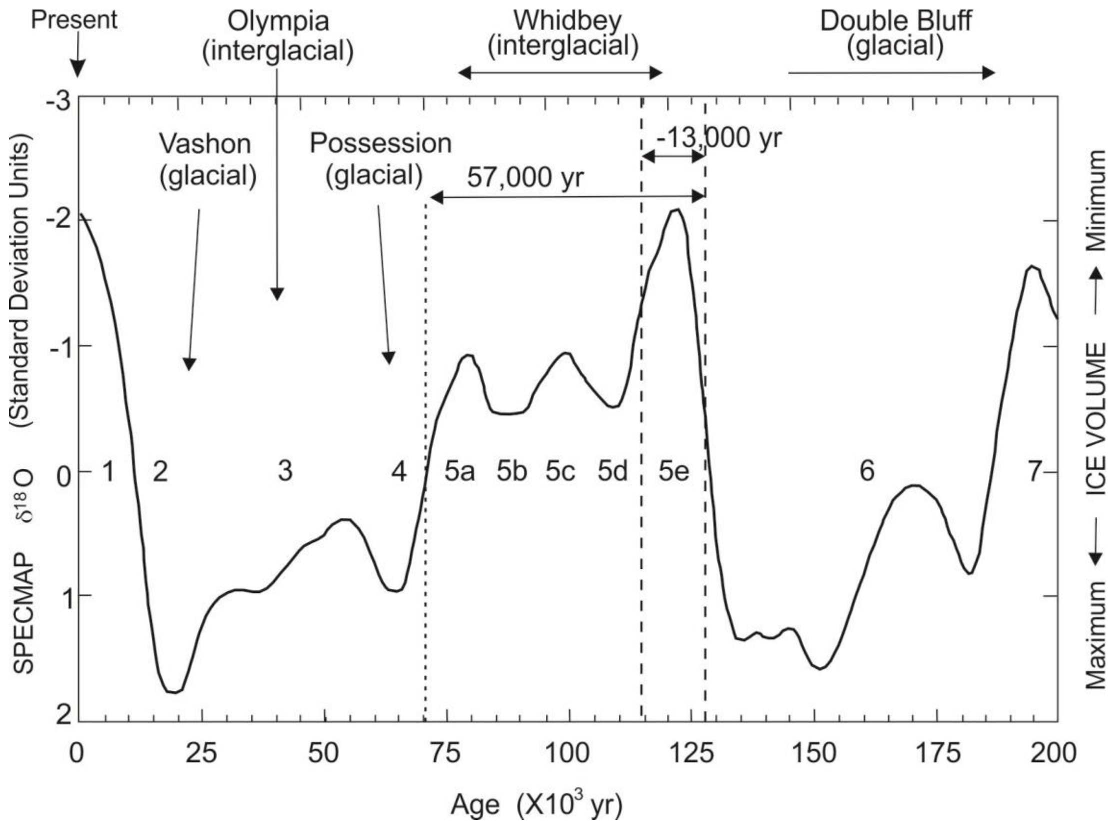


Figure 2-2. Marine Oxygen Isotope Stages (numbers 1 through 7) vs. mid to late Pleistocene Stratigraphic Units. Modified from Winograd et al., 1997.

The Possession glaciation is the second oldest lowland glaciation recognized in the central Puget Lowland, the youngest being the Fraser glaciation. Based on an amino acid age of 80 ka by Easterbrook and Rutter (1981), the Possession glaciation correlates with Marine Oxygen Isotope Stage (MIS) 4. The third oldest glaciation is the Double Bluff glaciation during MIS 6, first identified by Easterbrook et al. (1967). These glacial periods are separated by interglacial periods; deposits correlative with MIS 5 are named the Whidbey Formation, and deposits correlative with MIS 3 are named Olympia beds.

2.4 Summary of the History of Nomenclature and Evolution of Pleistocene Nomenclature in the Puget Lowland

The glacial geology of the Puget Lowland was first recognized by Willis (1898) and Bretz (1913). Willis (1898) identified the first stratigraphic units in the Puget Lowland - the Vashon till named for extensive upland deposits on Vashon Island, the Puyallup Sand near Alderton, and the Orting Gravel near Orting, WA (Figure 2-1). Bretz (1913) and Willis (1898) identified the Steilacoom gravel, forming the Steilacoom Plain, from or reworked by discharge from glacial Lake Puyallup.

Further stratigraphic differentiation was not published until the 1950s. In 1957, Armstrong recognized and named the Sumas glaciation in Canada near Sumas, WA. While Armstrong was working in the north, Crandell et al. (1958) were working in the southern Puget Lowland. Crandell et al. (1958) named the Salmon Springs Drift near Sumner; the Puyallup Formation, the Stuck Drift, and the Alderton Formation near Alderton; and the Orting Drift near Orting, WA. Crandell (1963) further recognized the Lake Tapps Tephra near Sumner at the type section of the Salmon Springs Drift.

Mapping and stratigraphic assignments continued in the 1960s. Easterbrook (1963), working in the northern Puget Lowland, named the Sumas Drift as a late stage of the most recent ice-sheet advance. Crandell (1963) working in the southeastern Puget Lowland, named the Evans Creek Drift of the Evans Creek stade of the Fraser Glaciation, designating an early advance of valley glaciers from the Cascade Range prior to the maximum advance of the Cordilleran Ice Sheet. In 1965, Armstrong et al. formally subdivided the Fraser glaciation into the Vashon Drift and Vashon stade, clarifying the early work of Willis; the Sumas stade; and the Everson interstade and Everson Glaciomarine Drift. Also in 1965, Mullineaux et al. further subdivided the Vashon Drift to include the Esperance Sand Member and the Lawton Clay Member, both named for deposits at Discovery Park in Seattle, WA (Figure 2-1). Armstrong et al. (1965) identified the Olympia interglaciation, also at Fort Lawton. Then in 1967, Easterbrook et al. identified and named the Possession Drift, the Whidbey Formation, and the Double Bluff Drift, for outcrops on Whidbey Island.

In the 1970's and 1980's geologic mapping efforts continued in the Puget Lowland, but few tools were available to recognize many new stratigraphic units that were either coincident in time with previously named deposits in other localities, or that predated named deposits but without clear stratigraphic relationships. Hicock (1976) recognized the Coquitlam Drift in Port Moody, Canada for deposits dating about 25 to 30 ^{14}C ka BP. Hicock et al. (1982) also recognized the Port Moody nonglacial deposits of the Port Moody interstade. Later Hicock and Armstrong (1985) identified the Coquitlam stade. Working on presumably similarly-aged deposits in an equivalent stratigraphic position, Minard and Booth (1988) informally named them the Olympia beds, a name that has persisted to the present.

In subsequent decades, absolute age data was published for many of the aforementioned recognized stratigraphic units. In the early 2000's, Troost et al. (2005) began the present effort on stratigraphic and age control, recognizing new glacial drifts and interglacial deposits described in later chapters (Table 2-4).

Table 2-4. Summary of Type Section and Age Data

Name (Climatic intervals in italics)	Type Section Location	Reference for Nomenclature	Reported Age (in 103 years)	Type of Date	Location	Reference for Age	Comment
Sumas glaciation	Near Sumas, Canadian side	Armstrong, 1957	na	na	na	na	na
Sumas Drift		Easterbrook, 1963	11.3–10.0 and pre 11.9	14C	Aldergrove–Fort Langley and Chilliwack R. valley, B.C.	Clague et al. 1997	New dates
			11.5–10.0	14C	Multiple locations, Fraser Lowland and Nooksack valley	Kovanen and Easterbrook, 2001; Kovanen, 2002	Compilation and new dates; table of 69 dates on the Sumas interval
Sumas stade		Armstrong et al., 1965	na	na	na	na	na
Everson Glaciomarine Drift, *Everson interstade*	Upstream of Everson, on the Nooksack R.	Armstrong et al., 1965	13.0–11.0	14C	Type section	Armstrong et al., 1965	New dates
			13.0–11.5	14C	Whidbey Is. to Campbell R.	Kovanen and Easterbrook, 2001	Compilation and new dates
			13.6–11.3	14C	Northern Puget Lowland	Dethier et al., 1995	New dates
	Southeast of Cedarville on the Nooksack R.	Easterbrook, 1963	na	na	na	na	Includes the Kulshan glaciomarine drift, Deming Sand, and Bellingham glaciomarine drift
Vashon till, *Vashon glaciation*	Vashon Island	Willis, 1898	>13.5	na	na	Rigg and Gould, 1957	Youngest limiting age

Name (Climatic intervals in italics)	Type Section Location	Reference for Nomenclature	Reported Age (in 103 years)	Type of Date	Location	Reference for Age	Comment
Vashon Drift, *Vashon stade*		Armstrong et al., 1965	25.0–13.5	14C	Multiple, Strait of Georgia to Lake Washington	Armstrong et al., 1965	New dates
			18.0–13.0	14C.	Fraser Lowland	Kovanen and Easterbrook, 2001	Compilation
			16.0–13.5	14C	Seattle, Bellevue, Issaquah	Porter and Swanson, 1998	Compilation and new dates
Steilacoom Gravel	Steilacoom plains	Willis, 1898; Bretz, 1913; Walters and Kimmel, 1968	Younger than 13.5	14C	Ft. Lewis, Tacoma	Borden and Troost, 2001	Multiple, young, sub–Vashon dates
Esperance Sand Member of Vashon Drift	Fort Lawton, Seattle	Mullineaux et al., 1965	15.0–13.5; 15.0–14.5	14C	Seattle; Issaquah	Mullineaux et al., 1965; Porter and Swanson, 1998	Limiting ages
Lawton Clay Member of Vashon Drift	Fort Lawton, Seattle	Mullineaux et al., 1965	15.0–13.5; 15.0–14.5		Seattle; Issaquah	Mullineaux et al., 1965; Porter and Swanson, 1998	Limiting ages
Port Moody nonglacial deposits	Port Moody	Hicock et al., 1982	23.0–21.0	14C	Port Moody	Hicock and Armstrong, 1981	New dates
Port Moody interstade					Port Moody	Hicock and Armstrong, 1985	Interstade informally introduced
Coquitlam Drift	Coquitlam–Port Moody	Hicock, 1976	21.7–18.7	14C	Type section	Hicock and Armstrong, 1981	New dates
Coquitlam stade		Hicock and Armstrong, 1985	30.0–25.0	14C	Multiple locations	Hicock and Armstrong, 1985	Compilation of 52 dates

Name (Climatic intervals in italics)	Type Section Location	Reference for Nomenclature	Reported Age (in 103 years)	Type of Date	Location	Reference for Age	Comment
			26.0–17.8	14C	Multiple locations	Clague, 1980; Armstrong et al., 1985	Equivalent to Evans Creek stade?
Evans Creek Drift, *Evans Creek stade*	Carbon River valley, near mouth of Evans Creek	Crandell, 1963;	25.0–15.0	14C	Type section	Armstrong et al., 1965	Alpine glaciation in Cascade Range
		Armstrong et al., 1965 (Crandell)	na	na	na	na	na
Olympia interglaciation	Fort Lawton	Armstrong et al., 1965	35.0–15.0	14C.	Fort Lawton and multiple locations in WA and BC	Armstrong et al., 1965 Troost, 1999	Compilation and new dates; may be partly equivalent to Quadra sediments at Point Grey in Vancouver (Armstrong and Brown, 1953)
			24.0–15.0	14C.	Fort Lawton and West Seattle	Mullineaux et al., 1965	New dates
Olympia beds		Minard and Booth, 1988	>45–13.5	14C	Multiple locations around Seattle and Tacoma	Troost, 1999; Borden and Troost, 2001	New dates
Possession Drift	Possession Point, Whidbey Island	Easterbrook et al., 1967	80	Amino acid	Multiple locations	Easterbrook and Rutter, 1981	New dates
Whidbey Formation	Double Bluff, Whidbey Island	Easterbrook et al., 1967	107–96, avg = 100; 151–102	Amino acid; Thermo–luminescence	Multiple locations	Easterbrook and Rutter, 1981; Easterbrook, 1994	New dates

Name (Climatic intervals in italics)	Type Section Location	Reference for Nomenclature	Reported Age (in 103 years)	Type of Date	Location	Reference for Age	Comment
Double Bluff Drift	Double Bluff, Whidbey Island	Easterbrook et al., 1967	250–150; 178–111; 291–177	Amino acid; Amino acid; Thermo–luminescence	Type section	Easterbrook and Rutter, 1982; Blunt et al., 1987; Easterbrook et al., 1992	New dates
Hamm Creek Interglaciation Hamm Creek Ash	Hamm Creek, Southwest Seattle	Troost et al, 2005	200 +/-10	Argon/argon	Type section	Troost et al, 2005	New unit, equivalent to MIS 7, also found in Snohomish County
Defiance glaciation Defiance drift	Point Defiance, Tacoma	Troost et al, 2005	225-250	IRSL	Type section	Troost et al, 2005	New unit, equivalent to MIS 8
Salmon Springs Drift	Near Sumner	Crandell et al., 1958	1000	Inferred, based on Lake Tapps	Type section	Easterbrook, 1994	Reversely magnetized (Easterbrook, 1986)
Lake Tapps Tephra	Near Sumner	Crandell, 1963; Easterbrook and Briggs, 1979	840	Fission track;	3 locations	Easterbrook and Briggs, 1979	Correlation of other locations to type section based on chemistry
			1000	Fission track	Multiple locations	Westgate et al., 1987	na
Puyallup interglaciation, Puyallup Sand	Near Alderton	Willis, 1898	1690-1640	Laser–argon	Type section	Easterbrook et al., 1992	New date; reversely magnetized (Easterbrook, 1986)
Puyallup Formation		Crandell et al., 1958	na	na	na	na	na

Name (Climatic intervals in italics)	Type Section Location	Reference for Nomenclature	Reported Age (in 103 years)	Type of Date	Location	Reference for Age	Comment
Stuck Drift	Near Alderton	Crandell et al., 1958	Close to 1600	Based on bounding ages	Type section	Easterbrook, 1994	Reversely magnetized (Easterbrook, 1986)
Alderton Formation	Near Alderton	Crandell et al., 1958	2400-1000, avg. = 1600	Laser–argon	Type section	Easterbrook, 1994	Reversely magnetized (Easterbrook, 1986)
Orting Gravel, Orting Drift	Orting	Willis, 1898; Crandell et al., 1958	2000 (?)	Inferred	Type section	Easterbrook, 1986; Easterbrook et al., 1988	Reversely magnetized (Easterbrook, 1986)

2.5 Definitions of the Whidbey interglaciation and the Olympia nonglacial interval

Easterbrook et al. (1967) defined the Whidbey Formation as low-energy deltaic deposits from the ancestral Snohomish River. These deposits were laid down during the Whidbey interglaciation, which has been dated from about 125 to about 80 ka (Easterbrook and Rutter, 1981) and is correlative with MIS 5. Age-correlative deposits are known to exist in the Seattle area and Southern Puget Lowland (Troost and Booth, 2008). While they are not deltaic deposits from the ancestral Snohomish River, they are none-the-less from similar depositional environments. If we presume that the Whidbey Formation is a time-stratigraphic unit rather than a litho-stratigraphic unit, then the age-correlative deposits away from Whidbey Island should also be included as part of the Whidbey Formation.

Based on an evaluation of depositional environments from Whidbey-age deposits in Seattle and nearby areas, environments and temperature were similar to today, and include peat bogs, river valleys with flood plains, low-gradient low-lying areas, lakes, estuaries, and drumlinized relatively flat uplands with steep slopes. During Whidbey time, reworking and redistribution of Double Bluff glacial deposits was occurring as was mixing of glacial deposits with alluvial deposits in streams from the Washington Cascades. Although there were fluctuations, sea level during part of MIS 5e was higher than modern sea level by up to 6 m (Lambeck et al., 2002). Streams in the Seattle area would have been graded to a base level similar to modern base level–namely, that of Puget Sound.

The Olympia nonglacial interval (Armstrong et al., 1965) was defined as "the climatic episode immediately preceding the last major glaciation, and represented by nonglacial strata beneath Vashon Drift." The type section is at Fort Lawton at Discovery Park in Seattle (Figure 2-1 and Table 2-4). If we presume that deposits that accumulated during the Olympia interglaciation are part of a time-stratigraphic unit rather than a litho-stratigraphic unit, then the age-correlative deposits away from Fort Lawton are also Olympia nonglacial deposits and should be considered part of the Olympia Formation.

The Olympia nonglacial interval spanned the time period from about 70 to 15 ka (Troost, 1999; Mahan et al., 2003), the time between the Possession glaciation and the Vashon glaciation, and it correlates with MIS 3 (Figure 2-2, and Table 2-4). In many parts of the world, glaciers were still near their maximum extend, and so sea level was still significantly lower than today. However, the Puget Lowland was ice-free for most of that time (Troost, 1999; Troost and Booth, 2008: Booth et al., 2004b). Evidence for alpine glaciation during MIS 3 from the Cascades has been described by Crandell (1963) and Armstrong et al. (1965) for the Evans Creek Drift at the Carbon River; and by Hicock (1976) and Hicock and Armstrong (1985) for the Coquitlam Drift at Port Moody. As during the Whidbey interglaciation, reworking and mixing of glacial deposits and Olympia-age alluvium continued. During the 55,000 years of the Olympia nonglacial interval, landscape stability in the lowlands was approached, but variations in sea level presumably caused changes in base levels.

Sea level during the coldest part of the Olympia nonglacial interval (about 40,000 years ago) was about 65 m (213 ft) lower than today (Lambeck et al., 2002), so the amount of relief on the pre-Vashon topography is perhaps 500 m (1600 ft) across the Puget Lowland (Troost, 2006), with narrow channels and ridges and broad troughs. Puget Sound is as much as 300 m deep but averages about 100 m deep while the elevation of the uplands near the perimeter is about 200 m (600 ft). Many Puget Lowland troughs are approximately 65 m (200 ft) deep (Troost, 2006) consistent with the maximum low sea level during the Olympia nonglacial interval.

2.6 Age of Volcanic Events

Little is known in the Puget Lowland about whether volcanic eruptions occurred during the times that ice occupied the Puget Lowland because of the incomplete record of both types of events. Old vents are destroyed with younger eruptions, and some volcanoes evolved during the Quaternary. In addition, volcanic deposits often get reworked and then are less continuous in the stratigraphic record. The predominant wind direction from nearby volcanic centers is to the east (Mass, 2008), so ash and pumice accumulation in the Puget Lowland is less common than in Eastern WA. Furthermore, the region's humid climate causes rapid alteration of volcanic materials such that most of the Pleistocene tephra deposits sampled have little original structure and composition left (Dr. Andre Sarna-Wojicki, USGS, 1999 and Dr. Richard Stewart, UW, 1999, personal communication).

Two volcanic events are known to have occurred during or right after a glaciation in the Puget Lowland. A Glacier Peak event, dating to 13,250 to 14,920 cal yr BP (BETA-WSU-155) based on a shell age in a lacustrine deposit 5 miles north of Soap Lake in Eastern Washington (Fryxell, 1965), and more precisely dated at 13,710–13,410 cal yr BP by Kuehn et al. (2009), occurred during the Vashon stade. Deposits of Glacier Peak ash were encountered in Vashon recessional lacustrine deposits in Lake Washington that date to (Troost, 2011). Troost (2011) determined that the glaciolacustrine period ended between 14,800 and 14,500 cal yr BP based on the age of marine inundation into the Lake Washington basin that occurred at this time.

The second volcanic event recognized to occur during a glacial period was first described by Crandell et al. (1958 and 1963), who noted that the Lake Tapps Tephra was overlain and underlain by Salmon Springs till. The Lake Tapps Tephra was initially dated by Easterbrook and Briggs (1979), using fission track methods, as 840 ka. Subsequent work by Westgate et al.

(1987) determined a more accurate age of 1 Ma, also using fission track methods.

Chapter 3 - Methods of New Data Acquisition

Multiple ice-sheet advances have traversed the central Puget Lowland during the Quaternary Period. In an area where each glacial and interglacial depositional sequence looks much like its predecessor, accurate stratigraphic identification cannot be accomplished using field observations alone and requires laboratory analyses and age determinations.

Many methods are needed to characterize and date the Quaternary deposits of the Puget Lowland, and those of Possession age are no exception. It was often necessary to identify and analyze deposits of the overlying Olympia beds and underlying Whidbey Formation to even recognize the Possession-age deposits. The following subsections describe the different techniques I have applied over the last two decades.

3.1 Methods of new data acquisition

My research has focused on determining if an MIS 4 glaciation did in fact advance into the Puget Lowland and, if so, determining its extent and depositional record, and the regional climatic conditions that were prevalent during this advance.

Identifying a pre-Vashon deposit requires the reconstruction of the majority of the exposed stratigraphic record above sea level, best exposed in the extensive shoreline bluff exposures that are most common along the central Puget Sound coastline. There are many tens of kilometers of such exposures, and their interpretation has required careful field mapping combined with extensive age control. The absence of either one (or both) of these activities in prior investigations has resulted in a rich history, over 60 years in the making, of misidentified chronological sections, misinterpreted ice-sheet advance chronologies, and published maps with misidentified geologic units.

3.2 Field Mapping

I have completed detailed field mapping of over 19 urban areas and USGS quadrangles to identify glacial deposits with the potential to correlate with the Possession glaciation. I constructed measured sections of appropriate locations to document the stratigraphic relationships and subsequent analyses (Figure 3-1). My mapping area has focused on coastal bluffs and deep ravines within the range of the Seattle uplift, Tacoma uplift, and Kingston arch (Pratt et al., 1997; Blakeley et al., 2002) as the most likely places to find pre-Fraser stratigraphic deposits. In addition, mapping and correlation work was also completed throughout the Tacoma basin and Seattle basin areas. The amount of chronological and lithological work varied by map area because of differences in the extent and quality of exposures, and also to some extent by the level of available funding. Measured sections were generally created at outcrops with more than one stratigraphic unit exposed and good access, with an overarching effort to get a broad geographic distribution of well-documented exposures across the central and southern Puget Lowland.

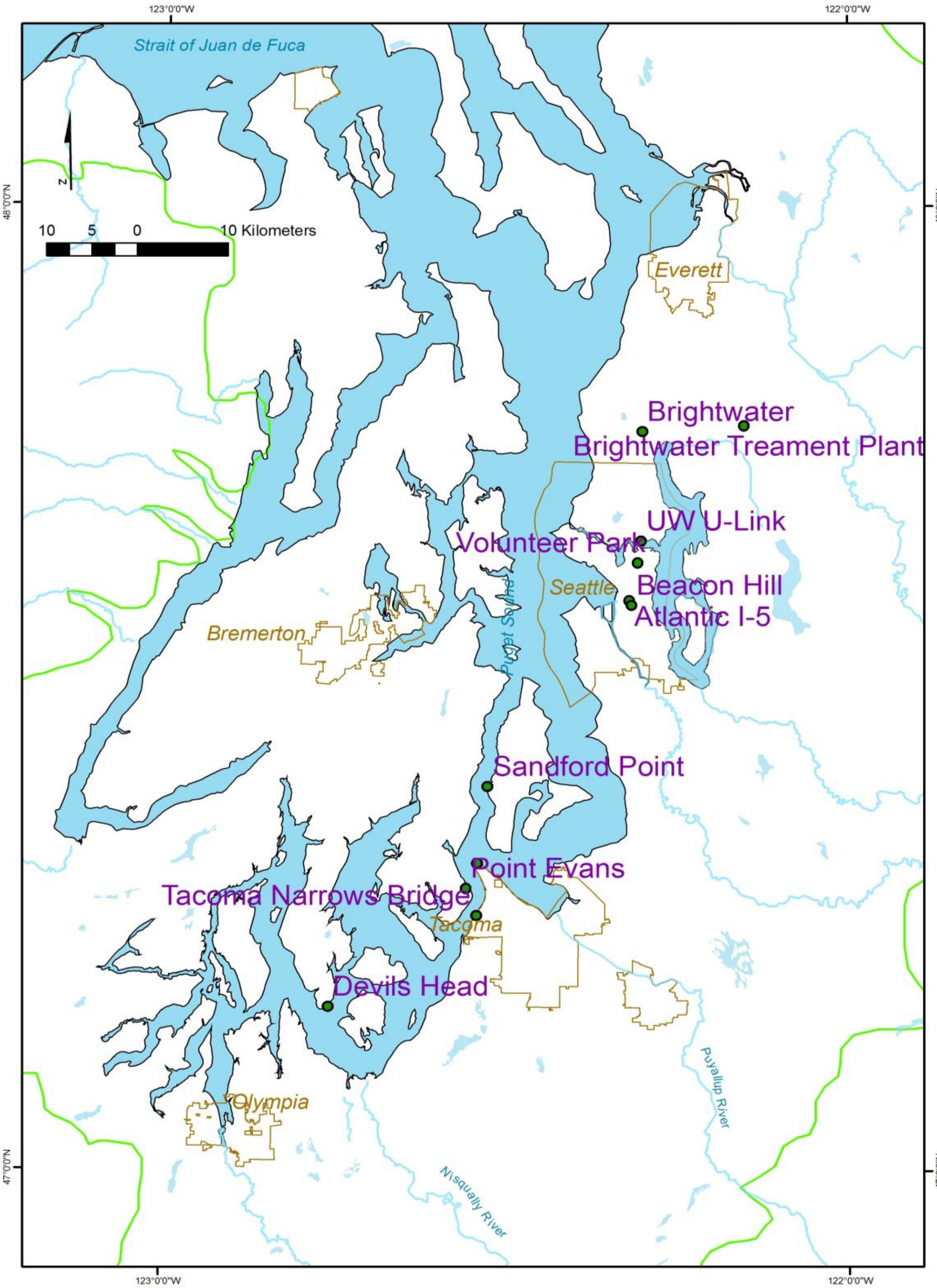


Figure 3-1. Map showing locations of measured sections.
Sections at solid circles, and labeled in purple. The green line shows the extent of the maximum extent of the Vashon-age ice sheet.

Although much of this work has been done in collaboration with other geologists, the stratigraphic mapping and analyses have been exclusively my work throughout this region. As a result of my stratigraphy and chronology work paired with outreach efforts, many regional practitioners began using geochronology since the late 1990's to help identify geologic materials. Some of the data presented here in were obtained by them, and noted as such.

3.3 Chronological Methods

When I first started this research, a mere handful of absolute dates existed and the published literature provided virtually no correlation to global climate and marine isotope stages. My first step was to correlate known stratigraphy, particularly existing type sections, with absolute age control. With this new chronological scale and new dating control, I then was able to start correlating deposits at outcrops to formal stratigraphic units. Absolute and relative age dating methods were used to identify Possession-age deposits, since age control is currently the only reliable means for positive correlation with the Possession Drift (Troost, 1999; Troost et al., 2003).

Samples were collected from across the Tacoma area for dating and analyses (Figures 3-2). Both absolute and relative age-dating methods were used to determine the ages of some of the Quaternary deposits mapped. Age control is currently the only reliable means for positive correlation with the Possession Drift; the absolute dating methods employed have included radiocarbon, Optically Stimulated Luminescence (OSL), and argon/argon. Relative dating techniques include paleomagnetic measurements, palynology, and provenance studies.

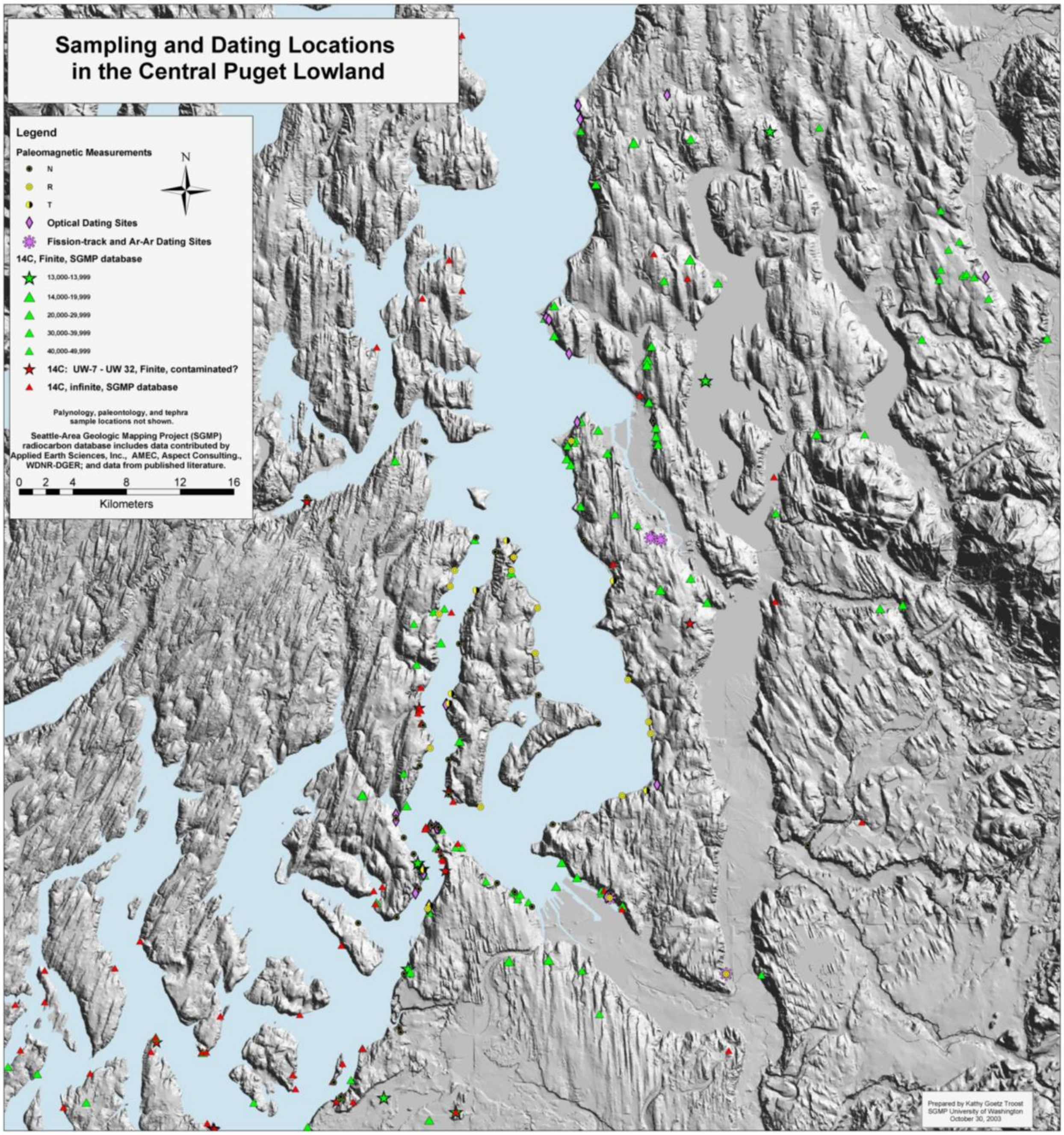


Figure 3-2. Map showing location of dating samples in the Seattle-Tacoma.

For absolute dating, I primarily used radiocarbon dating for unequivocal identification of overlying Olympia beds, and optically stimulated luminescence (OSL) for broader age ranges. Radiocarbon dating was used to determine the age of overlying deposits, thus constraining the upper age of deposits. OSL dating was used to identify deposits belonging to MIS 2, 3, 4, and older. Argon/argon (USGS Lab, Menlo Park, CA) and fission track methods (at the University of Washington) were utilized for dating pumice and ash layers in older deposits.

For relative dating, paleomagnetic measurements, palynology, and provenances studies were used for stratigraphic correlations across the Puget Lowland. Polarity measurements at outcrops of interest were provided by Jonathon Hagstrum of the USGS, Menlo Park, CA. Finding reverse polarity measurements correlating with the Blake subchron at about 110 ka helped identify Whidbey-age deposits at several locations in the Puget Lowland (Booth et al, 2004b; Hagstrum et al., 2002), providing a lower boundary on potential Possession-age deposits as well.

3.3.1 Radiocarbon Dating

Radiocarbon dating was used to identify younger (i.e., post-45,000 cal yr BP) Olympia beds and the Vashon Drift at measured sections and select outcrops. Carefully selected samples were submitted to Beta Analytic in Miami Florida and underwent full pretreatments to remove possible contamination from modern humic acids and organisms. Unless otherwise noted, samples were submitted by me, other radiocarbon dates were obtained by AESI, Aspect Consulting LLC, and Shannon &Wilson, Inc., but all used the same analytical laboratory, Beta Analytic, and similar pretreatment procedures. Samples were collected in the field, carefully cleaned under a microscope, sealed in aluminum foil, and then kept refrigerated until shipping to the laboratory. Care was taken to not introduce modern carbon. However some samples required pretreatment using acid-alkali-acid wash methods to remove humic acids. Standard radiometric dating was used when possible, and AMS was used in older materials or with smaller samples. For ages less than about 20,000 years, the age data were calibrated using INTCAL 98 and later using INTCAL13 (Stuiver et al., 1998).

As part of my study, sixty new samples were submitted for 14C dating.

3.3.2 Optically Stimulated Luminescence Dating

OSL dating was used to identify deposits belonging to MIS 2 through 8 as part of the mapping efforts. All optical laboratory dating was provided by Ms. Shannon Mahan of the USGS Thermoluminescence Laboratory in Denver, Colorado. She made several sampling trips to the Seattle-Tacoma-Everett area to collect material and calibrate dose rates from my sampling sites (Appendix B, Photographs 7, 34, and 35. In all 64 samples were analyzed for this study and an additional thirteen were analyzed for other work (Tables A-2 and A-3).

Samples for luminescence dating were collected in the field following standard sampling procedures to minimize potential exposure to light. Representative samples were obtained by excavating at least 35 cm into the face of an outcrop under an opaque black tarp or at night. Then one of two methods was used. If sampling sand, then an opaque 15-cm-long cylinder was driven into the sand at the back of the excavation to a depth greater than the length of the cylinder. The cylinder was carefully removed and caps taped on the ends. The tube was marked for orientation then wrapped in heavy duty aluminum foil. If sampling fine-grained sediment then a block, nominally 30 x 30 x 20 cm in dimension, was excavated, scored with orientation information, and wrapped immediately in multiple layers of heavy duty aluminum foil. For both material types, extra sample material was obtained for natural signal measurements. In the laboratory, aliquots were taken from the centers of each of the sample to further minimize the potential for contamination from light.

The methodology used was established by Mahan (Mahan et al., 2000 and 2003) and is summarized as follows. Although some prior workers have speculated that samples saturate out at 100-150 ka for IRSL, analytical procedures were used to minimize this problem, and the results show good correlation with independent stratigraphic relationships to about 300 ka. Following the work of Berger and Easterbrook (1993) and their subsequent recommendations we dated the fine-grained, polymineral component of the sample. The silt was run using blue TL and IRSL emissions. Samples were exposed to 4N HCl and 35% H_2O_2 before being separated in the lab to obtain the 4-11 micron size particles. A special form of the partial bleach method was used in which a heavy yellow filter (CS-3-67) covered the samples before exposure to a light source for bleaching tests. Comparisons were made of the natural signal acquired during burial with the artificial signals acquired from exposure of the sample to a beta source. In our studies we used the additive dose, multi-aliquot approach. We also tested for sub linearity responses in the samples, as this is a common complication in older samples. Elemental concentrations of K, U, and Th were measured on a low-level gamma spectrometer along with the addition of a cosmic ray component. These concentrations were then calculated together for a Dose Rate. Dose Rates for all deposits averaged 2.3 Grays/ka and these relatively low values might be one of the reasons that older ages can be obtained. Thermoluminescence ages that were in good agreement with magnetostratigraphic data marking the Blake event (110-125 ka) were recorded. Subsequent measurement of the same sample using infrared stimulated luminescence gave the same age results. Other ages ranging from 150 ka to 300 ka were also found to be reliable and to fit in well with current stratigraphy.

This method provided the means to obtain absolute age control for deposits ranging in age from 10,000 to 300,000 years old. Where possible, fine to medium-grained sands were selected for dating. However, fine-grained deposits were also dated using this technique when correlative coarse-grained deposit weren't available. An assumption inherent in luminescence dating is that the feldspar and quarts grains get totally bleached with exposure to ultraviolet radiation and that the age recorded in the lab is therefore the burial age. This is a reasonable assumption for fluvial deposits since bleaching can happen within seconds to tens of seconds for quartz and within hundreds of seconds for feldspar. For silt from lacustrine origins, this assumption is not as reliable and each sample requires careful consideration of the accumulated ionization signals and multiple test runs to obtain a reliable age.

3.3.3 Argon/argon Dating

Argon/argon methods were utilized for dating pumice in older deposits. Dr. Robert Fleck with the USGS in Menlo Park conducted the Ar/Ar analyses following the methods of Turrin et al. (2008) and Fleck et al. (1977). Three samples of pumice from exposures in Hamm Creek in the south Seattle area were dated using this technique. These samples were selected because of the unusually thick (2 m) deposit, apparently unaltered nature of the pumice, and extreme variations in elevation (65 m) between outcrops of the deposit within the Seattle fault zone.

3.3.4 Fission Track Dating

Fission track methods were utilized for dating pumice in two deposits in the southern Puget Lowland, one near North Puyallup and one at the base of the Woodworth quarry in Fife. These samples were selected for fission track dating because of the potential for finding apatite or zircon grains and the expected antiquity of the deposit. The late Dr. Richard Stewart conducted the fission track analyses at his laboratory at the University of Washington. Fission tracks come from the spontaneous fission of 238U in certain minerals as a rock cools. For rocks that cool quickly, the number of tracks and amount of 238U present can be used to calculate age.

3.3.5 Paleomagnetic Measurements

Paleomagnetic measurements were made to assist with stratigraphic correlations across Puget Sound particularly in the Tacoma area over the Seattle uplift. Over 93 polarity measurements were made during a 4-year period during several sampling trips by Dr. Jonathan Hagstrum of the USGS, Menlo Park, CA (Appendix B, Photograph 33). Of particular assistance was a unique reverse polarity correlating with the Blake subchron that has been instrumental in identifying Whidbey-age deposits in the Puget Lowland (Hagstrum et al., 2002).

Samples were collected in the field by first collecting site data, then by trimming a block of fresh material into cubic containers. The orientations of these cubes were recorded for later correction. At each of the sampling sites, at least 3 cubes were taken to determine the paleomagnetic signal. Care was taken to not collect samples from bioturbated, rotated, or otherwise disturbed sediment. Most samples were collected from fine-grained lacustrine and glaciolacustrine deposits. Samples were analyzed in the Paleomag Laboratory in Menlo Park, CA by Dr. Jonathan Hagstrum. Repeated sampling was needed to increase resolution at a few locations when the analyses from first round indicated that a transition was captured in the sampling interval.

The methods for determining polarity measurements and paleomagnetic correlations are described in Hagstrum et al. (2002).

3.4 Lithological Methods

Several lithological methods have been employed in identifying Possession-age deposits and to help characterize local depositional environments, including interpretations of sediment structure, presence of pollen and diatoms, organic matter, and sand-grain provenance. For example, the presence of dropstones typically indicates a glaciolacustrine deposit, and the presence of calcareous concretions signifies either deep-water glaciolacustrine or glaciomarine deposits (C. Schreiber, UW, 2014, personal communication). The presence of calcareous concretions as an indicator was first noted by Mullineaux (1967) and was verified numerous times during my fieldwork. Determination of sand-grain provenance has been invaluable to identifying glacial vs. interglacial environments (Troost, 1999; Troost et al., 1998), although streams emanating from the Cascades Ranges and Olympic Mountains carry sediment into the Puget Lowland during glacial and interglacial times alike, which intermix with the glacial deposits at the surface to create varying, intermediate assemblages of minerals. Lithological methods were of limited use for uniquely identifying deposits of any particular age, but several methods were employed to help characterize depositional environment and facies (Tables 3-1 and 3-2). The lithological methods employed are described below.

Table 3-1. Lithological Features and Depositional Environment

Criteria	Glacial*	Nonglacial
Source Area	Coast Range, Northern and Central Cascades	local; adjacent mountain ranges, Mount Rainier area
Lithology	granites and high-grade metamorphic rocks	abundance of meta argillite and meta sandstones; arkosic sandstone and siltstone volcanic rocks, and/or andesite
Mineralogy	garnets, epidotes, and magnetite; high polycrystalline/ monocrystalline quartz ratio	hypersthene, large yellow mica flakes; abundant monocrystalline quartz, K-spar, and plagioclase
Mode of Deposition	glacial ice, meltwater, lacustrine	fluvial, subaerial, lacustrine
Organics	detrital, cool climate pollen	peats, paleosols, fossils, warm climate pollen
Volcanic Deposits	detrital, rare tephras	lahars, tephras, pumice clasts
Silt/Sand Color	“salt and pepper”, gray, brown	lavender, pink, red, white, gray, dark brown

* Glacial deposits can contain an abundance of locally derived material near contacts with local bedrock or other sources.

Table 3-2. Marker beds and Sampling protocols

Marker Bed	Description	Significance	Sample Preservation	Sample Size
Diatomite	White, gray, or tan, chalky "Silt". Typically very low density when dry. Commonly associated w/peat. Hard to distinguish from ash in hand sample.	Indicates either fresh-water lake or marine water environment. Marine diatoms may provide information on age. Not much work has been done on fresh-water diatoms in the Quaternary of the PNW. Typically NONGLACIAL.	Jar or bag.	Few square inches.
Ash	White, gray, tan, pink, yellow, or lavender chalky "Silt". May contain volcanic glass. Can be identified in hand sample w/hand lens. Look for glass shards.	Indicates volcanic eruption. Can be used for chronostratigraphy. USGS is compiling a database of ages and composition. Typically NONGLACIAL.	Jar or bag.	As much as possible! Up to 20 pounds.
Pumice	White, yellow, or light gray "pebbles or clasts". Low density if fresh. May be altered to a fine-grained matrix. May see minerals (hornblende and hypersthene most common minerals from Cascade volcanoes)	Indicates volcanic eruption. Can be used for chronostratigraphy. USGS is compiling a database of ages and composition. May be able to do fission track or Argon/Argon dating. Typically NONGLACIAL.	Jar or bag.	As much as possible. A few clasts for screening, up to 50 pounds for dating.
Black and Red Sand	Black and red andesitic grains.	Volcanic sediment source. Distal (reworked) volcanic mudflow? Typically NONGLACIAL.		
Purple or Lavender Sand	Light-colored sand w/abundant quartz, pumice, and red andesite grains.	Volcanic sediment source. Typically NONGLACIAL.		
Mudflows	Heterogeneous, matrix-supported, gravelly sandy silt or sandy gravel diamicton. May or may not contain wood and clasts of till, silt, etc. If predominantly volcanic clasts, likely a lahar. Can be difficult (impossible) to distinguish from ice-contact deposits.	If volcanic, may be able to extract datable material for limiting date. If volcanic, typically NONGLACIAL. If wood present, may indicate NONGLACIAL.	Jar or bag if volcanic material present. Wrap wood in aluminum foil (no paper), then ziploc bag.	As much as possible of the volcanic material. As much as possible of the organic material (if less than 25 grams, will be expensive to date.

Shells	Fragmental or whole shells. White or purple smears and flakes.	Could be a shell midden if abundant and concentrated. If rare and matrix-supported can indicate glaciomarine drift. Could also indicate an estuarine environment. Can be dated. Species or genus could be identified providing clues to environment.	Jar or bag.	Pint.
Peat	Brown or black fibrous or compacted material. If pre-Vashon, may be quite brittle (like lignite).	May be within Carbon-14 range for dating. Pollen. If present may be used for determining vegetation type. Typically NONGLACIAL.	Wrap wood in aluminum foil (no paper), then ziploc bag, then freeze.	50 grams or more.
Detrital Wood		May be within Carbon-14 range for dating. Typically NONGLACIAL. But detrital wood may be found in glacial deposits, especially transitional beds and recessional deposits.	Wrap wood in aluminum foil (no paper), then ziploc bag, then freeze.	25 grams or more.
Organic Soil	Brown or black, clayey (sometimes) organic Silt. Typically has finely disseminated organic flecks. May be brittle if pre-Vashon.	May be within Carbon-14 range for dating. May represent A horizon formation or deposition in wetland-type environment. Typically NONGLACIAL.	Ziploc bag (no paper). Freeze.	As much as possible. Need at least 500 grams due to low carbon content.
Vivianite	Pool cue chalk blue or white chalky secondary mineral	Represents replacement of phosphate bearing organism or organic matter, commonly found near base of glaciolacustrine deposits and in clay deposits near transition to glacial lacustrine environments	Store in airtight container to maintain blue color, oxidizes quickly	na
Paleosols	Blue, green, white, brown, orange, gray or black silt, clay, sand, or gravel. Fine-grained versions typically have gleyed colors. May have root casts and organic matter. May have clay coatings on clasts.	May represent any of a number of soil horizons. Typically NONGLACIAL.	Bag.	Pint.
Concretions *Clay Babies*	Hard intraformational concretions that appear along bedding planes. Many have unusual shapes and are normally tabular and somewhat oval.	These have only been documented in glaciolacustrine deposits here in the Puget Lowland. They are commonly cemented with calcium carbonate perhaps reflecting partial glaciomarine conditions. One of the few truly “cemented” matrices found in the Quaternary of the Lowland.		na

Bioturbation	Undulatory to vertical to horizontal fillings within the host deposit. Fillings and tracks indicate translocation of sediment by plants and/or organisms.	Usually indicates long period of time and therefore typically NONGLACIAL. Can be difficult to differentiate from liquefaction.	na, but take measurements and photographs.	na
Liquefaction Features	Sand (can also be gravel) dikes, boils, or flows.	Indicates shaking or dewatering.	na, but take measurements and photographs.	na
Shear zones	Broken, blocky, and fragmented parent material. Usually of lower density than parent material. May include blocks w/rotated bedding. Sheared material may be altered.	Indicates movement. Many possible origins: earthquake, landsliding, glaciotectonic forces, settlement, sampling technique.	na, but take measurements and photographs.	
Slickensides	Shiny, possibly striated clay.	Indicates movement. Many possible origins: earthquake, landsliding, glaciotectonic forces, settlement, sampling technique.	na	na
Dipping Beds	Not horizontal.	May indicate primary deposition, tectonic movement, landsliding, glaciotectonics, soft-sediment deformation.	na, but take measurements and photographs.	na
Varves	Alternating light and dark thin layers in fine-grained sediments.	Color changes may represent differences in organic content, grain size, or mineralogy. Indicates lake sedimentation, may provide clues to climate and water body (fresh or marine).	Bag or block wrapped in foil.	Pint or more.

3.4.1 Palynology

Palynology is used regionally (Whitlock, 1992) and worldwide (i.e., Leopold, 1987; Reinink-Smith and Leopold, 2005) to reconstruct vegetation patterns thus providing strong indicators of local climatic conditions. This method was applied for samples from measured sections to assist in making stratigraphic assignments, determining glacial or interglacial origins, and assessing paleovegetation, temperature, and humidity. I processed my samples for pollen, prepared pollen slides, identified and counted pollen working in Dr. Estella Leopold's botany/pollen lab in the Biology Department of the University of Washington. Pollen slides were prepared by me and Leopold's pollen lab assistant with help from Dr. Leopold. These samples, ranging from organic rich sediment to silty sands, underwent pollen preparatory procedures using standard methods described and used by the USGS (Doher, 1981).

The basic wet lab procedure involves centrifuging sediments, removing carbonates with HCl and silica using HF and mounting the fossil pollen in glycerine jelly. I evaluated the pollen for eleven sites (Figure 3-3) and I analyzed an additional 63 samples for the Brightwater and U-Link tunnel projects (McCormack, 2002, 2005; Northlink Transit Partners, 2007,2008). Palynology was often the only means for telling the depositional environment of some of the fine-grained deposits in the region.

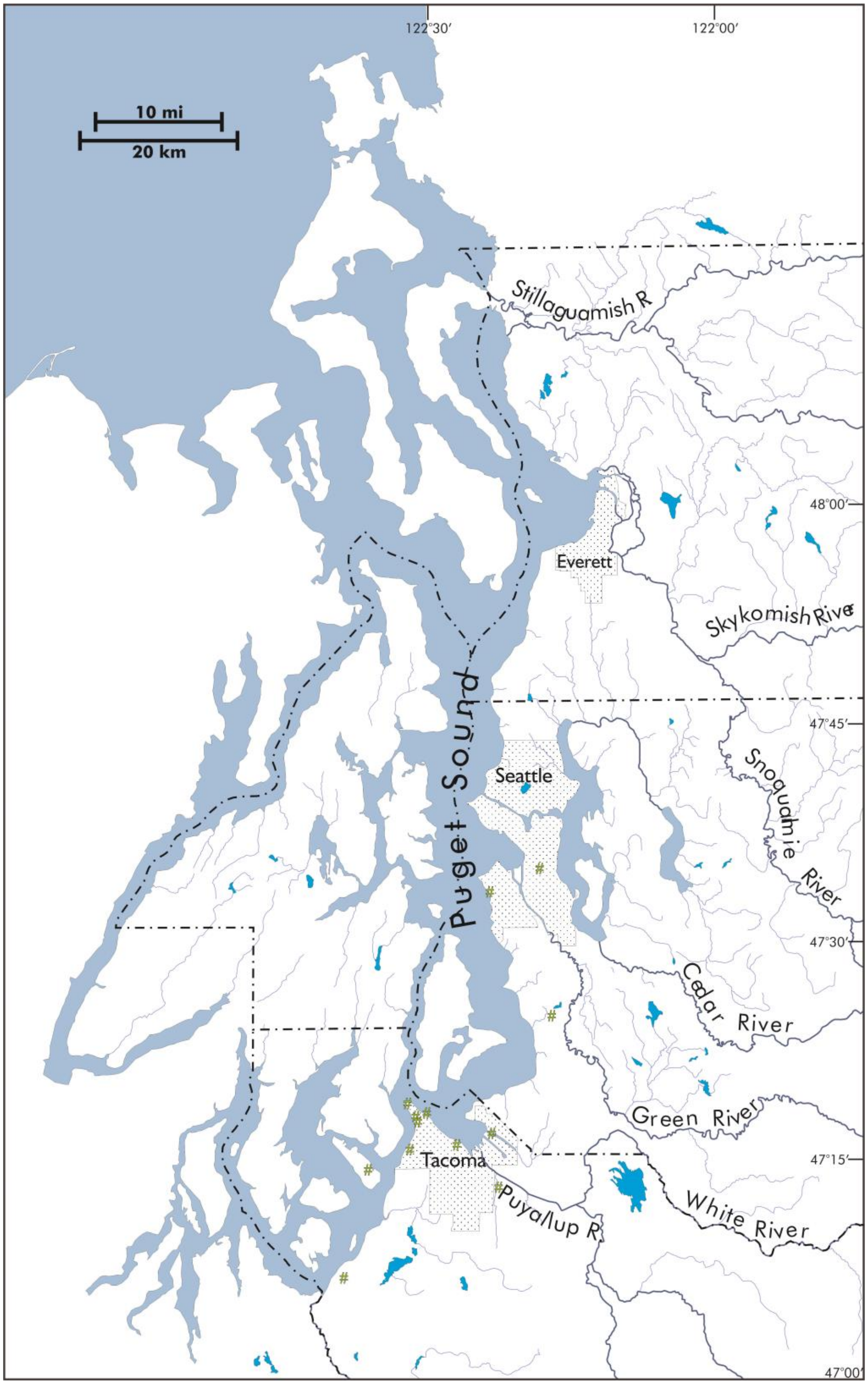


Figure 3-3. Map showing locations of pollen analyses ("#" symbol).

3.4.2 Diatoms

Diatoms were also evaluated at a few locations to help with depositional environment, particularly for distinguishing fresh water vs. marine depositional environments. Diatom slides were prepared and analyzed by Dr. Brian Sherrod of the USGS in Seattle following the procedure of Patrick and Reimer (1966) and Sherrod (1999). Preparations involve wet chemical lab methods such as dispersing the sediment in weak KOH solution; sample cleaning with Nitric acid, and mounting diatoms on a slide under a coverslip.

3.4.3 Tephra and Pumice

Tephra and pumice are present in the Quaternary strata in the Puget Lowland only sporadically. When encountered, the materials were described, sampled, and analyses were performed. Most of the samples were sent to Dr. Andrei Sarna-Wojicki, then with the USGS in Menlo Park, CA. Dr. Sarna-Wojicki came to the Puget Lowland to accompany me on several sampling trips to better analyze the volcanic materials. Some samples were sent to Dr. Fleck for argon/argon dating. Chemistry composition determinations were attempted on most of the samples. Tephra and pumice samples ranged from Vashon in age to older than 1 Ma.

3.4.4 Provenance

Several provenance methods were employed to help determine depositional environments and source areas. These methods include bulk-sand geochemistry, microscopic viewing with and without point counting of sand grains, use of hand lenses in the field, and organic content evaluations.

Bulk sand geochemistry was undertaken with Dr. Brian Mahoney of the University of Wisconsin, Eau Claire following the method of McLennan et al. (1993). The goal of this method was to determine if bulk geochemistry could be used to differentiate stratigraphic units, particularly glacial vs. interglacial provenance. The method requires the collection of sand samples of similar grain size, grinding of the sand, then running the resulting powder or pellets through an XRD (Mahoney et al., 2003). Two-hundred and thirty-nine samples were collected from throughout the Puget Lowland, including of modern alluvium, Pleistocene glacial outwash, and Pleistocene interglacial fluvial deposits. The samples were analyzed for major, minor, and trace elements.

Sand grain provenance determined using a dissecting microscope is a very useful method for identifying glacial vs. interglacial environments (Troost, 1999; Troost et al., 1998; Dragovich et al., 2012), because characteristic minerals and mineral assemblages can help determine provenance (Tables 3-1 and 3-3). All sand deposits encountered in the field were evaluated for provenance using either a hand lens in the field or a microscope at the UW. Typically, northern British Columbia/Cascade rocks and minerals are found in the deposits generated by glaciers that advanced in the Puget Lowland (Borden and Troost, 2001; Walters and Kimmel, 1968; Booth and Howard, 1996).

Table 3-3. Sediment Characteristics of Selected Puget Lowland Rivers

River	Sand Color[1]	% Quartz	% Red Andesite	% Mica	Source Lithologies[2]
Nisqually	dark brown (7.5 YR 3/2)	60	5	Trace	andesite, Mt. Ranier volcanics
Puyallup	black (5 YR 2.5/1)	40	10	Trace	andesite, Mt. Raneir volcanics
Carbon	very dark gray to reddish black (5 YR 3/1 to 10R 2.5/1)	50	10	Trace – 1%	andesite, Mt. Ranier volcanics, granites
White	dark brown to reddish black (7.5 YR 3/2 to 10R 2.5/1	40	10	0	andesite, Mt. Ranier volcanics
Green	very dark grayish brown (2.5 Y 3/2)	50	Trace	Trace	andesite
Cedar	very dark grayish brown (2.5 Y 3/2)	45	Trace	Trace	andesite, granites
Snoqualmie	very dark grayish brown to black (2.5 Y 3/2 to 5 Y 2.5/2)	65	0	Trace – 2%	granites, greywacke, argillite, andesite
Skykomish	olive gray to dark olive gray (5 Y 3/2 to 5 Y 4/2)	65	0	2-3%	granites, greywacke, argillite, andesite
Stillaguamish	very dark gray to dark olive gray (5 Y 3/1 to 5 Y 3/2)	60	Trace	Trace – 1%	sandstones, argillite, metasediments, granites
Skagit	very dark grayish brown (10 YR 3/2)	70	2	1-2%	sandstones, argillite, gneiss, granites, Mt. Baker volcanics
Nooksack	very dark gray (10 YR 3/1)	45	5	Trace – 1%	sandstones, argillite, metasediments Mt. Baker volcanics
Snow Creek	dark brown (10 YR 3/3)	50	0	0	sandstones, argillite
Little Quilcene	very dark grayish 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 grayish brown (2.5 Y 3/2)	10	0	0	basalt, greywacke, argillite

[1]Munsell color chat designation listed in parenthesis.
[2]Listed in order of decreasing exposure surface area in drainage basin.

From Borden and Troost, 2001.

During interglacial times, streams emanating from the Cascades and Olympics carry sediment into the Puget Lowland. These streams also mix with the glacial deposits at the surface with fresh alluvial sediment, creating an "intermediate" assemblage of minerals. This intermediate assemblage varies depending on position in the Lowland, i.e.: near Tacoma the assemblage can be dominated by volcanic material; near the Olympics the assemblage can have an abundance of basalt; near bedrock highs the assemblage will contain more Tertiary lithic grains and take on a hue similar to the underlying bedrock. The most challenging geographic areas for making discriminations are where the lithology of the interglacial sediments looks similar to that of the glacial sediments, such as in Snohomish County and parts of Seattle near the center of the Seattle basin.

3.4.5 Organic Content

Organic matter is present in many environments, glacial and interglacial; the nature of the organic matter is the key to discerning the probable environment. Finely disseminated organic debris is common at transition zones between the glacial and interglacial stratigraphic units. Detrital wood fragments can be found in any deposit in the Lowland, including till. Rooted trees, peat layers, and masses of grass/reeds tend to be found more often in interglacial environments, although these deposits could have developed on glacial deposits. When possible, the nature of all organic matter was determined to help differentiate glacial vs. interglacial environments. Paleosols, although not common, were encountered in the deposits in the Puget Lowland. They will most typically develop during interglacial periods although they may develop in the top of glacial deposits. Borden and Troost (2001) determined that if the modern landscape is a proxy for past interglacial landscapes, then only about 20% of the landscape is accumulating sediment while the other 80% is simply undergoing weathering of deposits at the land surface (generally from the previous glaciation).

3.4.6 Clay Mineralogy

The only systematic clay mineralogical data for the Puget Lowland are from prior studies. Mullineaux et al. (1964) and Mullineaux (1967) reported data for a varved clay deposit on the west side of Beacon Hill that is herein correlated with Possession Drift. The clay mineralogy of unweathered Possession glaciolacustrine material consists of, in order of decreasing abundance, chlorite, illite, and montmorillonite with a little kaolinite (Mullineaux et al., 1964; Mullineaux, 1967). This deposit was historically used for the manufacture of bricks in Seattle in the early 1900's. This fact indicates that the clay must have been of sufficient plasticity for brick making and the exporting of bricks. Remnants of clay pits and associated equipment are visible on the west face of Beacon Hill near the Beacon Hill USGS deep boring (Odum et al., 2004). Other than clay, the fine-grained deposits also contain quartz, feldspar, and ferromagnesium minerals.

Clay mineral determinations were not conducted for this study; however, the presence of expandable minerals helped to identify paleosols and some interglacial deposits.

3.4.7 Macrofossil Identification

Macrofossils are rare in the Vashon and pre-Vashon deposits in the Puget Lowland. During the mapping for this study, several types of macrofossils were found including: flattened cones, flattened stems, flattened wood, in-situ flattened tree roots, grasses, reeds, leaves, beetle fragments, and shells of a number of different species. When possible, identifications were made to determine genus, species, and depositional environment. Most of the fossils were of inferior quality - not well preserved, fragile, or fragmentary. Fossil samples were cleaned in the field, wrapped in aluminum foil or plastic wrap, labeled, and then taken to the laboratory for further cleaning and identification. Shell fossils were identified by Dr. Elizabeth Nesbitt of the UW Burke Museum. I identified the well-preserved cones, needles, and leaf. Beetle fragments were generally unidentifiable however; Ashworth and Nelson (2014) completed a robust study of beetles at the Olympia formation type section for paleoenvironmental reconstruction.

Chapter 4 - A Summary of Chronological and Lithological Findings

The purpose of this chapter is to present an overview of my findings in the context of the Quaternary stratigraphy of the Puget Lowland. In combination with the overall stratigraphic framework of the Lowland (Chapter 2), this presentation focuses on how these new findings have impacted and improved our state of knowledge.

4.1 New Chronological Data

4.1.1 New Radiocarbon Dates

New radiocarbon dates were obtained on 110 samples from the Puget Lowland between 1998 and 2011 (Table A-1 of Appendix A and Figures 4-1 and 4-2). Data from an additional 79 samples were compiled from other sources; most notably AESI of Kirkland, Washington (included on Figures 4-1 and 4-2). Combined these two data sets are nearly double the amount of radiocarbon data previously published for the Lowland. These dates provided the age control needed to identify deposits at outcrops as belonging to the Olympia Formation and the Vashon Drift. Only part of the Olympia interglacial period (which, in total, spans 18,000 to 60,000 yr) falls within the limits of radiocarbon dating (up to about 45,000 cal yr BP). Having age control on even a subset of the deposits from MIS 2 and MIS 3, however, can provide a basis for determining the relative age of underlying older deposits. These new radiocarbon dates and the readily accessible radiocarbon dates from previous workers were entered into an ArcGIS map and database (Booth et al., 2006). These data were also transmitted to WDNR-DGER in 2011 for serving on the web on their interactive map portal, and thus they are now available to all researchers through tabular data and a map-based interface (http://www.dnr.wa.gov/geologyportal).

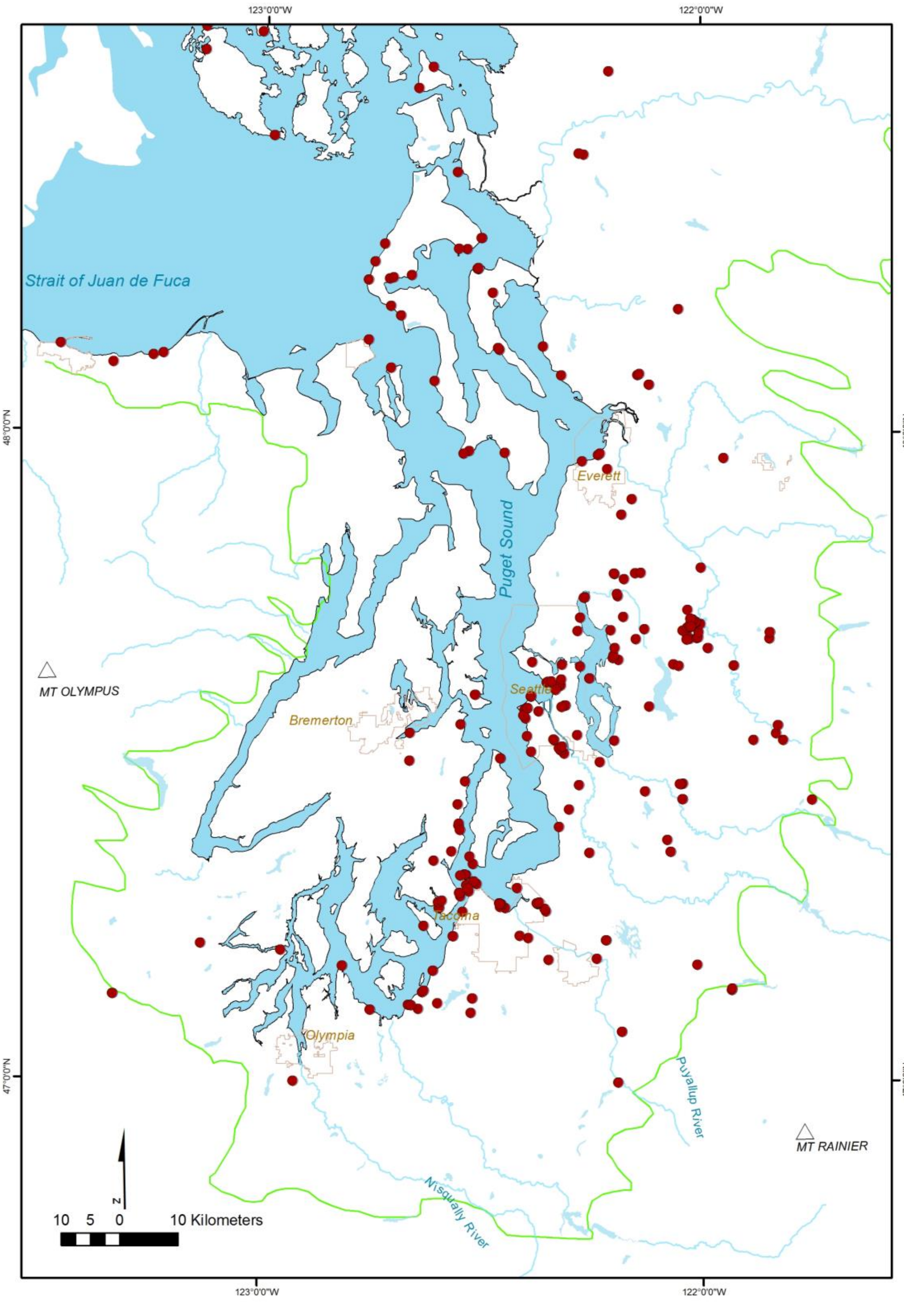


Figure 4-1. Map showing locations of 14C data used for this study.

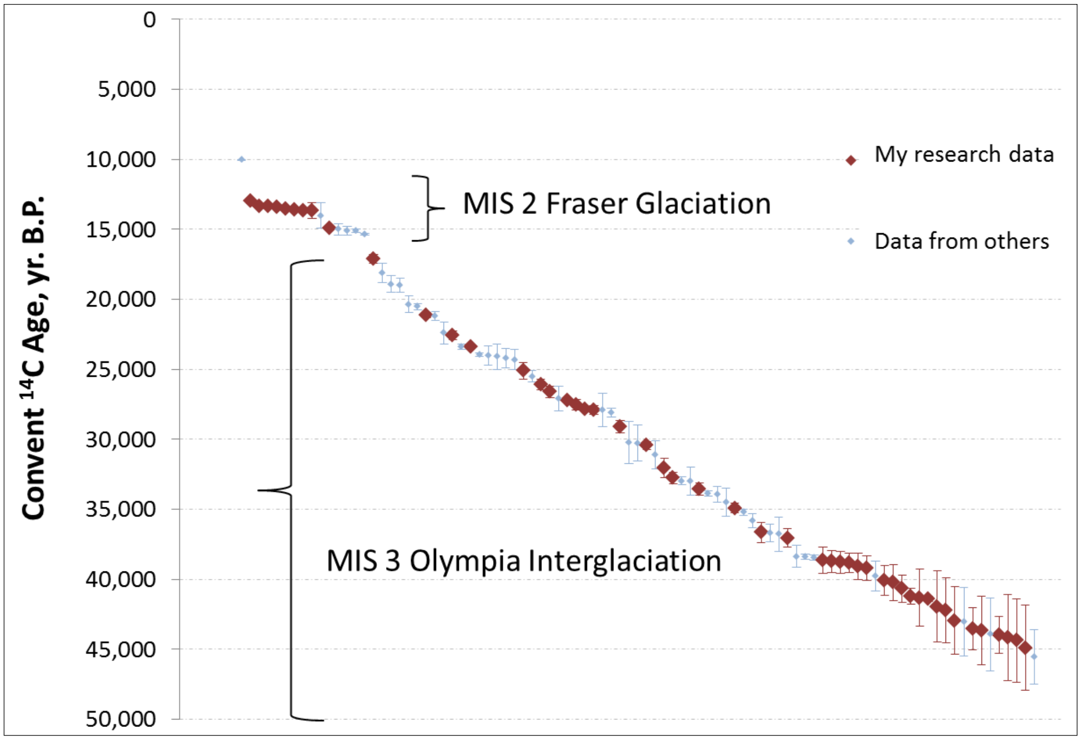


Figure 4-2. New radiocarbon dates.

4.1.2 New OSL/IRSL Dates

New OSL/IRSL dates were obtained on seventy-seven samples from the Puget Lowland between 2000 and 2008 (Table A-2 and Figures 4-3 and 4-4). Several samples were submitted for both radiocarbon and OSL dating to see how well the OSL/IRSL method would work on these deposits. These results showed that the method is not precise for Vashon-age deposits, yielding large error bars from partial bleaching (Mahan et al., 2003). However, in all but a few cases, the method was adequate for making a reliable stratigraphic unit assignment since the time frames for each stratigraphic unit are sufficiently broad. Greater age uncertainty was associated with fine-grained deposits, such as silt and clay, than with sandy deposits; but even so, assignment to stratigraphic unit was typically still possible (Figures 4-4 and 4-5).

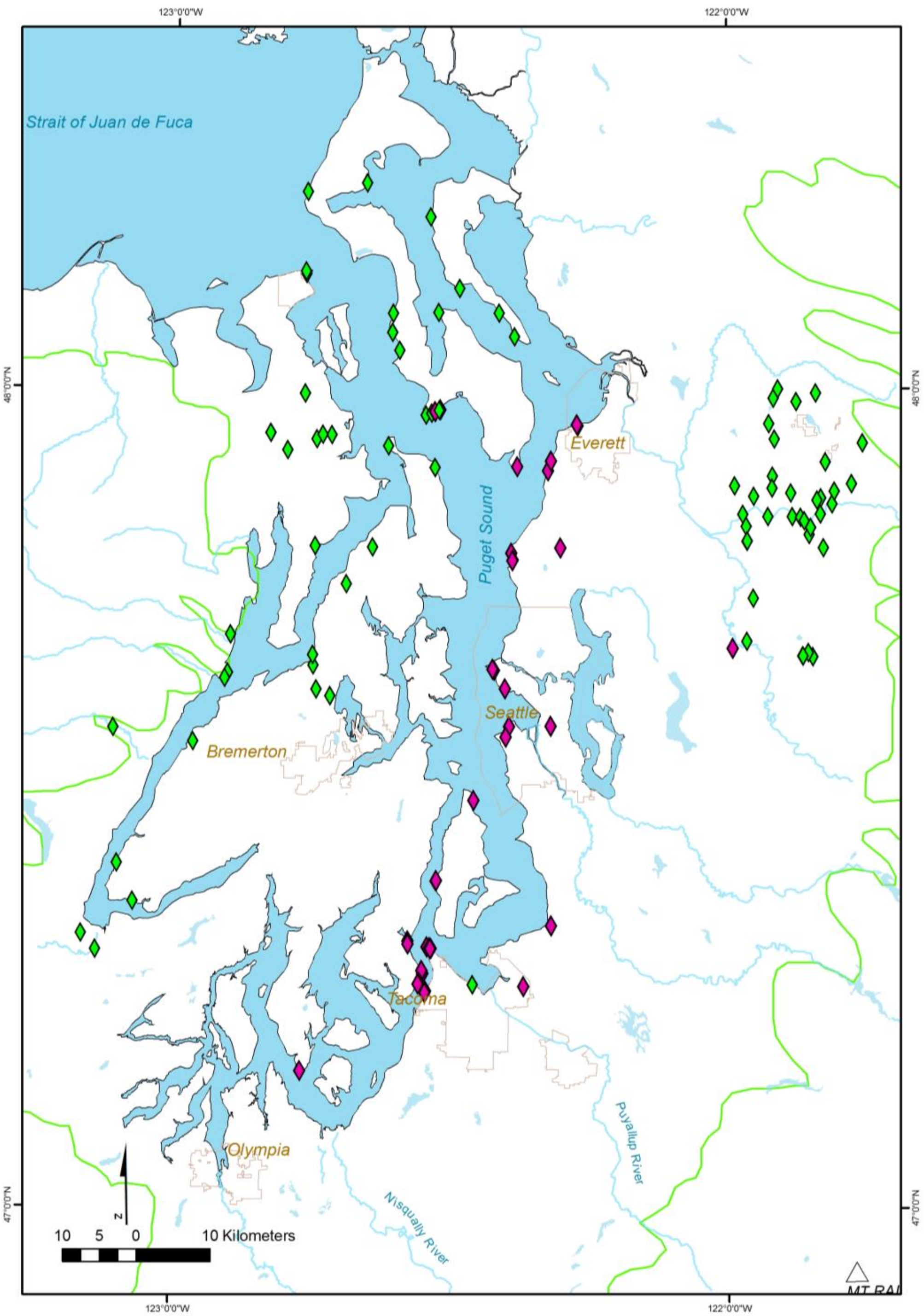


Figure 4-3. Map showing locations of luminescence dates.
New dates (in magenta) and dates obtained by others (in green). Most of the dates obtained by others were done for geologic quadrangle mapping by WNDR after 2008 (Czajkowski, 2016; Jeschke et al., 2016); some on Whidbey Island are from Easterbrook et al. (1992). The green line represents the maximum Vashon-age ice limit.

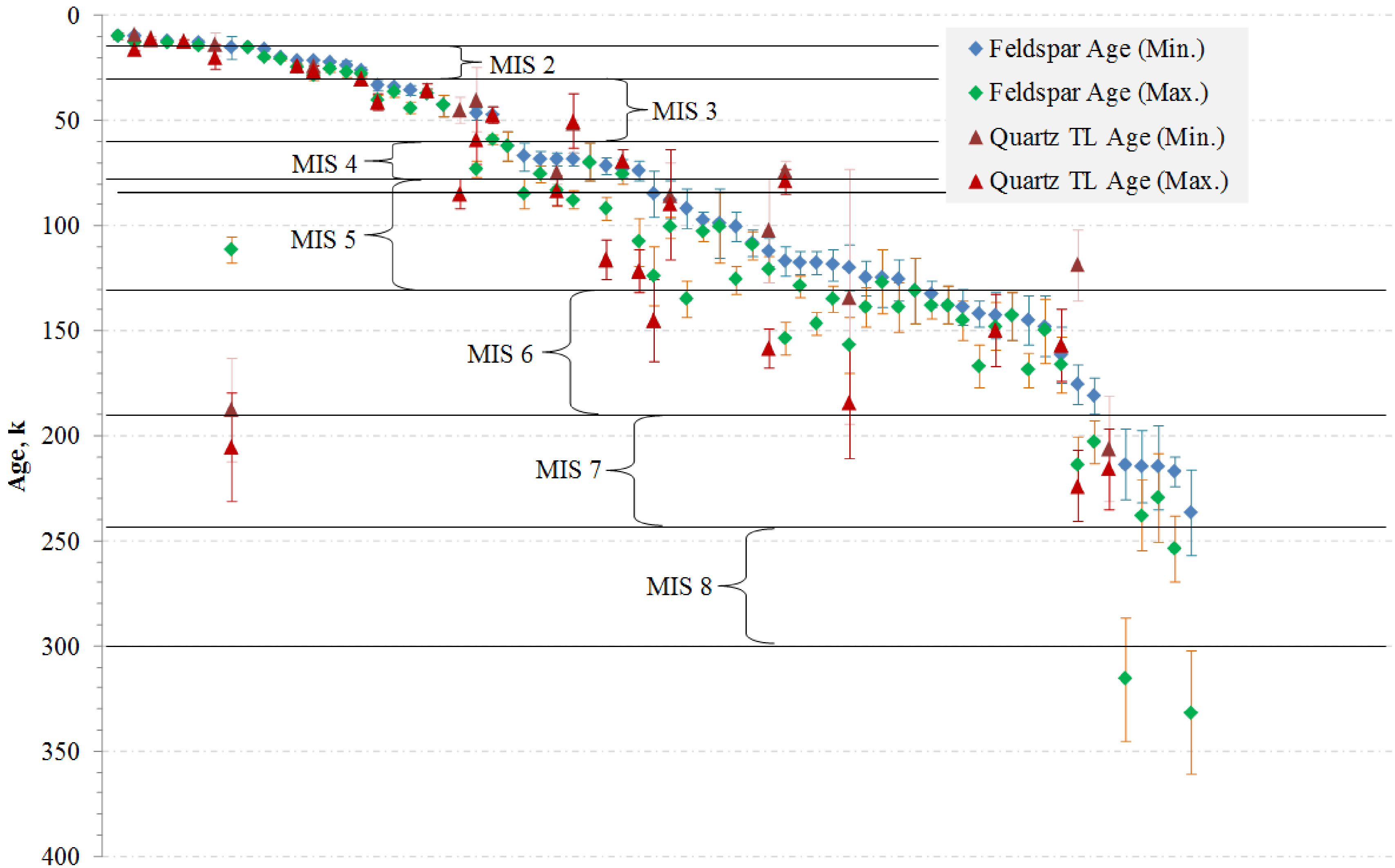


Figure 4-4. Graph of luminescence dates showing error bars and results from multiple methods. Note that for a few samples, the results for the quartz and feldspar methods did not overlap, indicating problematic test runs.

Since this focused effort on luminescence dating in the Puget Lowland beginning in the early 2000s, others have also obtained such dates on pre-Vashon Pleistocene deposits. All of the locations with data pertinent to my study, including earlier results reported in Easterbrook et al. (1992), are shown on Figure 4-3.

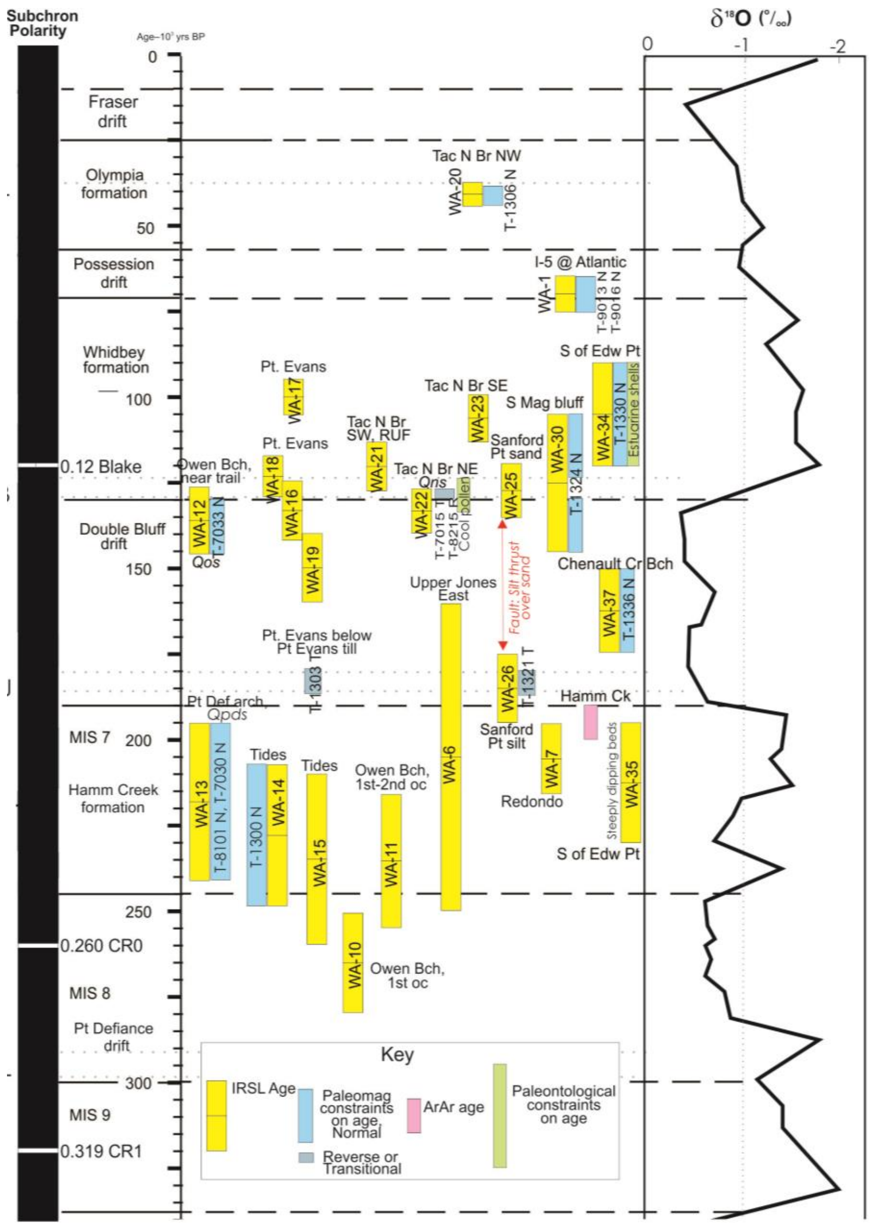


Figure 4-5. OSL results and paleomagnetic measurements.
Brunhes polarity scale on the left and MIS scale on the right. Sample numbers are keyed to the data tables in Appendix A.

These new OSL/IRSL dates allowed for the identification of outcrops dating to MIS 4 (Possession Drift), 5 (Whidbey Formation), and 6 (Double Bluff Drift); and newly identified deposits of MIS 7 and 8. IRSL proved to work particularly well for identifying MIS-4 Possession-age deposits (57,000 to 71,000 yr; according to Lisiecki and Raymo, 2005).

4.1.3 New Argon/Argon Dates

Three dates using the argon/argon method were obtained on pumice from outcrops along 3 different tributaries of Hamm Creek in south Seattle (Figure 4-6). The pumice was distributed in fluvial deposits and mixed with some organic debris indicating redeposition. According to Dr. Robert Fleck (USGS, 2004, written communication) the ages yield good reproducibility with relatively small error bars at 200,000 +/- 10,000 yr. These ages correlate with MIS 7, not previously recognized in the Puget Lowland. This newly identified interglacial unit was informally named Hamm Creek Formation by Troost et al. (2005). Similarly aged material was found near Redondo Beach (Mahan et al., 2003).

Several years after identifying the Hamm Creek formation, more deposits of the same age were identified in south Snohomish County during drilling for the proposed Brightwater sewer tunnel alignment (McCormack and Troost, 2016) and in Snohomish County (Dragovich et al., 2010 and 2011 ; see Chapter 5).

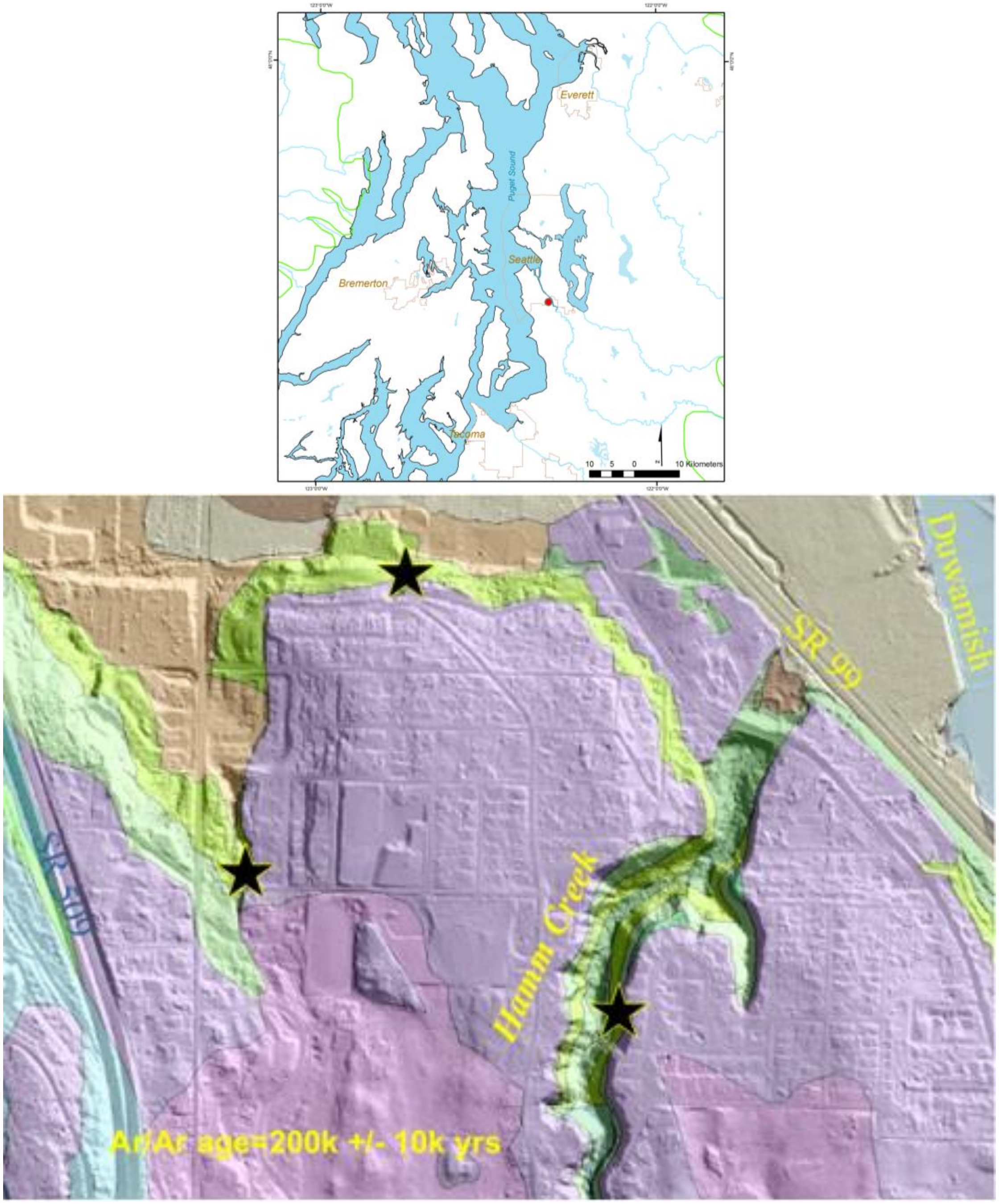


Figure 4-6. Maps showing location of sampled Hamm Creek formation. Geologic (bottom) and index map (top) showing locations (stars) of pumice sampled for Ar/Ar. Geologic map from Troost et al., 2005.

4.1.4 Fission Track Dates

Only a limited number of fission track dates were obtained due to the death of Dr. Richard Stewart (University of Washington) who was helping with the ages of the pumiceous sands in the Puyallup Valley and had accompanied me on sampling trips. Samples were collected in 1999 from the east and west ends of the valley (Figure 4-7). The two pumiceous sands sampled from an interglacial deposit were determined to be 1 Ma, based on fission track dating. Sand on the east side of the valley had been previously mapped the Puyallup Formation (Crandell, 1961); the sand in Fife (west end) had been mapped as Salmon Springs Drift (Smith, 1976).

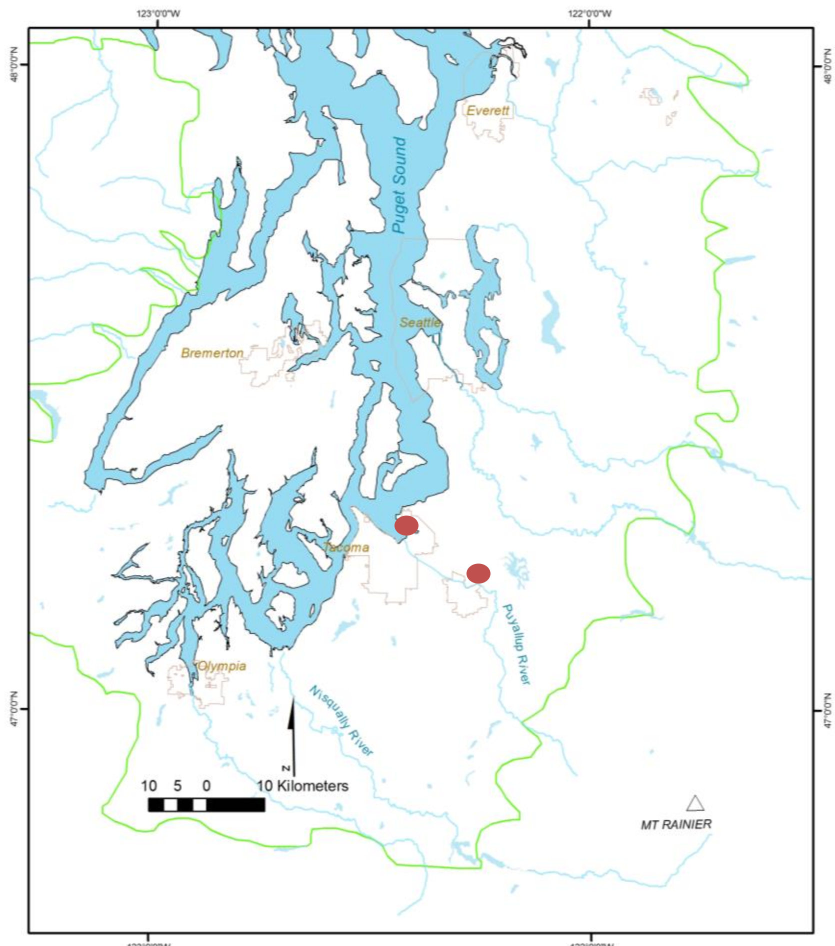


Figure 4-7. Map showing location of Fission Track dated samples (red dots).

4.1.5 Paleomagnetic Measurements

Polarity measurements were obtained from eighty-three sites throughout the southern, central and northern Puget Lowland at locations initially determined to help identify stratigraphic units and to correlate fine-grained deposits from one map area to another (Figures 4-5 and 4-8, and

Table A-3). The measurements were made by Dr. Jonathan Hagstrum (USGS) and have been largely reported in two published manuscripts (Hagstrum et al., 2002; Booth et al, 2004b). Hagstrum et al. (2002) described the applicability of using this technique on Quaternary strata in the Puget Lowland. They also described some unique pole orientations that allow a more precise degree of stratigraphic correlation than had been expected. Secular variation proved to be applicable for this region because the age of some of the Quaternary strata spans some unique polarity orientations (Hagstrum et al., 2002). Booth et al. (2004b) used these polarity measurements to constrain the location of Quaternary fold axes and rates of Quaternary deformation in the southern Puget Lowland.

Most of the reversely magnetized deposits found in the Seattle uplift area are likely correlated with the Matuyama Reversal (Figures 4-5 and 4-8). This correlation is made on the basis of the antiquity of associated deposits, many beyond the range of IRSL dating at 400,000 years.

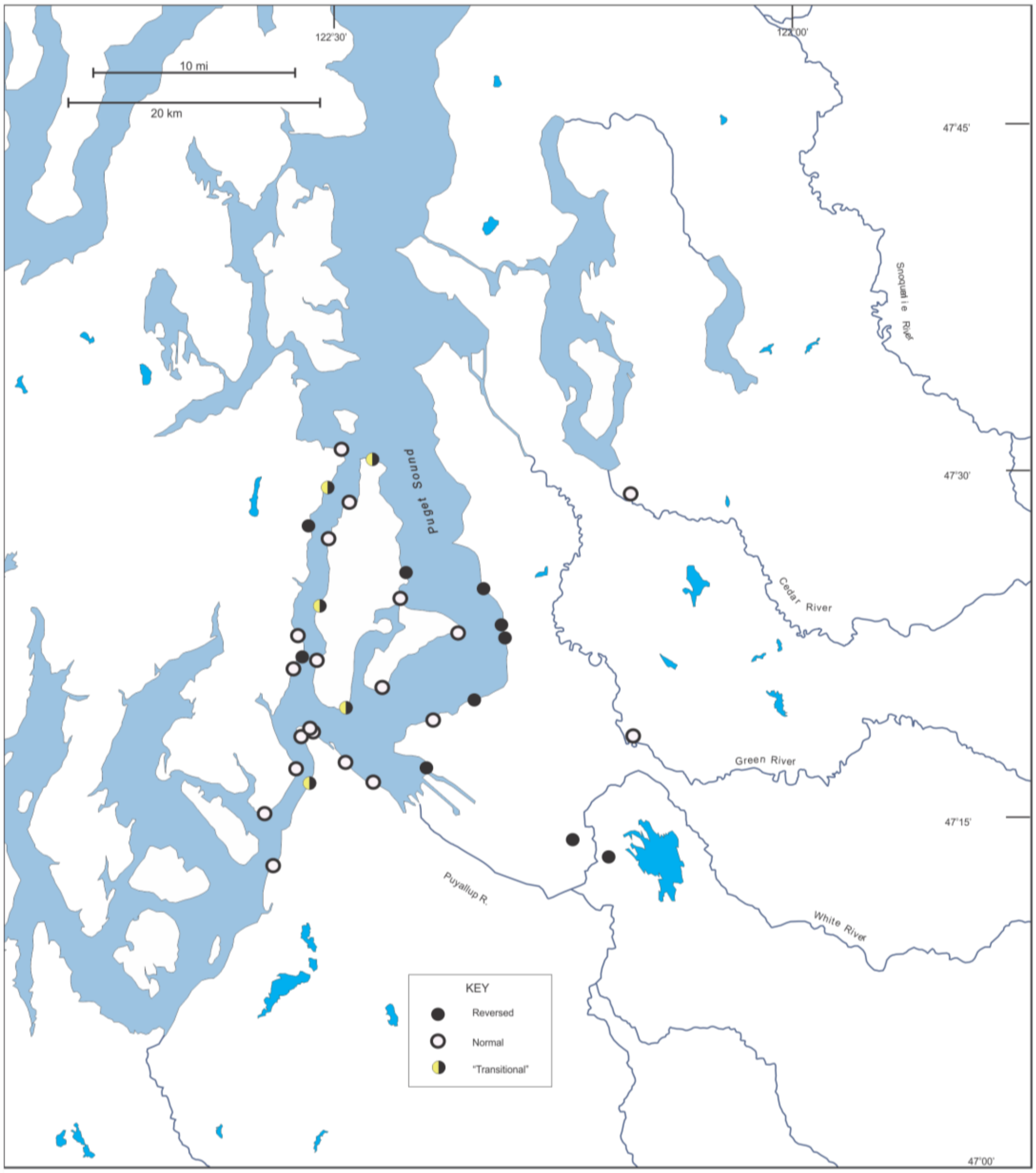


Figure 4-8. Map showing results of paleomagnetic measurements. Paleomagnetic measurements either reversed (black circles), normal polarity (open circles), or transitional (black and white half circles).

4.1.6 Palynological Results

Pollen counting proved to be a successful method for identifying interglacial deposits, and moderately successful for identifying glacial deposits, at outcrops across the Puget Lowland (Table A-4). I found pollen grains to be generally abundant in samples, with many species present in interglacial deposits but minimal in glacial deposits—many of the latter with zero pollen or with only a few cold-climate species. None of my sites allowed for a detailed profile through a complete section of MIS 4-age deposits, due to multiple unconformities.

Pollen results were also used as confirmatory evidence for depositional environment interpretation. For example, deformed fine-grained lacustrine sediments in southeast Seattle (the "I-5/Atlantic Street" site) had no pollen, diatoms, or organic matter (see Chapter 5). The IRSL date yielded an age of 70,000 years BP and dropstones are present. These lines of evidence are all consistent with this deposit being an MIS 4 (Possession-age) glaciolacustrine unit.

4.2 Lithological Results

4.2.1 Tephra and Pumice Analyses

Many tephra layers were encountered in the field but most could not be correlated to a known volcanic event. Unfortunately most of the tephra deposits are reworked and altered to the point that original glass has decomposed such that reliable chemical compositions cannot be determined (Dr. Sarna-Wojicki, USGS, 2001, personal communication). Tephra layers were also encountered during drilling for the Brightwater Sewage Tunnel and could be correlated with the MIS 7 Hamm Creek formation (McCormack and Troost, 2016).

Pumice clasts are present in some of the gravel and sand layers in the Pleistocene strata, particularly in the interglacial fluvial deposits. Most of the pumice clasts have chemical compositions that do not match known events (Dr. Sarna-Wojicki, USGS, 2001, personal communication). Devil's Head, in the southern Puget Sound is one site that does yield identifiable pumice layers, and which have been correlated with the Sunset Amphitheater tephra of Mount Rainier and possibly to Mount St. Helens set Cy of Mullineaux (1996, as quoted in Walsh et al., 2003).

4.2.2 Provenance Study Results

Provenance studies consisted of 3 types: bulk geochemistry, microscopic viewing with and without point counting, and use of hand lenses in the field. Two-hundred and thirty-nine samples were submitted for bulk geochemistry, some of known glacial or nonglacial provenance and some of unknown provenance. Ratios of trace minerals proved to be the most effective for separating glacial, interglacial, and transitional deposits (Mahoney et al., 2003). Bulk geochemistry was particularly useful for those sand grains that were so oxidized that hand-specimen identification was not possible. Major glacial advances, such as that of the MIS 2 Vashon stade, yield sediment that is high in SiO_2, Ba, Sr, Cr, Ni, and Cr/V, and low in TiO_2, Nb, Ce, V, La, Zr and Th/Sc. These values suggest derivation from exposed continental arc plutons in southern British Columbia, combined with detritus from ocean mélanges. Conversely, sediments deposited during interglacial periods were derived from Cascade volcanic rocks, and are correspondingly higher in TiO_2, Nb, Ce, V, and La. Many of the samples have mixed chemistry, however, suggesting that the samples were reworked–glacial and interglacial sediments would have been mixed together by natural processes, particularly the flushing of Cascade Range grains into the lowland by mountain rivers during nonglacial periods, followed by reworking by subsequent fluvial and glacial processes, particularly subsequent advance of the Cordilleran Ice Sheet. In total, the prevalence of interfingering facies, diachronous sedimentation, and intrabasinal reworking make basinwide correlation and comprehensive basin analysis using bulk chemistry or diagnostic mineralogy difficult at best and only rarely definitive.

4.2.3 Organic deposits

The nature of organic material in Puget Lowland deposits can indicate depositional environment and whether a particular deposit is of glacial or interglacial origin (Troost, 1999).

Peat layers and in-situ rooted trees are found more commonly in interglacial deposits, while single pieces of detrital wood and cones can be found in either environment since trees are also known to grow close to the edges of glaciers. Pleistocene wood fragments are often found in saturated deposits and so are relatively well preserved, may still have bark, and can be burned to produce heat. In-situ rooted trees, generally planed off by glacial ice, are uncommon in the Pleistocene record in the central Puget Lowland, having been encountered in only a few locations to date. Broadleaf and grass impressions, some with native material still intact, are more common in interglacial deposits than in glacial deposits. They are commonly preserved in paleosols, floodplain deposits, and depression fillings. Cones, when encountered, are particularly helpful for environmental information, because often the tree genus and species can be identified. Wood material that has been overridden by a glacier is flattened, due to the compression by the overriding ice sheet. Thus, virtually all organic material older than Vashon-age recessional deposits is compacted.

Most of the organic material found in the Puget Lowland correlates with either the Olympia or Whidbey Formations, in part because they are the most prevalent interglacial units exposed in the Puget Sound coastal bluffs. Rooted trees found in the DuPont gravel pit and at the coast opposite Mee Kwa Mooks Park in West Seattle were radiocarbon dated and correlate with the Olympia Formation. Peat layers can be relatively continuous over a kilometer or more, such as a layer traced between the Mee Kwa Mooks site and the West Seattle sewer tunnel investigation (Mr. David McCormack, Aspect Consulting, 2004, written communication).

4.2.4 Macrofossil Identification

Finding shells and/or shell debris is uncommon in the Pleistocene deposits in the central Puget Lowland. Where present, however, they can contribute to the understanding of depositional environment: for example, by virtue of distinguishing freshwater, estuarine, and marine species. Fresh-water mussels are present in the Olympia Formation at the type section (Fort Lawton at Discovery Park; Mullineaux et al., 1965). Estuarine clam species are present in interglacial deposits near sea level along Hamm Creek in South Seattle (Figure 4-6). The age of this deposit is not known but it is at least as old as the overlying ash, dated at 200,000 +/-10 ka (MIS 7). Estuarine mussels (Dr. Elizabeth Nesbitt, University of Washington, 2005, personal communication) are also present in interglacial deposits OSL dated as part of the Whidbey Formation that was encountered in the borings for the Brightwater Sewer Tunnel (McCormack and Troost, 2016).

Chapter 5 - Updated Quaternary Stratigraphy of the Puget Lowland

Based on my analytical results and new dates, I have developed a comprehensive update to the composite Quaternary stratigraphic column for the Puget Lowland (Figure 5-1). Most of the geologic units are chronostratigraphic units, rather than strictly lithologic units, since the provenance and depositional environments have been similar for each glacial and interglacial package, and so lack unique lithologic assemblages. The stratigraphic column includes two geological units first identified through this work, the Hamm Creek formation and Defiance drift, and these two units each has a designated type section in the Seattle and Tacoma areas (Figure 5-2).

The following sections compile the results of my findings related to each of the major stratigraphic units. A more comprehensive discussion of MIS 4 deposits is included as Chapter 6. The lengthy discussion about the Fraser glaciation (MIS 2), below, is provided to help understand the processes and deposits of glaciation during MIS 4, processes that likely were similar during earlier Cordilleran Ice Sheet advances into the Puget Lowland. Appendix B contains photographs of some of the geologic units and important outcrops.

5.1 Fraser Glaciation – the Last Glacial Maximum in the Puget Lowland

The Fraser glaciation began about 25,000 cal yr BP with an expansion of alpine glaciers in the Coast Mountains of British Columbia, the Olympic Mountains, and the Cascade Range of Washington. Glaciers in the Coast Mountains coalesced to form piedmont ice lobes that reached the Fraser Lowland of British Columbia about 21,000 cal yr BP (Figure 5-3). The Puget lobe advanced into northern Washington at about 18,750 cal yr BP (Clague et al., 2005; Porter and

Swanson, 1998; Clague, 1981; Easterbrook, 1986) reaching the Seattle area by 17,600 cal yr BP, then reaching

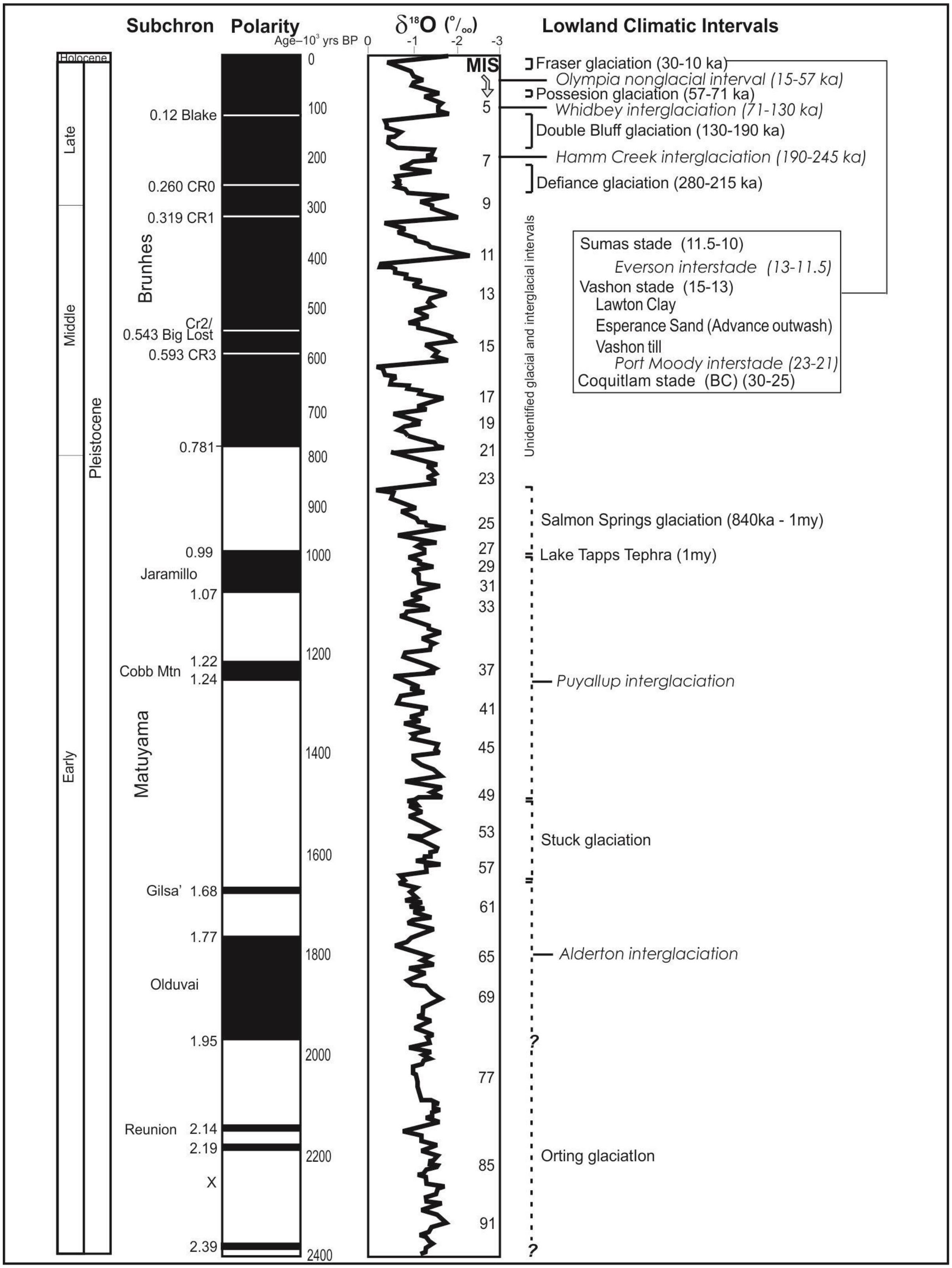


Figure 5-1. Composite stratigraphic column for the central Puget Lowland.
Polarity scale from Cohen and Gibbard, 2011. Deep-sea oxygen-isotope data for ODP677 from Shackleton et al., 1990. Refer to Table 2-4 for references for ages of the stratigraphic units.

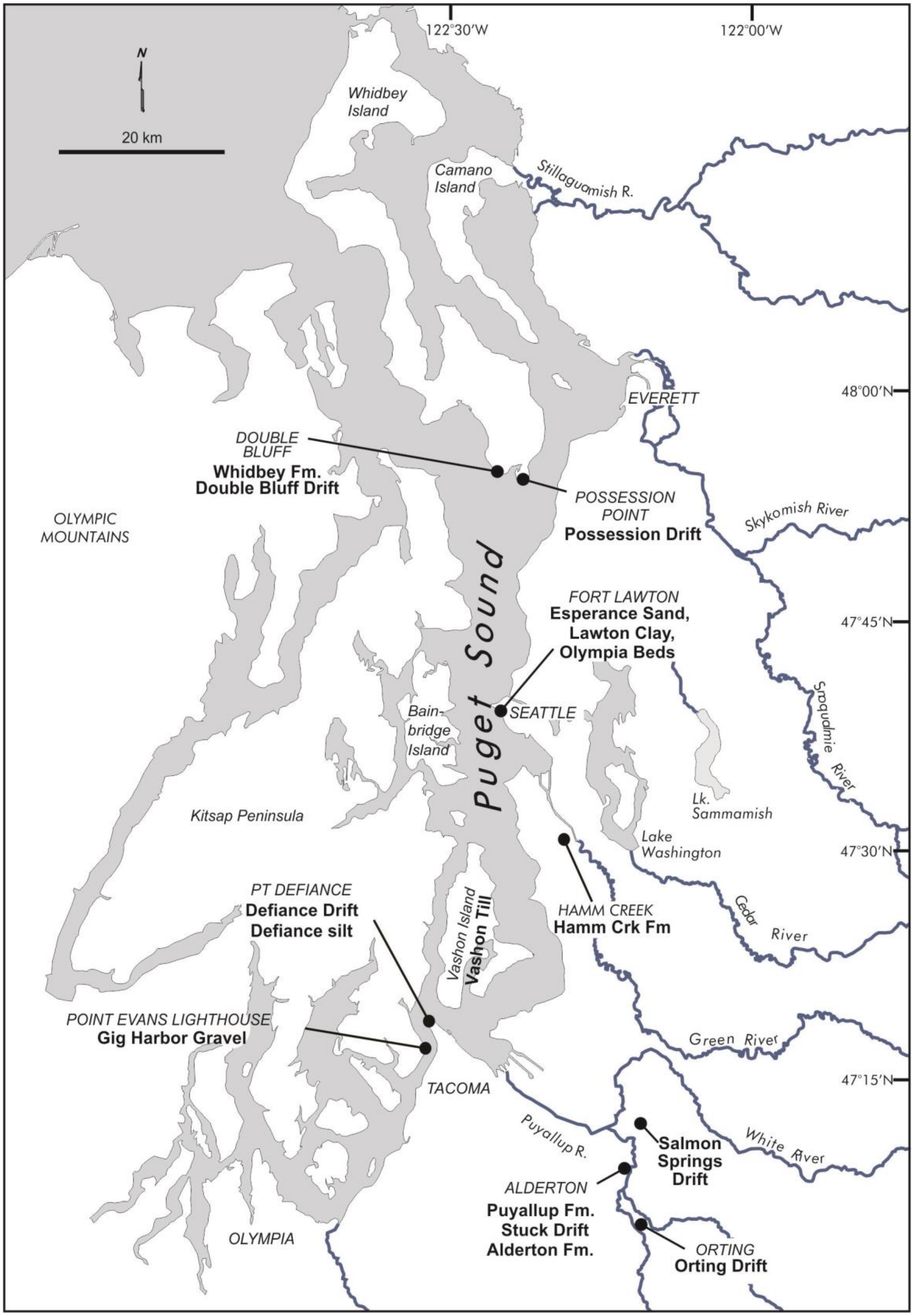


Figure 5-2. Type section locations including newly identified glacial units.

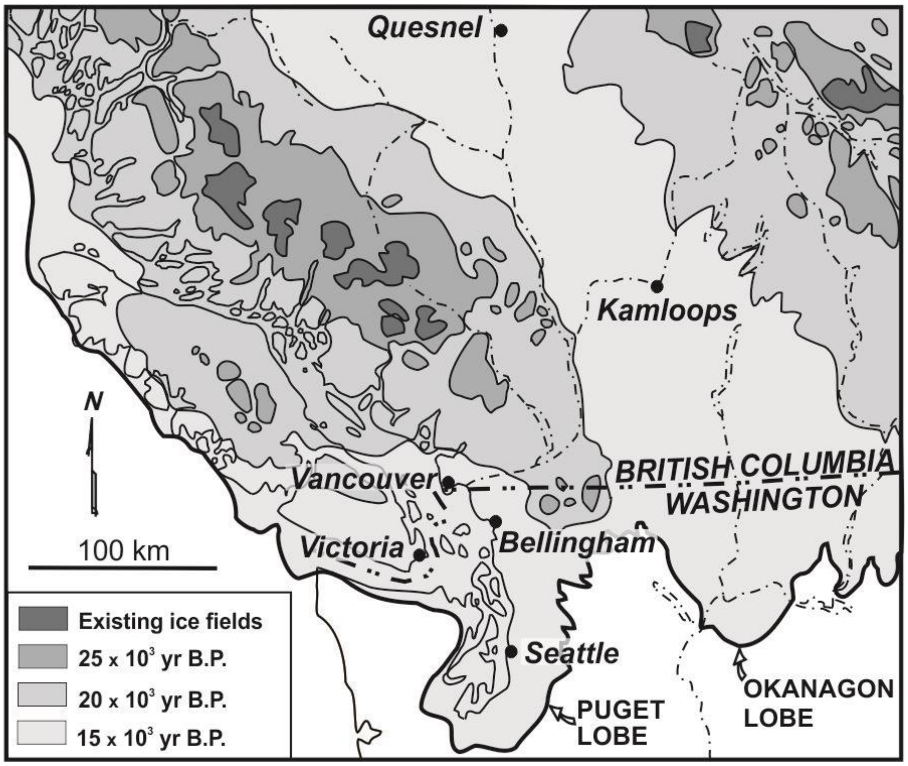


Figure 5-3. Map showing expansion of the Cordilleran ice sheet and the Puget Lobe. Modified from Booth et al., 2004b.

its maximum position near Tenino, WA after 16,950 cal yr BP. The Puget Lobe retreated rapidly beginning around 16,850 cal yr BP (Booth, 1987; Booth et al., 2004; Clague, 1981; Easterbrook, 1986; Porter and Swanson, 1998; Troost, 2011).

New dates constraining the advance and retreat of the Puget Lobe during MIS 2 were obtained during this study (Figure 5-4; also Figure 4-4, Table A-1). In general these dates are compatible with those of Porter and Swanson (1998); however, assuming that all of the radiocarbon dates are valid here and in Porter and Swanson (1998), the rates of advance and retreat must have been faster than previously reported. Alternatively, these dates support possible differences in retreat rates for different segments of the ice sheet. More work is needed to address the concept of streaming or semi-independent sub lobes of the Puget Lobe of the MIS 2 ice sheet.

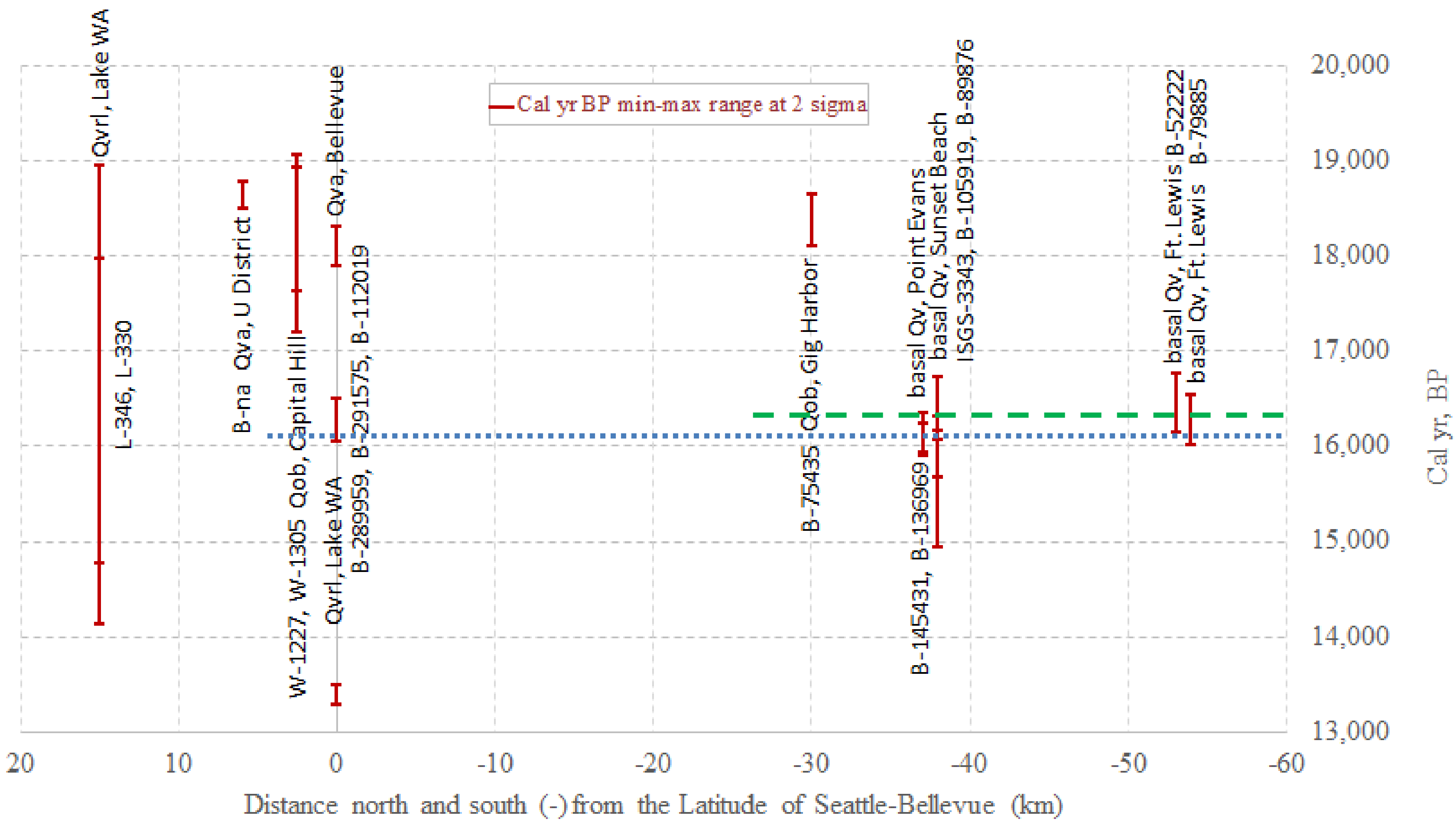


Figure 5-4. Limiting ^{14}C ages for the advance and retreat of the MIS 2 ice sheet.
The blue dotted line shows the earliest age at which recessional deposits could have accumulated, at 16150 cal yr BP. The green line shows the latest age at which the ice sheet must have still been present in the Tacoma area, at 16350 cal yr BP.

The Fraser glaciation in the Puget Lowland expresses the Last Glacial Maximum (LGM) for the piedmont ice-sheet advance in the region, although it occurred one to several thousand years later than most other Northern Hemisphere ice sheets (Porter and Swanson, 2008). Only one other glaciation reportedly extended further than the LGM, most likely the Double Bluff-age ice advance (Figure 5-5, and see subsection below) (Lea, 1984).

The Cordilleran Ice Sheet covered the Puget Lowland to a maximum depth of about 1,500 m (Booth, 1987) during the Vashon stade of the Fraser glaciation. Deposits of the Vashon stade express a wide variety of textural characteristics and topographic expression, owing to rapidly changing depositional environments caused by the advance and retreat of the ice sheet, as described in the following subsections.

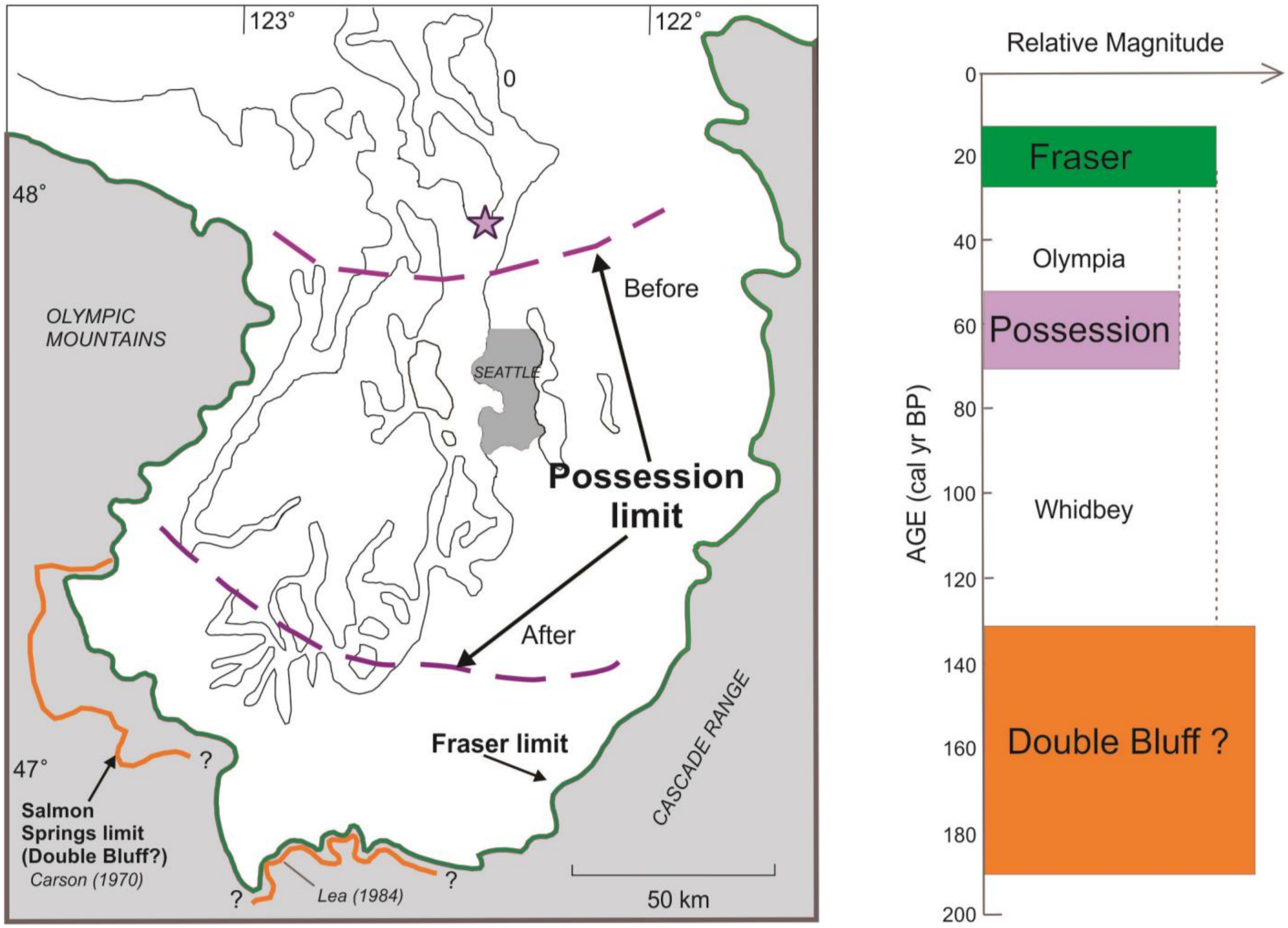


Figure 5-5. Map showing relative extents of the Vashon (MIS 2), Possession (MIS 4), and Double Bluff (MIS 6) ice sheets. The star marks the location of the Double Bluff type section. “Before” position of the Possession-age ice limit marks state of the knowledge prior to this study. “After” marks the ice limit determined from study.

5.1.1 Lawton Clay – Advance of the Cordilleran Ice Sheet

As the ice first advanced, it blocked northward lowland drainage out the Strait of Juan de Fuca, which now connects Puget Sound with the Pacific Ocean. In the impounded lakes that formed in the course of establishing southerly drainage out of the Puget Lowland, laminated silt and clay were deposited. This material was first named and mapped in the Seattle area as the "Lawton Clay Member of the Vashon Drift" (Waldron et al., 1962) with a type section at Discovery Park in Seattle (Appendix B., Photographs 9 and 10). Equivalent deposits to the east and west were later named "Transitional beds" (Minard and Booth, 1988; Yount et al., 1993), because the mappable were recognized to potentially include deposits of pre-Vashon (i.e., MIS 3) lowland lakes as well as those formed in the subsequent ice-dammed environment. Current usage, reverting back to the terminology of Mullineaux et al. (1965), is "Lawton Clay", particularly where dropstones or other indications of a proglacial environment are present. Conversely, absolute age dating has provided more certain identification of MIS 3 deposits of similar lithological characteristics.

The Lawton Clay is discontinuous and likely consists of diachronus lake deposits from the northern to the southern extent of the Puget Lowland. Given the amount of relief expected on the Olympia-age paleotopographic surface, over which these lake sediments were deposited, the Lawton Clay should consist of relatively continuous deposits in the Seattle area, but forming more linear deposits in the Tacoma area and farther south. In Seattle, the Lawton can reach thicknesses of over 50 meters. In Tacoma, the thickest section of Lawton Clay is 30 meters in a linear channel.

The Lawton Clay varies from silt to clay and from low-plasticity silt to low plasticity clay, depending on texture and clay mineralogy. It locally contains finely disseminated organics and rare detrital wood pieces, especially near its base. The unit varies from massive to rhythmically bedded light gray silt and dark gray clay. Pollen is mostly absent from the deposit (Leopold and Crandell, 1958); however insect fragments are present (Ashworth and Nelson, 2014). Calcareous concretions are present and of varying shapes, saucer to branch shaped, likely inherited from the original organic matter that triggered precipitation. Vivianite, a secondary replacement mineral, is also present in the Lawton Clay and other glaciolacustrine deposits in the Lowland. The presence of this mineral indicates that phosphate material was present during deposition, and it commonly occurs with marine and bone fossils.

Secondary permeability is higher than primary because fine sand partings and joints are common throughout the deposit. Water is often seen seeping from the top of the unit and from joints during the wet season. Landslide failure involving the Lawton Clay often produces large blocks and cubes, expressing the preferential fracturing along these joints.

The Lawton Clay is difficult to identify unequivocally in outcrop in the absence of absolute dates or fully gradational sequences through overlying sandy advance outwash up into the Vashon till. New radiocarbon and luminescence dates, however, (Tables A-1 and A-3) confirm previous limiting ages provided by Mullineaux et al. (1965) and demonstrate multiple localities of the Lawton Clay.

5.1.2 Esperance Sand and the Advance of the Cordilleran Ice Sheet

Vashon advance outwash, the fluvial deposit associated with the advance of the Puget Lobe into the Puget Lowland during MIS 2, was first formally defined as the Esperance Sand by

Mullineaux et al. (1965) (Appendix B, Photographs 6-10). The Esperance Sand consists predominantly of well-sorted fine to medium sand, which commonly coarsens upward to gravel and fines downward (where exposed) to a gradational contact with the Lawton Clay. The outwash deposits are relatively continuous in upland areas, absent where they abut higher relief of older topography, and absent where they have been eroded from subglacial channels, such as Puget Sound and Lake Washington (Booth and Hallet, 1993). This deposit inundated the pre-Vashon topography of the lowland and resulted in a south-sloping surface at about 120 m (400 ft) elevation in the Tacoma area (Booth, 1994). Thickness varies from less than a meter to over 100 meters. Lateral variability in thickness is substantial, however, and is well displayed in a cross section from the Brightwater Sewer Tunnel in south Snohomish County (Figures 5-6 and 5-7). The degree of iron oxidation varies significantly throughout the unit depending on exposure and groundwater flow. In the Tacoma area, it is common for the Esperance Sand to directly overlie a pre-Vashon outwash or fluvial deposit rather than Lawton Clay (which is commonly absent farther south in the Lowland).

Minor detrital wood and finely disseminated organic matter have been noted in the outwash. This material has provided local opportunities for radiocarbon dating, of which a particularly useful limiting age on the Vashon advance outwash, 17,800 cal yr BP, was determined from detrital wood in an excavation in downtown Bellevue (Table A-1; date from K. Troost, reported in Porter and Swanson, 1998).

Other ages, radiocarbon and luminescence, were obtained for the Esperance Sand (Tables A-1 and A-3). The deposit accumulated over a time period of about 17,750 to 17,000 cal yr BP (Porter and Swanson, 1998; and this study).

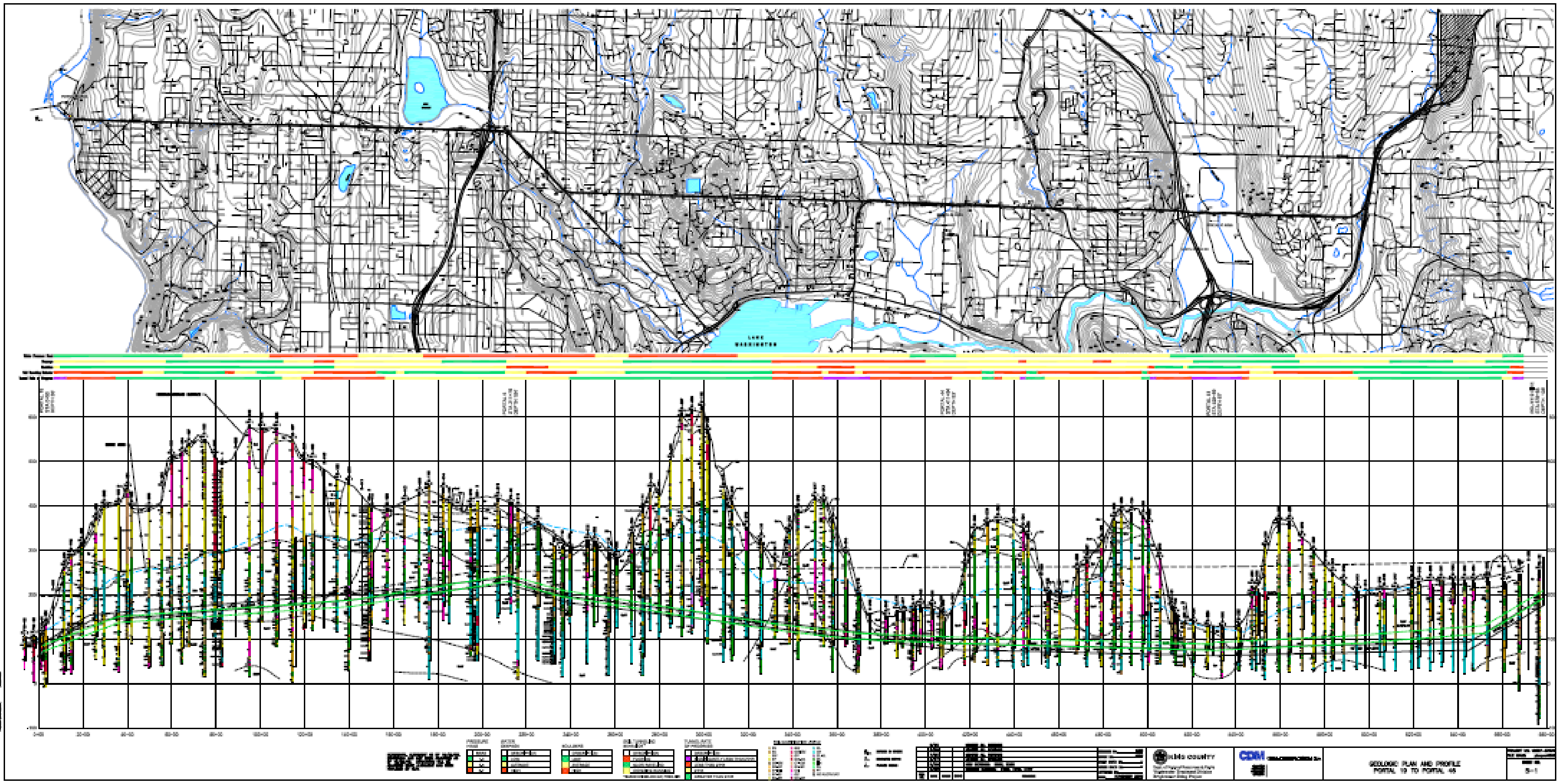


Figure 5-6. Map showing location of Brightwater alignment in Snohomish County.
From McCormack (2002, 2005).

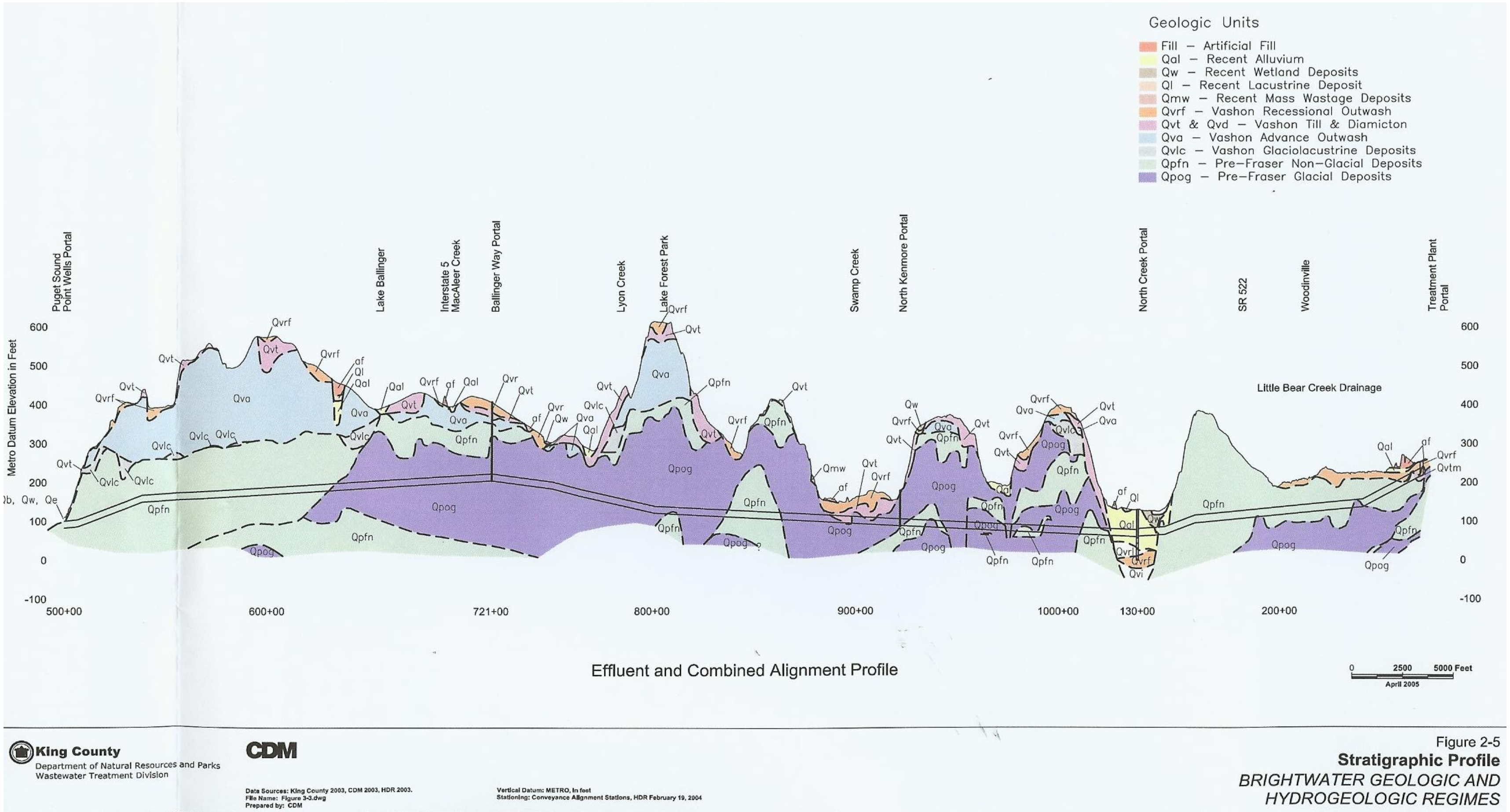


Figure 5-7. Stratigraphic profile of the Brightwater tunnel alignment.
The uppermost unit "Qpog" correlates with the Possession drift; the lowermost "Qpog" correlates with the Double Bluff drift. The uppermost unit "Qpfn" correlates with the Olympia Formation; the lowermost "Qpfn" correlates with the Whidbey Formation. Other unit symbols on Figure 5-17. From McCormack (2002, 2005) and McCormack and Troost (2016).

5.1.3 Vashon till

As ice covered the region, Vashon till was deposited by the melt-out of debris at the base of the Cordilleran Ice Sheet. This heterogeneous, compact sediment discontinuously blankets the area to depths of, at most, a few tens of meters; the ground surface underlain by this deposit is locally fluted with elongated hills displaying a weak but uniform orientation.

The Vashon till was once mapped as a near-continuous surficial deposit across the constructional land surface across the Puget Lowland. Mapping over the last two decades by Troost and Booth supported by tens of thousands of subsurface explorations, however, show that the till is not nearly as continuous as once believed. The simplified geologic map of Seattle (Troost et al., 2005) displays the discontinuous nature of the Vashon till. It is likely that even in some of the more continuously mapped areas of till, additional detail would show the till to not be as continuous there as well.

The base of the Vashon till is a mappable unconformity. Till drapes the pre-Vashon topography locally in erosional contact with any of a number of underlying units. Because the till drapes an irregular surface, the bottom elevation typically ranges from around 120 m (400 feet) above sea level to well below sea level. The contact between the till and underlying advance outwash is gradational in places and sharp in others in about equal measure (Troost, 2006) (Appendix B, Photographs 5 and 6).

Thicknesses of Vashon till range from less than a meter to several tens of meters. It is typically a very dense, matrix-supported deposit of gravelly sandy silt to gravelly silty sand. In Seattle, the till varies from homogenous basal till to subglacial meltout till in origin. Mr. William Laprade (Shannon & Wilson, Inc., 2002, personal communication) has noted that the till on the lee sides of hills typically contains many more intercalated sand and gravel lenses than on the stoss sides. In the Tacoma area, much of the till appears to be from subglacial meltout processes, given that the till is thin and contains abundant sand and silt lenses.

The matrix of the till differs from place to place in relative proportions of clay, silt, and sand, but mostly it is silty sand to sandy silt. Voids have been noted in the Vashon till at excavation sites and in boreholes (Mr. Ed Heavey, Landau Associates, 2001, personal communication). In many places, the till is substratified and contains lenses of sand, gravel, and silt. Rock fragments, scattered throughout the till, are mostly pebble to cobble size; boulders more than 1 m in diameter are uncommon, and only a few more than 4 m in diameter have been seen. The unoxidized till is light gray and compact; the oxidized till is light yellowish gray and is generally loose. Although a weak brown soil tends to develop on the till, oxidation rarely extends more than about one meter below the surface. Clast lithology within the Vashon till is relatively consistent except locally the till contains clasts of underlying bedrock (i.e. Appendix B, Photograph 4).

The Vashon till normally has a low hydraulic conductivity value because of its fine-grained matrix and degree of compaction. However, the presence of fractures (Appendix B, Photograph 3) and sand lenses (Appendix B, Photograph 2) significantly increases the secondary hydraulic conductivity by two or more orders of magnitude (Galster and Laprade, 1991). Near-vertical and subhorizontal fractures in the till are likely the result of multiple factors: lateral stress relief at coastal bluffs, freeze-thaw cycling, root penetration, isostatic rebound and depression, and tectonic and glaciotectonic compression. One or more of these conditions are present in most settings; consequently, when undercut, large blocks of the till can fall from steep faces as intact masses.

5.1.4 Recessional deposits and features

New dates obtained during my study further limit the timing of retreat of the Vashon ice sheet from the southern Puget Lowland. These dates, from the Tacoma and Gig Harbor areas, place the ice in the Tacoma area at close to 16250 cal yr BP (Table A-1, Figure 5-4). Timothy Walsh (Washington State Department of Natural Resources, 1995, written communication) has also collected organic material from below Vashon till yielding relatively young limiting dates for the recession of the ice sheet. These young ages are in seeming conflict with limiting recessional dates from the northern Puget Lowland but they are consistent with new limiting dates obtained on recessional lacustrine deposits at between 16,506 and 16,512 cal yr BP in Lake Washington (Troost, 2011). These young dates suggest that the ice broke up nearly instantaneously in the north, central, and southern reaches within Washington.

As the ice sheet wasting began, meltwater drained into the axis of the Lowland but could not follow what would become its modern drainage path north and west out the Strait of Juan de Fuca, because the strait was still filled with many hundreds of meters of ice. Instead, meltwater was diverted into the Lowland south of the retreating ice sheet, coalescing into ever-broader rivers.

During this period, proglacial lakes formed south of the retreating ice front, draining through a spillway to the Chehalis River (Bretz, 1913). The first of these basin-wide lakes to form, named glacial Lake Russell by Bretz (1913), began as a smaller lake occupying the southern extent of the main Puget Sound trough. As more subsidiary troughs became ice-free, the lake enlarged in extent as the ice continued to retreat (Figure 5-8). Other, isolated lakes that had formed in valleys to the east and west of Puget Sound eventually coalesced into a single lake, Lake Bretz (Waitt and Thorson, 1983; originally named Lake Leland by Thorson, 1980), which enlarged northward as the ice front retreated until ultimately a northern marine spillway into the Strait of Juan de Fuca was uncovered.

In Seattle, Vashon recessional lake deposits began accumulating in the Lake Washington trough by 16,575 cal yr BP (Troost, 2011), and continued throughout (and following) the retreat and ultimate collapse of the Puget Lobe. Glacier Peak ash, dated at 13,710–13,410 cal yr BP by Kuehn et al. (2009), was encountered in these deposits during drilling for the new SR-520 Bridge (Troost, 2011).

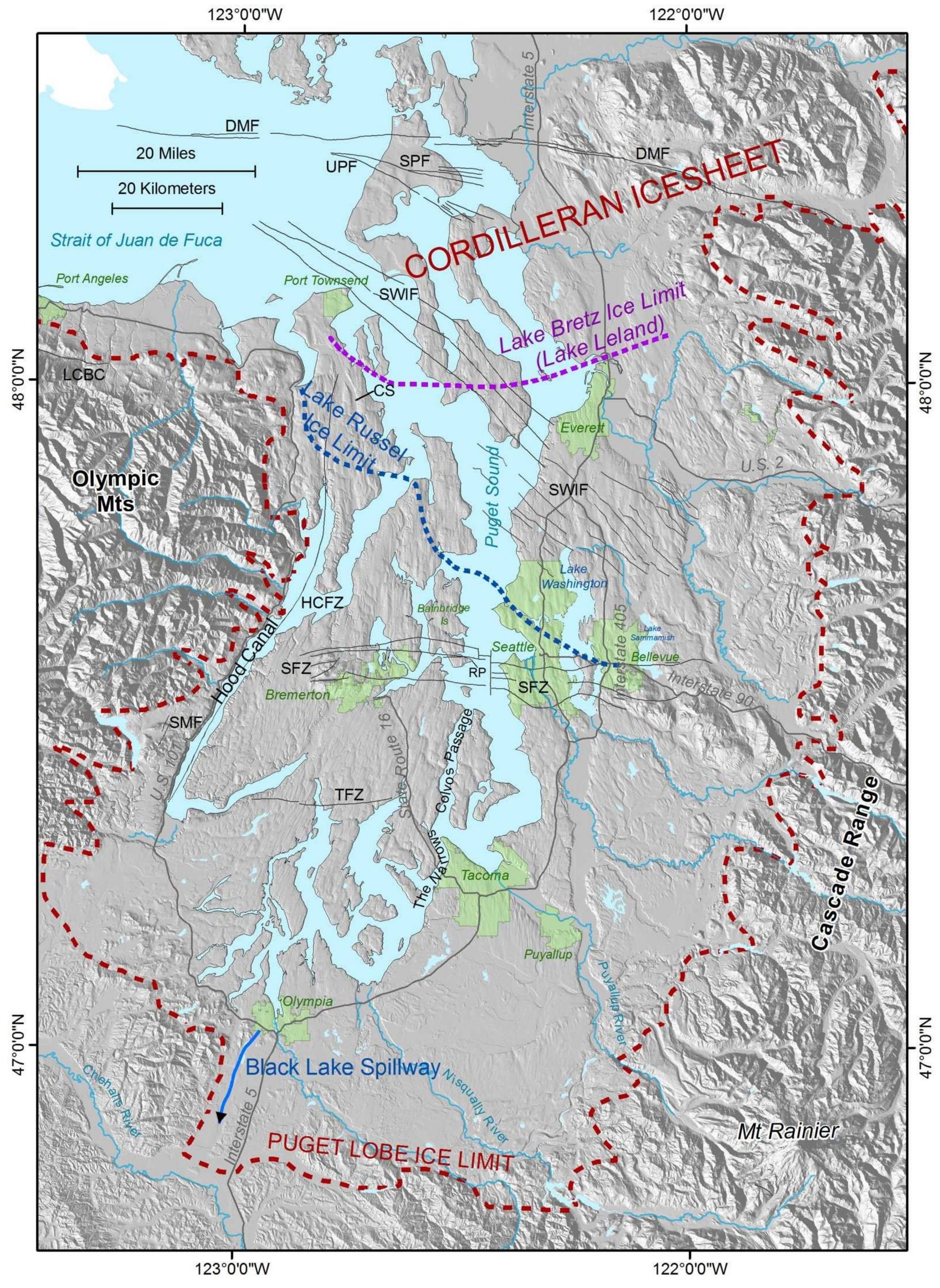


Figure 5-8. Image showing the Vashon recessional lake extents, together with active faults.

Water level in glacial Lake Russell was controlled by its south-draining outlet elevation in the Black Hills near Olympia. Water level in glacial Lake Bretz was controlled by its north-draining outlet elevation via the Chimacum valley, south of Port Townsend (Haugerud, 2006). Thorson (1989) mapped two of the ice limits responsible for major glacial lakes in the Puget Lowland (Figure 5-8). Subsequent mapping (Troost and Wisher, 2008, 2009, 2010; Haugerud, 2006) shows that more than two major lakes filled the lowland, but the most significant, with respect to obvious shorelines, are Russell and Bretz.

Once the Puget lobe had wasted enough so that the ice dam separating the Puget Lowland from the Pacific Ocean breached (or floated), seawater reentered the lowland through the Strait of Juan de Fuca. Marine water inundated the Lake Washington trough at around 14,800 cal yr BP (Troost, 2011). Glaciomarine drift accumulated in the northern lowland where land had not yet rebounded from isostatic depression. This interstade—named the Everson interstade by Armstrong et al. (1965)—ended in the Seattle area by about 14,700 cal yrs BP (Troost, 2011). Isostatic rebound subsequently raised the glaciomarine and marine deposits of Everson age above sea level between about 14,500 cal yr BP in Seattle (Troost, 2011) to 13,000 cal yr BP in the northern lowland (Dethier et al., 1995; Peterson et al., 1983; Waters et al., 2011).

During ice recession, streams built thick Gilbert-type deltas where entering proglacial lakes (Porter and Swanson, 1998). Outwash accumulations in these deltas reach 60 m in thickness (Figure 5-9) (i.e. Appendix B, Photograph 1).

In central Pierce County, multiple recessional channels cross the Steilacoom Plain (Figure 5-9) likely having conveyed water during repeated jökulhlaups (Troost, 2007) from glacial Lake Puyallup southwest into glacial Lake Russell, the main proglacial lake along the axis of the Puget

Lowland. As the ice receded to the north, progressively lower channels were carved and so were occupied with meltwater. The Steilacoom Gravel, defined by Willis (1898) and Bretz (1913), comprise the deposits that formed from or were reworked by the discharge of glacial Lake Puyallup.

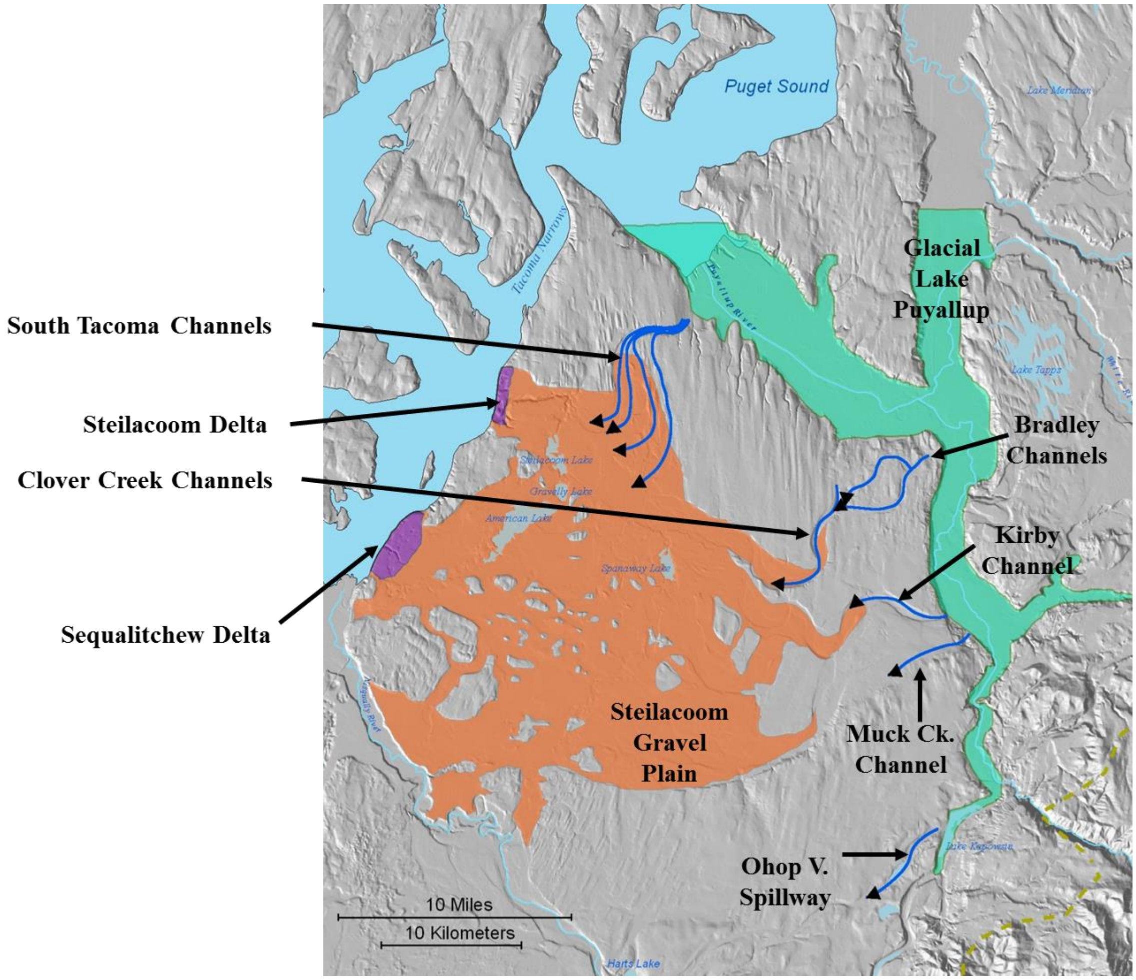


Figure 5-9. Map of jökulhlaup deposits and channels in Pierce County.
From Troost, 2007.

Localized lake deposits are present along the margins of former glacial lakes Russell and Bretz. They consist of normally consolidated, stratified, silt and sand, ranging in thickness from less than a meter to tens of meters. Swelling clays are present in some of these lake deposits or in isolated recessional lake deposits (Mr. Richard Smith, CDM, 1999, personal communication).

The swelling clays are likely the result of weathering of Glacier Peak ash, which was deposited during recessional lake occupation of the lowland.

In Seattle, Vashon recessional outwash and recessional lake deposits occupy valleys that form anastomosing channels with deep pockets tens of meters thick, filled with loose sand and soft silt and clay. The channels are graded to former recessional lakes in Puget Sound and Lake Washington. Peat bogs developed in the upstream ends of many of these recessional channels.

5.1.5 Vashon-age ice-contact deposits

Numerous areas of Vashon-age ice contact deposits are present across the Puget Lowland, particularly (but not exclusively) in the southern part of the lowland where deglaciation must have occurred rapidly. Kettle complexes, eskers, and kame terraces are all represented in these landforms. In addition glaciotectonically deformed deposits are present. Kame-terrace deposits are composed of glaciofluvial sand and gravel deposited between a valley wall and active or stagnant ice, and they typically include steeply dipping stratified sand and gravel with diamicton lenses. Kame-terrace deposits occur in the Tacoma area along the west wall of the Green River Valley north of Sumner. They are good sources of sand and gravel and have been extensively mined.

Kames are isolated mounds or hummocks of irregular drift deposited in ice-walled depressions; they are commonly associated with kettles, depressions or lakes scattered across recessional outwash surfaces that mark the location of melted-out ice blocks. Most kames consist of poorly sorted and poorly bedded sand and pebble to cobble gravel, in which steep foreset bedding and slump structures are common.

Kettles and lines of kettles are common across the lowland landscape. Black Point on Hood Canal is an excellent example of stagnant ice terrain, its position consistent with a northern outlet for glacial Lake Bretz. Likewise, an area of numerous kettles is present near the Nisqually River valley, along a recessional outwash channel. In addition to areas of concentrated kettles, lines of kettles and individual kettles are distributed across the lowland surface. Two lines of kettles cross the Steilacoom plain demarking a grounding line for ice blocks in the discharge water. The largest and deepest of these is American Lake in Pierce County at 27 m (90 ft) deep and nearly 3.2 km (2 mi) long. American Lake itself is likely the result of a group of kettles, lodged against each other during the waning flow of one of the jökulhlaups (Troost, 2007). Most of the crudely circular lakes on the upland surface of the Puget Lowland are likely kettles. The best known is probably Green Lake in Seattle (Booth et al., 2009), which is surrounded by a heavily visited park. Former kettles are commonly filled with saturated peat and organic silt and are susceptible to consolidation with time and/or dewatering (Troost and Wisher, 2007). Greenwood bog in Seattle is one such example (Booth el al., 2009). Differential settlement of structures built over this feature subsequently led the City of Seattle to regulate development on buried peat deposits.

In the last fifteen years, the use of LiDAR (Haugerud, et al., 2003) has revealed many more glacially-derived landscape features than previously recognized, particularly eskers. Eskers, sinuous ridges of recessional sand and gravel, are typically found within and parallel to large glacially-carved recessional channels, and they are generally assumed to have originated in subglacial channels (Boulton et al., 2007; Brennand, 1994). Two good examples are in Kelsey Creek Farm in Bellevue (Troost and Wisher, 2009) and on the east side of the Key Peninsula between Minter Creek and Glen Cove (Logan et al., 2006).

5.2 Olympia Formation – MIS 3

The Olympia nonglacial interval was originally defined by Armstrong et al. (1965) as “the climatic episode immediately preceding the last major glaciation, and represented by nonglacial strata beneath Vashon Drift.” The type section for the Olympia nonglacial unit is at Fort Lawton (Mullineaux et al., 1965). Correlative deposits t the type section and elsewhere, called "Olympia beds” by Minard and Booth (1988), are most easily identified by provenance of clastic detritus, depositional environments, and age. I herein name these deposits the Olympia formation, for three reasons: 1) extensive deposits have been identified in the Puget Lowland making this a mappable geologic unit, 2) Armstrong et al. (1965) had already coined the term, and it has enjoyed long-standing use by worker throughout the Puget Lowland; and 3) alternative nomenclature, such as “Olympia beds” is unnecessarily awkward.

The Olympia formation accumulated between about 60,000 and 15,000 years ago, the limiting ages of MIS 3 and the Fraser glaciation (MIS 2). Because nonglacial deposits of the Olympia formation do not have a uniquely distinguishing lithology, they can only be identified stratigraphically by direct or indirect radiometric age or positive identification of Mount St. Helens set Cy-Cw ash, dated at about 50 ka (Berger and Busacca, 1995).

Both radiocarbon and luminescence dates have now been obtained on deposits throughout the Puget Lowland that demonstrate correlation with the Olympia formation (Tables A-1 and A-3). A number of localities of Olympia formation, well beyond those of the type section, have now been identified. For example, dating allowed the recognition and mapping of thick Olympia formation deposits in the Edwards Point and north Woodinville areas (Figures 5-6 and 5-7). Previously, forty radiocarbon dates on peat and paleosols confirmed their correlation with the Olympia nonglacial interval (Troost and Borden, 1996; Borden and Troost, 2001; Troost, 1999).

At least five Olympia-age tephras and lahars have been identified near Tacoma, with source areas including Mt. St. Helens and Mt. Rainier. Fourteen radiocarbon dates were obtained on the Olympia formation for the Brightwater sewer tunnel investigation (McCormack, 2002 and 2005; McCormack and Troost, 2016). Overall, the topographic relief on the Olympia formation is likely greater than 230 m, ranging as high as 170 m above sea level and 60 m below modern sea level.

The Brightwater geologic cross section displays much about the distribution of the Olympia formation (Figures 5-6 and 5-7), with a paleosurface around 60 m (200 ft) to 90 m (300 ft) in elevation and a bottom depth of below -30 m (-100 ft) in elevation. The thickest occurrence is nearly 90 m (300 ft) near Point Edwards, south of Edmonds at the west end of the tunnel alignment. The Esperance Sand (Vashon advance outwash) is likewise at its thickest at the west end of the alignment. Puget Sound may have existed as a basin/lowland during the Olympia time (MIS 3) since these thick deposits are immediately adjacent to the modern Puget Sound trough. The Olympia formation is significantly thinner on the east side of I-5: 30 m (100 ft) and less, vs. 90 m (300 ft) thick to the west. The Olympia formation is absent in some deep valleys and troughs, indicating that the troughs were scoured during the Vashon stade, or at least were deepened during the Vashon stade. An Olympia-age paleosol and some thin Olympia deposits are present in the subsurface of the Swamp Creek and North Creek valleys, at lower elevations than elsewhere along the tunnel alignment for the top of the formation, indicating that these toughs were present in the Possession paleosurface and at least partially reoccupied during the Vashon stade.

Since the Olympia formation is a dated, mappable unit, it can provide limiting ages on tectonic deformation in the Puget Lowland at a number of locations in the Puget Lowland (Booth et al., 2004b). Examples of relatively tight folding in the Olympia formation can be seen at the Emma Schmitz Memorial overlook, opposite Me Kwa Mooks Park in Seattle, and near the Tahlequah ferry terminal in Tacoma. Some evidence of tectonic deformation of Olympia-age material is suggested by possible anticlinal folding in the Olympia formation visible in the Lake Forest Park area, where older units may also be folded (Figure 5-8). This folding is consistent with deformation within the Southern Whidbey Island fault zone (Sherrod et al., 2005, 2008) and gentle folding of the Olympia formation seen elsewhere in the Puget Lowland (Booth et al., 2004b; Booth et al., 2006).

In the Seattle area, along the U-Link route from downtown Seattle through the University of Washington campus (Figures 5-10 and 5-11), the Olympia formation occurs as high as 120 m (400 ft) and as low as -15 m (-50 ft) in elevation. Thickness ranges from a few meters to nearly 46 m (150 ft). Eight radiocarbon dates were obtained for the subsurface investigation of this tunnel alignment (Northlink Transit Partners, 2007 and 2008). An abrupt, near-vertical contact between the Olympia formation and older glacial drift on Capitol Hill may reflect a former bluff line, a steep valley wall, or an unidentified fault. Whatever the origin, however, it reflects the paleosurface on which the Olympia formation was deposited.

The topographic relief on the Olympia formation is likely greater than 230 m, ranging as high as 170 m above sea level and 60 m below modern sea level (Troost, 2002). The Olympia formation along the west end of the Brightwater tunnel route tops out at about 90 m (300 ft) in elevation; but from about I-5 east to Woodinville, the top is at about 60 m (200 ft) in elevation (Figure 5-9). The Olympia formation is absent in some deep valleys and troughs, indicating that the troughs were scoured during the Vashon, or at least deepened during the Vashon. An Olympia-age paleosol and some thin Olympia deposits are present in the subsurface of the Swamp Creek and

North Creek valleys, at lower elevations than elsewhere along the tunnel alignment, indicating that these toughs were present in the Possession paleosurface and at least partially reoccupied during the Vashon stade.

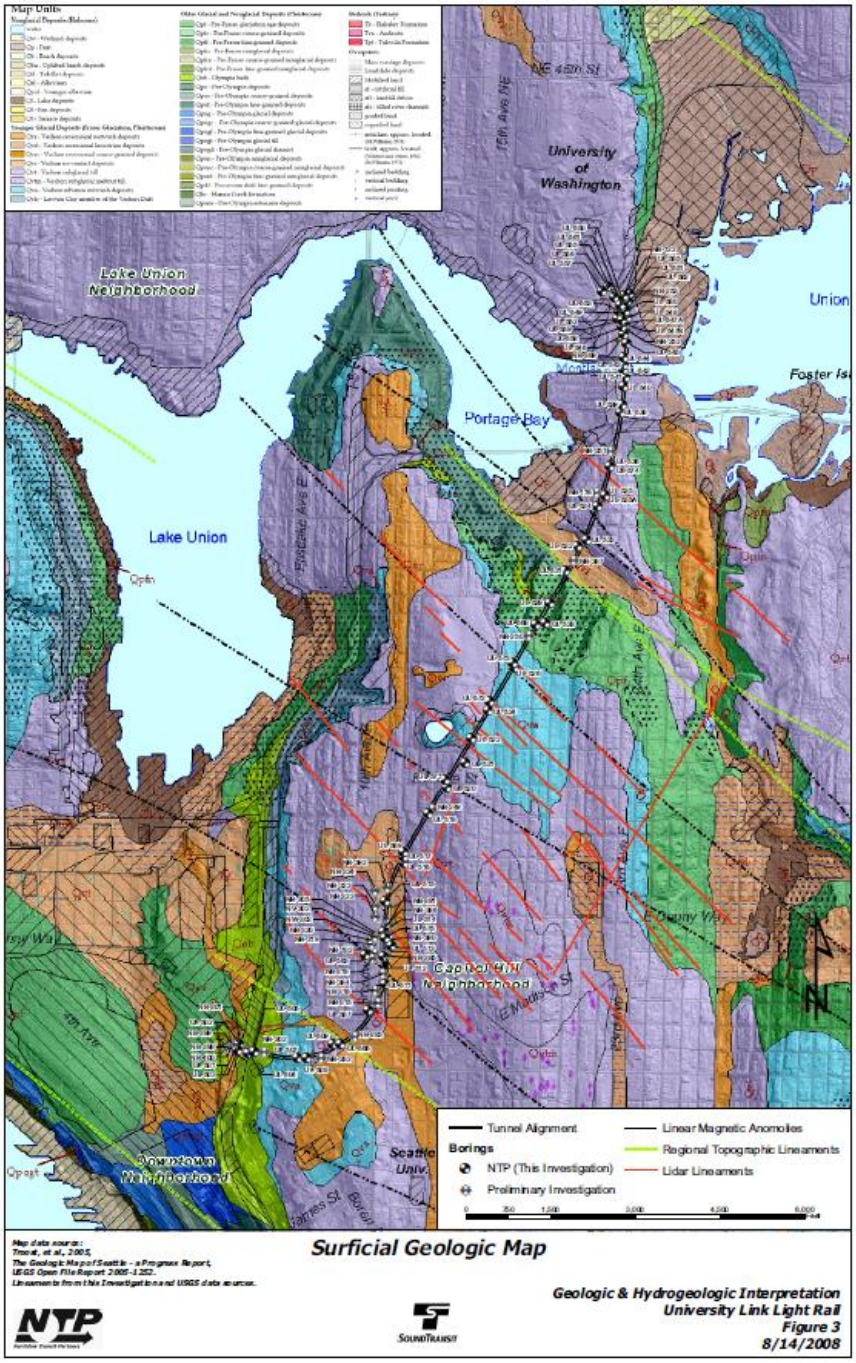


Figure 5-10. Map showing location of University Link route and borings.
From Northlink Partners, 2007 and 2008. Geologic base map from Troost et al., 2005.

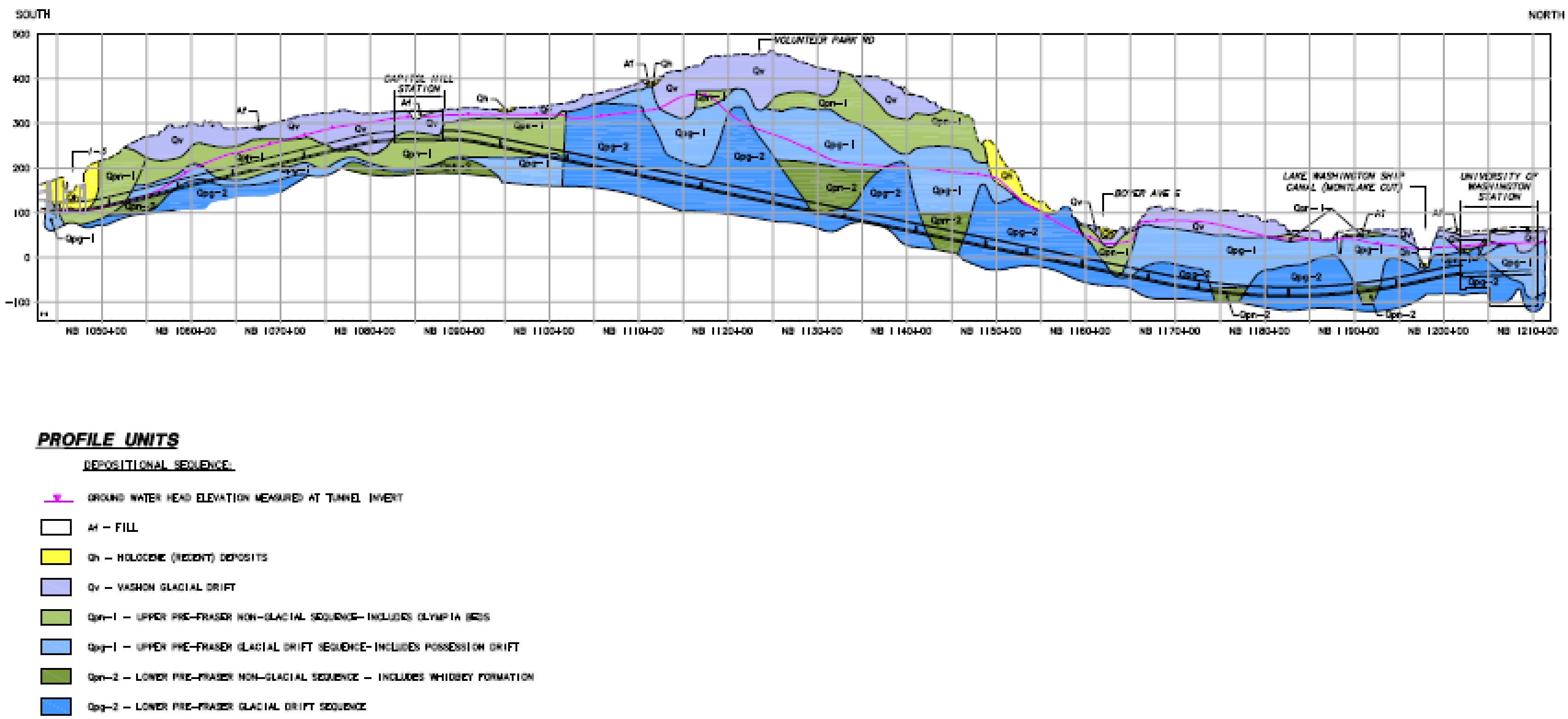


Figure 5-11. Stratigraphic profile of the University Link route.
Unit “Qpg-1” (lighter blue) correlates with the Possession drift. Unit “Qpg-2” (darker blue) correlates with the Double Bluff drift. Unit “Qpf-1” (lighter green) correlates with the Olympia formation. Unit “Qpn-2” (darker green) correlates with the Whidbey Formation. Unit “Qv” (purple) correlates with the Vashon drift. The purple line shows the water elevation in the tunnel zone. The parallel black lines show the proposed tunnel alignment. From Northlink Partners (2007 and 2008).

Criteria for recognizing the Olympia formation in outcrop vary with location, although absent absolute dating there are no uniquely identifying features except the rare presence of Mount St. Helens tephra set Cw/Cy. Near volcanic source areas, common attributes include lavender/gray outcrop color, andesite-rich sand, organic layers and paleosols, diatomite, and tephra. In the central Puget Lowland, away from those streams with headwaters near Mt. Rainier, the Olympia formation contains sand sourced in the central Cascades, and typically also includes peat, tephra, mudflows, and fluvial deposits.

Thickness, elevation, grain size, and composition all vary significantly over short lateral distances. The thickest Olympia formation (> 25 m), found near Tacoma, includes multiple tephra, lahar, peat, and diatomite layers. The lack of Olympia-age lahars and andesitic sand on the west side of Puget Sound suggest that Olympia-age equivalents of Colvos Passage and the Tacoma Narrows channels were present near their current locations during that time, blocking westward transport from volcanic eruptive centers in the Cascade Range.

Paleoecological analyses indicate a wide range of paleoenvironments existed across the Puget Lowland during the Olympia nonglacial interval. Many outcrops of the Olympia formation yield excellent pollen preservation with a predominance of pine and spruce; freshwater diatomite suggesting clear, shallow lakes and large littoral areas; and macrofossils including mammoth teeth and tusks (i.e., Barton, 2002), Pinus sp.?, cones, needles, branches, leaf prints, and in-situ tree roots (Appendix B, Photographs 10-18).

5.3 Late Pleistocene Pre-Olympia Deposits

Abundant but fragmentary evidence of Pre-Olympia glacial and interglacial deposition throughout the Puget Lowland exists. Because the evidence is scattered and discontinuous, however, reconstructions of Pre-Fraser depositional environments and climate are difficult. Only the two latest nonglacial periods (MIS 3 and 5) are reasonably well-described through abundant organic- and pollen-bearing material, good exposures, and absolute dating.

These pre-Olympia, late Pleistocene, deposits in the Lowland have been named as follows (Figure 5-1), with type section locations and outcrop descriptions for those of MIS 4, 5, and 6 age in Easterbrook (Figure 5-2 and Table 2-4).

Possession Drift (Possession Point type section–)MIS 4

Whidbey Formation (at the Double Bluff type section)–MIS 5

Double Bluff Drift (Double Bluff type section)–MIS 6

5.3.1 Possession Drift - MIS 4

Refer to Chapter 6 for a discussion of the Possession Drift.

5.3.2 Whidbey Formation - MIS 5

The Whidbey Formation, named by Easterbrook et al. (1967), correlates with MIS 5 and is considered the "last full interglacial" (i.e., Clark et al., 1993; Helmens, 2014) and spanning 71,000 to 125,000 years ago (Lisiecki and Raymo, 2005). Heusser and Heusser (1981) and Easterbrook (1994) determined that, for the bulk of the exposures of Whidbey-age deposits, the climate was similar to today and sea level may have been slightly higher than today. Global eustatic sea level fluctuated during MIS 5 from well below modern (Lambeck et al., 2002) to as much as 9 m above modern (Muhs et al., 1994, 2006) depending on the climate during each of the substages.

At its type section (Easterbrook, 1994), the Whidbey Formation includes a wide range of sedimentary deposits, from ash and diatomite through gravel, commonly with peat layers. On Whidbey Island, the extensive sand deposits at the type section are thought to be deltaic in origin.

Like the deposits of the Olympia formation, the relief on the Whidbey-age topographic surface across the Puget Lowland may have been similar to today's. Because of the difficulty dating material as old as 100 ka, however, little work has been done to define or reconstruct the paleotopography. Prior efforts (e.g., Johnson et al., 1996) generally lacked any absolute age control to constrain their presumptive correlations and paleotopographic reconstruction, and so their findings are not reliable.

Deposits correlating with the Whidbey Formation (MIS 5) have been confirmed in Snohomish County, Seattle, and Tacoma, based on luminescence dating and paleomagnetic correlations. In Snohomish County, core drilling for the Brightwater sewer tunnel encountered discontinuous Whidbey-age deposits in the subsurface (Figure 5-7). The correlations were confirmed with eight luminescence dates (Table A-3) and the presence of nonglacial indicators. The surface of the Whidbey deposits range from about sea level on the west end to nearly 120 m (400 ft) in elevation at the east end of the tunnel route, north of Woodinville. Therefore, the amount of relief is greater than 140 m (450 ft). Overall, the surface drops from east to west, toward the center of the Puget Lowland, exhibiting some minor fluctuations suggestive of post-depositional folding. Near the Brightwater treatment plant site, north of Woodinville, Whidbey deposits are exposed near the ground surface.

In Seattle, Whidbey age material was sampled at the south end of Magnolia Bluff (Table A-3) and is confirmed in the subsurface along the U-Link route (Figure 5-11) by three luminescence dates below and limiting overlying radiocarbon dates. Along the route, Whidbey-age material is present only in east-west trending buried troughs, which were presumably carved into the older glacial drift by that older ice sheet. These troughs are not expressed at the modern ground surface of Capitol Hill, having been completely filled in by younger deposits and remolded by subsequent glacial and nonglacial processes

In Tacoma, several exposures of Whidbey age deposits have been mapped (Appendix B, Photographs 28, 29, and 32). At the east side of the Tacoma Narrows bridge, just above the RR grade, paleomagnetic measurements yield a transition of normal, to reverse, and back to normal within a thick lacustrine clayey silt (Hagstrum et al., 2002; Booth et al., 2004b). This transition is believed to be the Blake subchron at about 125,000 years, confirmed by a luminescence age of from 91 +/- 7 ka to 133 +/- 6 ka lower in the deposit (Table A-3, samples WA-21-23) and further supported by overlying dated Olympia-age deposits. Drilling and outcrop examination on both sides of the Tacoma Narrows reveals that the thickness and grain size of the Whidbey Formation varies from one side to the other (Figure 5-12). On the west side, the Whidbey Formation consists of fluvial deposits overlying a lacustrine deposit compared to having just lacustrine deposits on the east side. The lacustrine deposit suggests that the Tacoma Narrows area was a basin, or possible trough, prior to the advance of the Possession ice sheet (MIS 4). The provenance of the overlying fluvial deposits suggests andesitic volcanic headwaters; therefore a stream must have flowed from the east across what is now the Tacoma Narrows. The pollen assemblage in the fine-grained lacustrine deposits indicates a warm climate, similar to the modern climate.

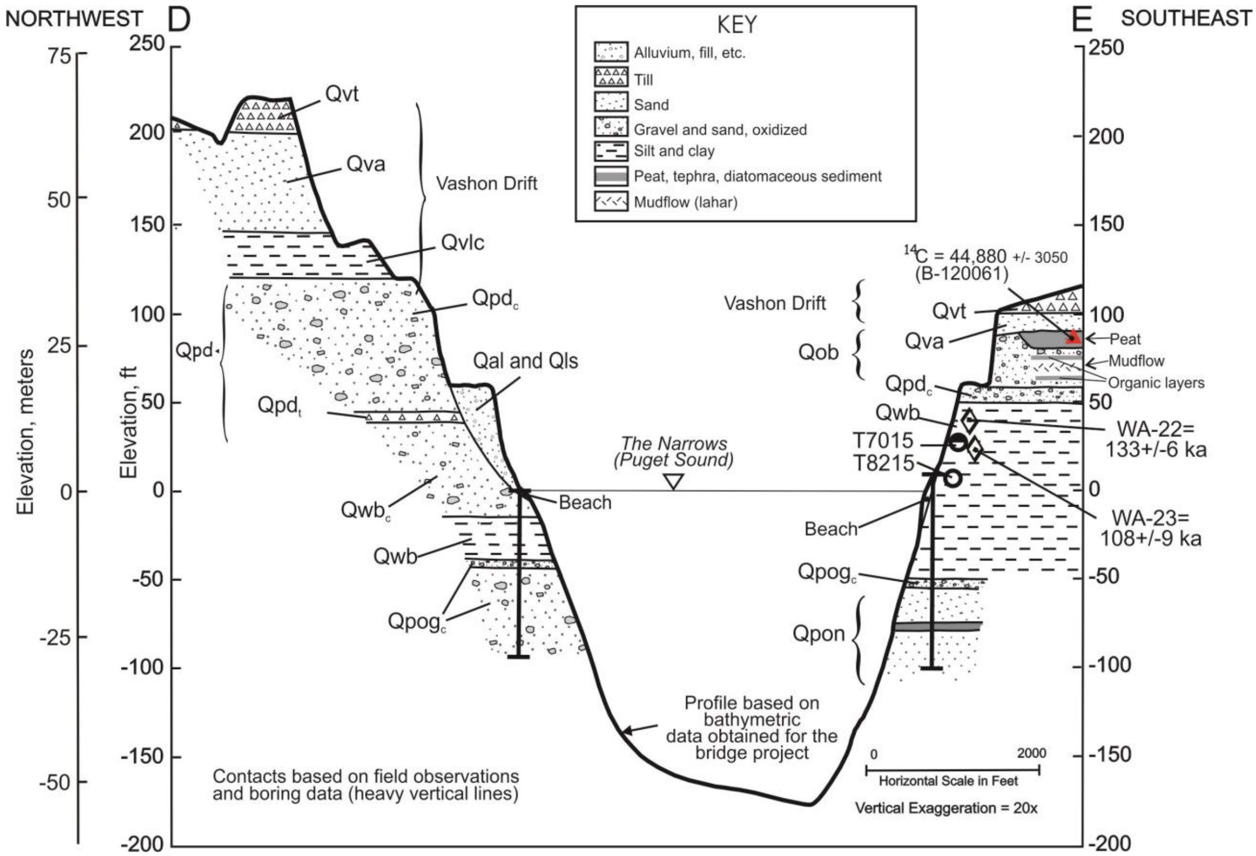


Figure 5-12. Cross section across the Tacoma Narrows at the bridge.
Unit symbols are defined on Figure 5-17 and other symbology defined on Figure 5-16. Boring data from Shannon & Wilson, Inc., 1999, written communication.

Thick fluvial deposits in the Gig Harbor area have also been correlated with the Whidbey Formation through luminescence dating along the coast and at the Point Evan measured section (Figure 5-13). Here, too, volcanic lithology (pumice clasts and andesitic sand) in the fluvial deposits suggests streams flowing across what is now the Tacoma Narrows and perhaps even Commencement Bay.

The Whidbey deposits exhibit gentle folds along the Gig Harbor and Point Defiance coastlines (Figures 5-14 and 5-15). These folds are a series of anticlines and synclines consistent with tectonic and glaciotectonic north-south stresses (Booth et al, 2004b). Folding here involves both older and younger deposits with increased amplitude with increasing age, suggesting progressive folding throughout the Quaternary.

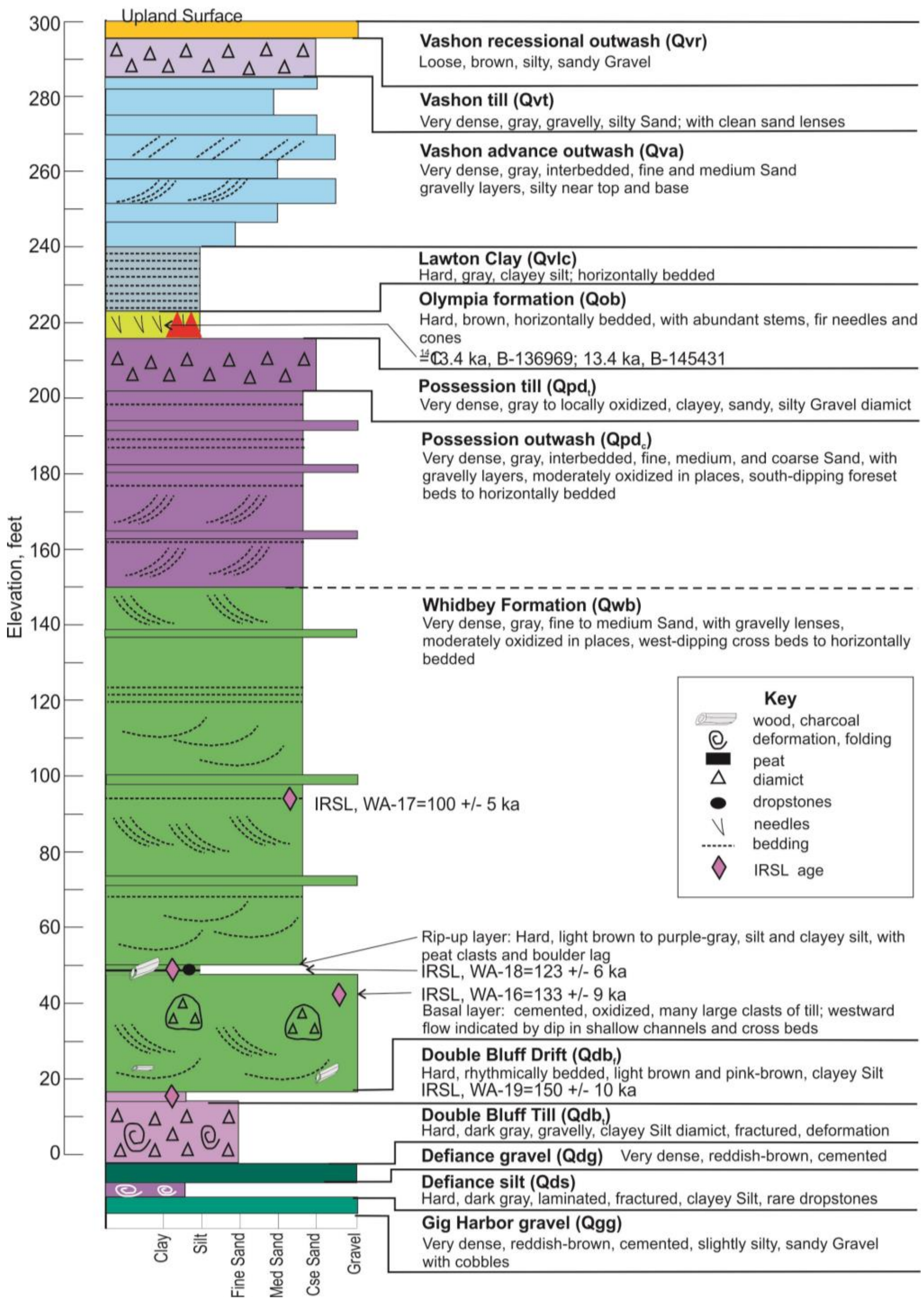


Figure 5-13. Point Evans measured section.
Location shown on Figure 3-1. Appendix B, Photographs 26-29.

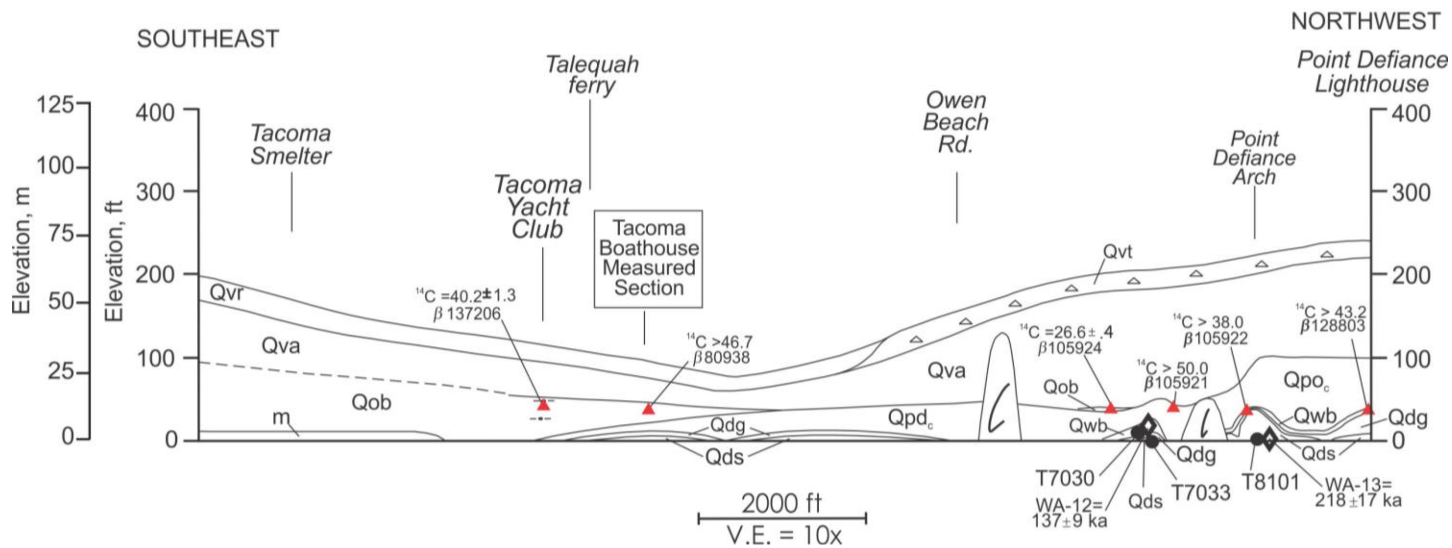


Figure 5-14. Bluff sketch along northeast side of Pt. Defiance.
Figures 5-16 and 17 contain keys for symbology used and geologic unit definitions. From Troost et al., in review.

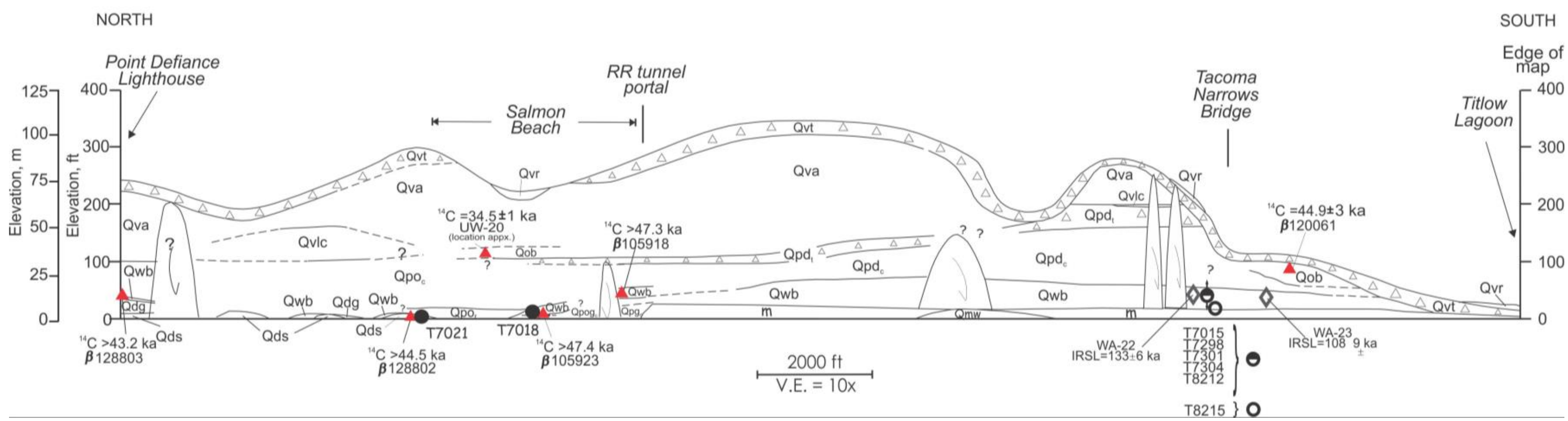


Figure 5-15. Bluff sketch along east side of the Tacoma Narrows.
Figures 5-16 and 17 contain keys for symbology used and geologic unit definitions.

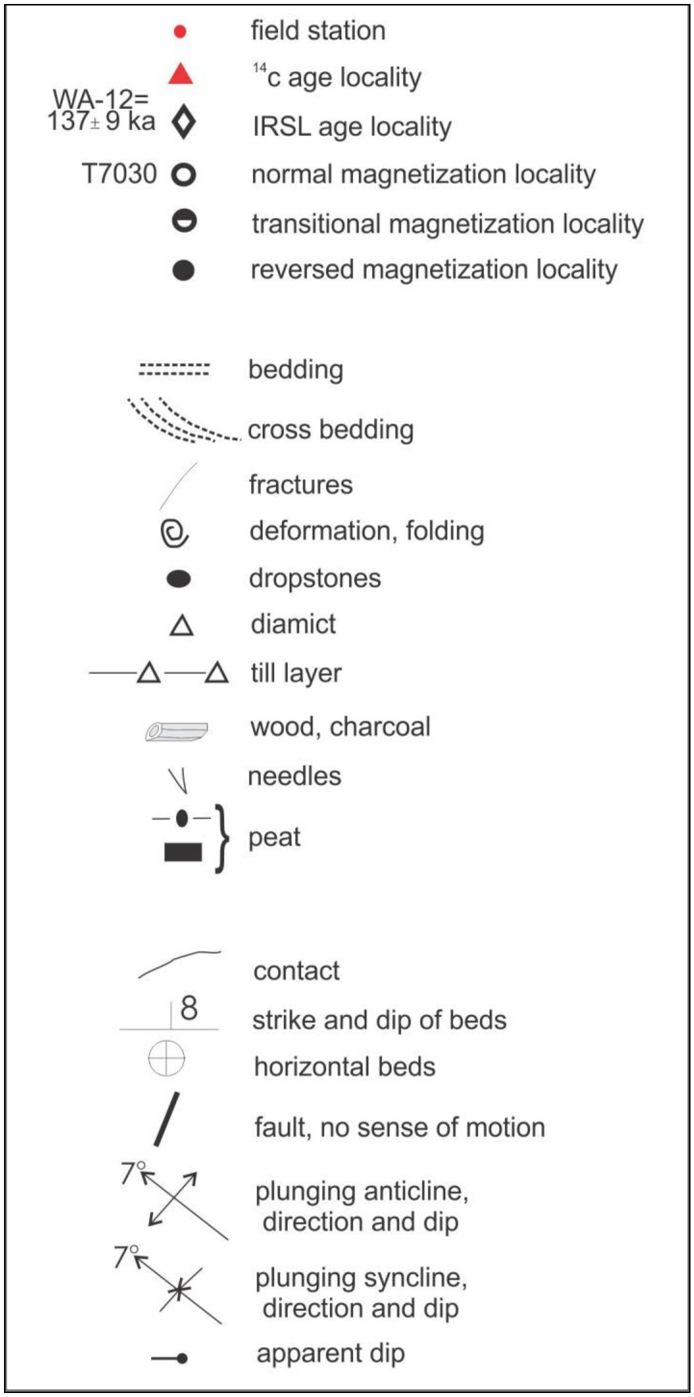


Figure 5-16. Key to the cross sections, measured sections, and bluff sketches.

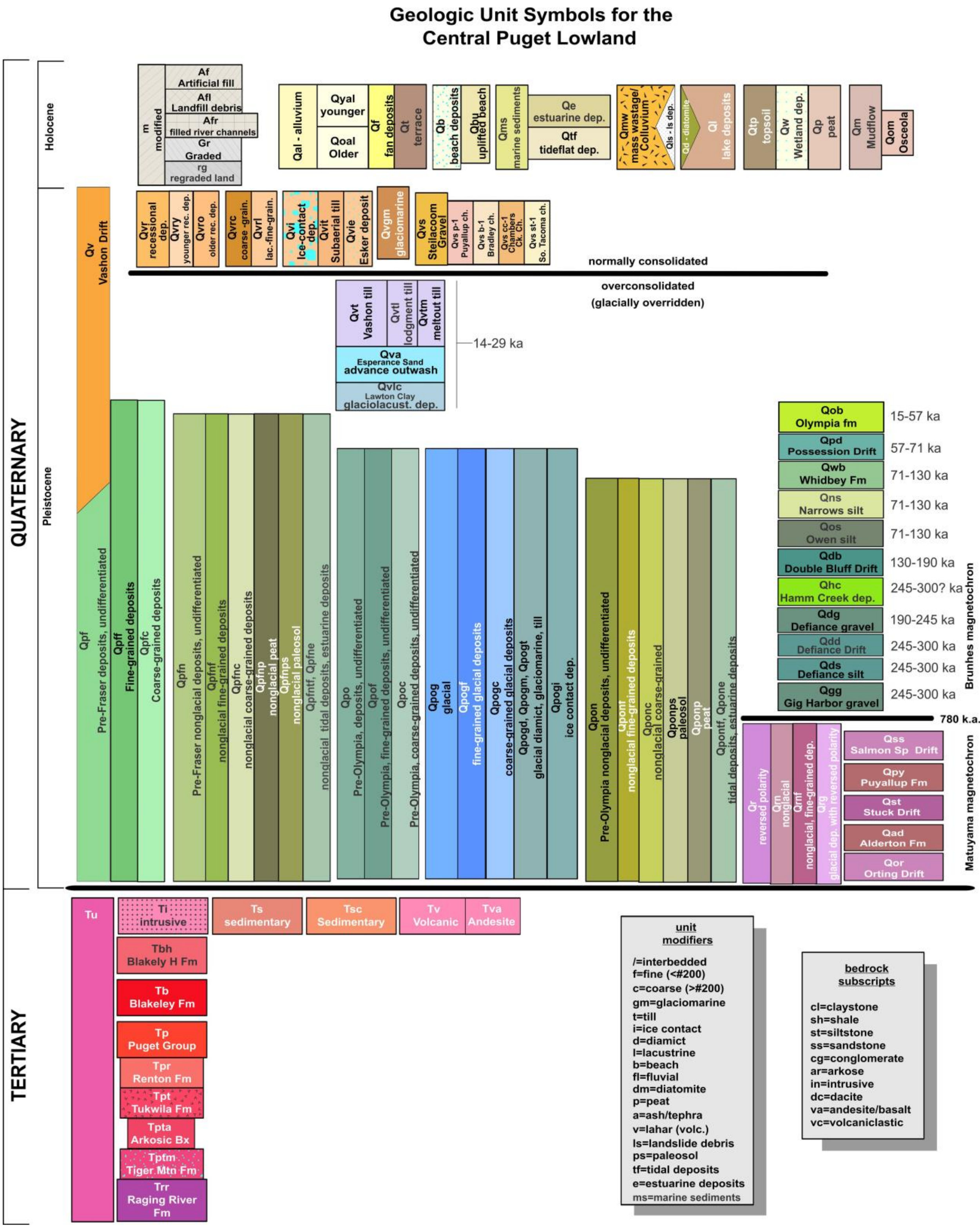


Figure 5-17. Geologic unit symbols and correlation chart.

5.3.3 Double Bluff Drift - MIS 6

The Double Bluff Drift, named for its type section on Whidbey Island by Easterbrook et al. (1967) had not been confirmed south of Whidbey Island prior to this study. Deposits correlating with the Double Bluff Drift are now recognized to be present in Snohomish County and the Tacoma area, based on luminescence dating (Table A-3).

The Double Bluff Drift, correlative with MIS 6, dates to glaciation by the Cordilleran Ice Sheet during the cool climate from 130 to 190 ka (Lisiecki and Raymo, 2005). Based on sea-level curves and ice volume estimates, glaciation during MIS 6 was likely more extensive than during MIS 4 or 2 (Figure 5-5). In the Puget Lowland, Lea (1984) mapped moraine remnants as Double Bluff Drift age, based on weathering rind thickness on basaltic and andesitic clasts (Colman and Pierce, 1981), a few km outside of the maximum Vashon (MIS 2) ice limit.

In Snohomish County, along the Brightwater tunnel route, three luminescence dates confirm the presence of the Double Bluff Drift in the subsurface (Figure 5-7). Like the surface of the Whidbey Formation deposits, the Double Bluff deposits drop in elevation from east to west. At the east end of the route, Double Bluff deposits reach an elevation of 53 m (175 ft), but drop to near sea level west of Swamp Creek. Because these glacial deposits were encountered close to modern sea level in the borings, only a few occurrences were encountered. Most of the occurrences are associated with apparent anticlinal folding in which these older deposits were uplifted, within the reach of the borings.

In the Seattle area, Double Bluff Drift is confirmed in the subsurface of Capitol Hill (Figure 5-11) based on three luminescence dates (Table A-3). The Double Bluff Drift is relatively continuous north of about the latitude of Mercer Street north to the UW district, and its surface drops to the north. South of Mercer Street, the surface of the Double Bluff Drift drops in elevation to the south. A steep face is present at the south end of the deposit at about Mercer Street. Deep troughs in the surface of the Double Bluff Drift suggest that numerous troughs were carved into the deposit, possibly by subglacial streams similar to what happened in the Puget Lowland during MIS 2 (Booth, 1994).

In the Tacoma area, Double Bluff Drift was also confirmed by using luminescence dating (Figure 5-18, Table A-3). Along the west side of the Tacoma Narrows, the Double Bluff Drift (Qdb on Figure 5-18) occurs in a series of anticlines and synclines at the top of the beach such that the deposit appears and disappears with the folding. The best dated section, the Point Evans measured section, indicates a thin till that correlates with MIS 6 (Figure 5-13). The till here exhibits subglacial deformation in the form of roll-up structures, thinly layered sand and diamict rolled jelly-roll fashion. The sand is more easily eroded leaving fins of diamict in the outcrop.

Folding and faulting are present in exposures of the Double Bluff Drift. A reverse fault places cross-bedded sand of the Whidbey Formation in near-vertical contact with Double Bluff glaciolacustrine deposits at Sanford Point (Figure 5-19) on the west side of Vashon Island

At several other sites in the Puget Lowland three till layers can be seen, for example on the west side of Mercer Island and the west side of Vashon Island (Booth et al., 2015), but without absolute dating the age of the underlying tills at these and other localities cannot be determined.

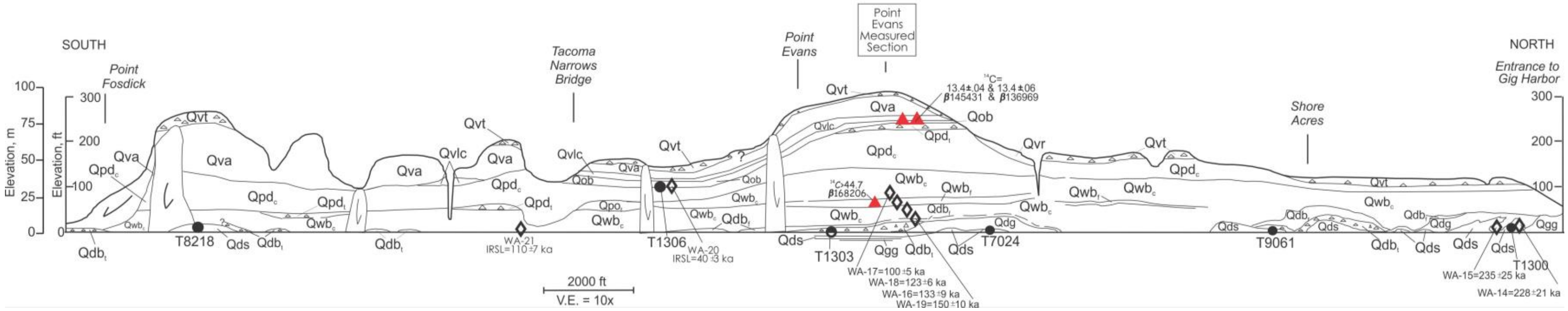


Figure 5-18. Bluff sketch from Point Fosdick to Gig Harbor.
Figures 5-16 and 17 contain keys for symbology used and geologic unit definitions. From Troost et al., in review.

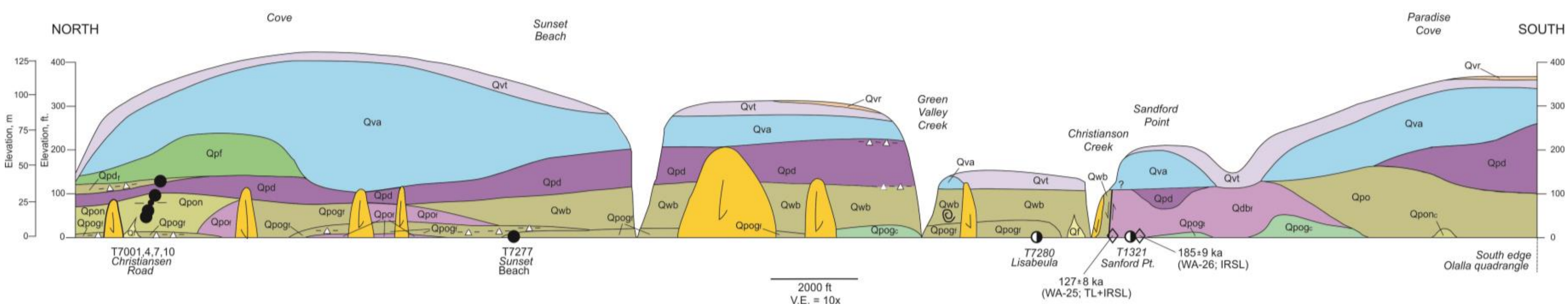


Figure 5-19. Bluff section of west side of Vashon Island from Christiansen Road to Paradise Cove.
Figures 5-16 and 17 contain keys for symbology used and geologic unit definitions. Modified from Booth and Troost, 2005.

5.4 Hamm Creek formation - MIS 7

Newly identified interglacial deposits correlating with MIS 7 were encountered during my study. MIS 7 deposits were initially identified using Ar/Ar dating on pumice encountered in a 2-m-thick deposit along Hamm Creek in Seattle. The Hamm Creek formation is informally named for this locality and comprises interglacial deposition during MIS 7. MIS 7 spans the interval from 190 to 240 ka years ago (Lisiecki and Raymo, 2005). Three Ar/Ar dates of 200,000 +/- 10,000 were obtained on different exposures of the deposit at varying elevations (Section 4.1.4). Other isolated exposures of Hamm Creek formation have subsequently been identified across the Puget Lowland using luminescence dating (Table A-3).

Tephra deposits are found in 3 different places along Hamm Creek in south Seattle (Figure 4-6). One of the exposures, where the pumice and tephra are 2 meters thick, is near the top of the upland at elevation 61 m (200 ft). The other two locations are considerably lower in elevations 35 and 15 m (ft). Although preexisting topographic relief could explain these differences, an inferred strand of the Seattle Fault Zone passes between the first and second two exposures, on which post-eruption dip-slip movement could also contribute to their differences in elevation.

5.5 Defiance drift – MIS 8

This newly defined glacial drift, identified by luminescence dating of deposits at Point Defiance, correlates with the globally cool MIS 8 interval. MIS 8 spans the interval of 240 to 300 ka years ago (Lisiecki and Raymo, 2005). Defiance drift is named for the thick glaciolacustrine clay/silt (locally referred to as the "Defiance silt") well exposed at the point of Point Defiance Park in Tacoma (Figures 5-14 and 5-15). It has a unique polarity measurement and so can be traced in the Seattle uplift area using paleomagnetic measurement (Booth et al., 2004b; Hagstrum et al., 2002). Defiance drift is also mapped at the Point Evans measured section on the basis of the unique polarity and overlying luminescence dates (Figure 5-13).

In the Point Defiance and Point Evans areas, the glaciolacustrine silt of the Defiance drift is folded into a series of anticlines and synclines that pop up and down at beach level (Appendix B, Photographs 37 and 38). The thickness of the silt is in excess of 30.5 m (100 ft) at Point Defiance where it is also folded and faulted.

5.6 Early to Mid-Pleistocene Deposits

The early to mid-Pleistocene deposits in the Puget Lowland (Figures 5-1 and 5-2) include:

Unknown/Unidentified glacial and interglacial units (data gap at 300ka – 780ka)

- Salmon Springs Drift
- Puyallup Formation
- Stuck Drift
- Alderton Formation
- Orting Drift

The ages on these deposits are generally limited to one or two dates each and the older deposits, greater than 780 ka, are also reversely magnetized (Table 2-4).

Deposits that fall within the data gap of 300 to 780 ka have been identified in the Puget Lowland but most are not sufficiently dated to warrant naming at this time. The informally named “Gig Harbor gravel” is one such deposit which was first identified at the Point Evans measured section (Figures 5-13 and 5- 18). This deposit contains heavily oxidized and iron-cemented coarse gravel. Since it appears at the base of the Defiance silt, it may be correlative with MIS 8 (but may also be indeterminately older). The Gig Harbor gravel was mapped along the Tacoma Narrows and Colvos Passage where it is also folded along with the Defiance drift (Figures 5-18 and 5-19).

Deposits in Powder Mill Gulch near Everett, below an angular unconformity, also date to this data gap with a luminescence age of >400 ka (Table A-3) (Appendix B, Photograph 39).

Reversely magnetized deposits that are known to be older than the main Brunhes/Matuyama boundary (780 ka) have been identified in the Puget Lowland. These are helping with stratigraphic correlation across the Tacoma area on the Seattle Uplift (Booth et al., 2004b). Outcrops of reversely magnetized deposits also exhibit folding in the Tacoma fault zone (Booth et al. 2004b; Figures 5-20 and 5-21) (Appendix B, Photographs 33 and 40).

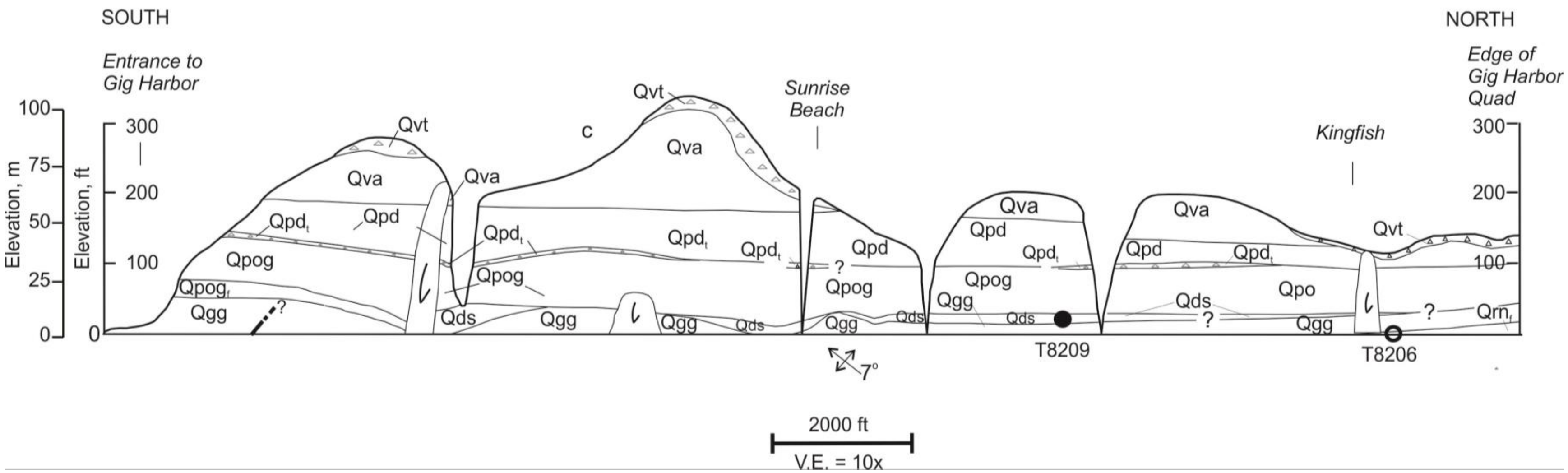


Figure 5-20. Bluff sketch along the coastline on the west side of Colvos Passage.
Figures 5-16 and 17 contain keys for symbology used and geologic unit definitions.

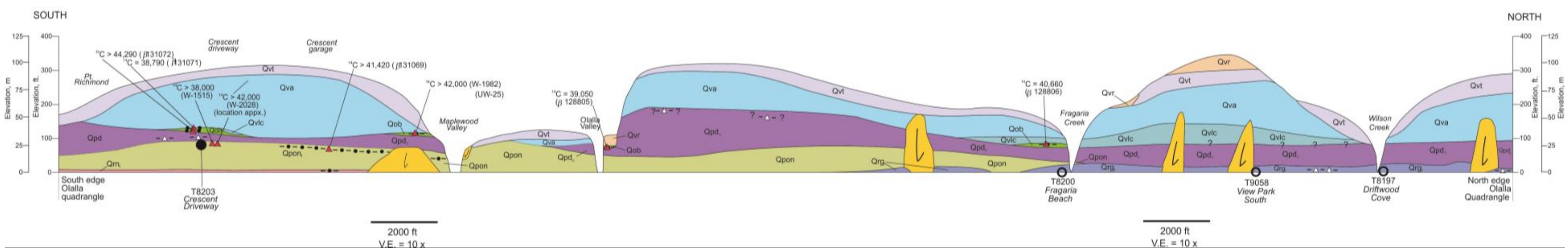


Figure 5-21. Bluff section along the Kitsap Peninsula coastline in the Olalla quadrangle.
Figures 5-16 and 17 contain keys for symbology used and geologic unit definitions. Modified from Booth and Troost, 2005; and Tabor et al., 2013.

Chapter 6 - Discussion of MIS 4 Glaciation in the Puget Lowland

MIS 4 is typically considered part of the last glacial stage and continuous through MIS 3 to MIS 2 (Shackleton and Opdyke, 1973; Shackleton et al., 1990), but for many decades practitioners in the Puget Lowland assumed that either the Puget Lowland remained ice-free or, at most, that an MIS 4 glaciation occurred but did not advance as far south as Seattle (Fulton, 1975; Lea, 1984; Clark et al., 1993; Walsh et al., 2003; Dr. Stephen Porter, University of Washington, 1999, personal communication). We know that glacial conditions did not persist from MIS 4 to MIS 3 in the Puget Lowland; instead, interglacial conditions during MIS 3 prevailed (Armstrong et al., 1965; Troost, 1999; this study).

In the following discussion, I will describe the climate, and the extent and facies of deposits dating to MIS 4 (the "Possession glaciation") in the Puget Lowland. Globally, MIS 4 is the cool climate stage from 57,000 to 71,000 years ago (Lisiecki and Raymo, 2005).

6.1 Extent of MIS 4 Glaciation in the Puget Lowland

Based on the global oxygen-isotope record, the Cordilleran Ice Sheet advanced out of British Columbia into the Puget Lowland at least seven times during the last 1 Ma of the Pleistocene. The most extensive was presumably during MIS 6 (Lea, 1984), given that glacial deposits have never been identified beyond the MIS 6 ice limit. The next most extensive was apparently during MIS 2, the most recent ice advance and corresponding to the last glacial maximum in the Puget Lowland. In MIS 4, a piedmont glacier also presumably advanced from the Coast Mountains of British Columbia, Canada into the Puget Lowland, but its maximum extent has heretofore never been constrained (Figure 6-1).

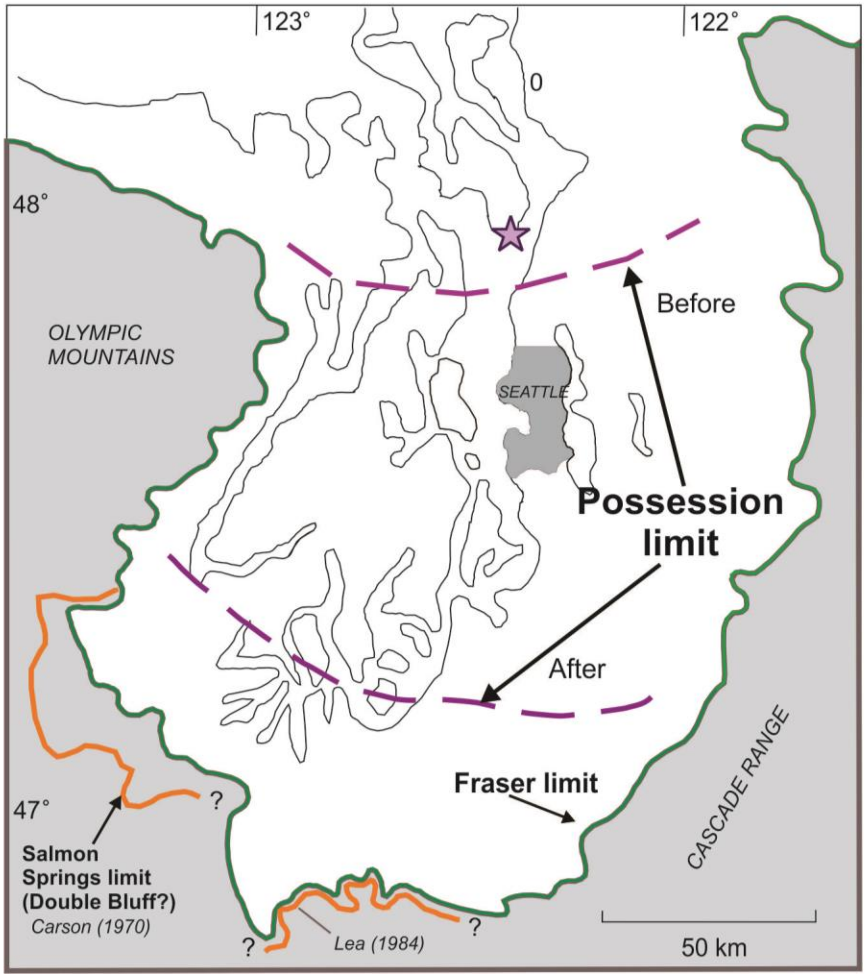


Figure 6-1. Image showing relative extents of the most recent ice sheet advances. The star marks the type section location of the Possession glaciation. "Before" and "after" reference the state of knowledge relative to the collection of data presented in this dissertation.

6.1.1 Recognition of Possession-age Deposits

To determine the extent of the MIS 4 Possession glaciation, I had to first identify time-correlative glacial deposits. In general, Possession-age deposits cannot be visually distinguished from glacial deposits of Vashon age (MIS 2) or Double Bluff age (MIS 6), except in the case of Vashon recessional deposits that have never been compacted by the overriding by ice. The provenance for the Possession ice sheet was likely similar to that of the Vashon ice sheet, which would explain the similar clast lithology. Where Possession Drift was mapped in the past, it was identified simply on the basis of “counting-down-from-the-top”, a technique that is now demonstrably invalid due to the multiple subsurface unconformities in the Puget Lowland (Troost and Booth, 2008). Some local practitioners have suggested that the Possession-age deposits are locally darker and harder than Vashon deposits (i.e., Mr. Louis Lepp, AESI, 1996, personal communication). They also have found that the Possession-age glaciomarine drift and till react positively to dilute hydrochloric acid (Mr. Curtis Koger and Ms. Jenny Saltonstall, AESI, 1996, personal communication). However these findings by the local practitioners have never been systematically tested.

Based on existing knowledge, unequivocal identification of Possession-age deposits requires the use of multiple field-mapping, geochronologic, and lithologic methods. Stratigraphic identification is also being facilitated over time by improved success at identifying and analyzing stratigraphically overlying deposits of the next-youngest Olympia formation (MIS 3) and the underlying Whidbey Formation (MIS 5), whose nonglacial origins have made indirect identification of Possession-age deposits more feasible. The ability to recognize prospective Possession-age deposits starts first with the ability to determine glacial vs. interglacial origin, as described by Troost (1999) based on provenance, characteristics of organic matter, presence of volcanic material, and facies assemblages.

Historically, such determinations were based solely on grain size, such that fine-grained deposits were identified as interglacial in origin and coarse-grained deposits were considered glacial in origin (Hanson and Mackin, 1949; Noble, 1990). Such a facile basis for discrimination is almost guaranteed to result in much misinterpretation. However, even a well-founded identification of provenance does not, in and of itself, constrain a “glacial” deposit to the Possession ice advance. For this, additional chronological data are necessary.

6.1.2 Chronological Data and Confirmed Occurrences

Over the past fifteen years, sixty OSL ages have been obtained to assist with stratigraphic correlation for geological mapping efforts and to construct the geological framework of the Puget Lowland (Table A-3). Of these, ten dates directly identify Possession-aged deposits, and many of the others served to limit the age of the bracketed deposits of glacial provenance. Some of these dates have rather large errors but nonetheless lie well within the range of dates for MIS 4 and so correlative with the Possession glaciation. In addition, thirteen dates from consultant-generated OSL analyses and eleven dates from the Washington Geological Survey also confirm localities of Possession-age deposits Table 6-1. Based on these data, the age range for Possession glacial conditions in the Puget Lowland is likely 61 to 76 ka (Figure 6-2).

Table 6-1. Summary of Possession-age Sediment Occurrences

Site Name	Location	Site ID	Dating Method	Age Control (ka)	Notable Features	Elevation (m)
Devils Head	South Puget Sound	KT-14-05	IRSL, 14C on overlying Qob	69.9 +/- 9.04	Interbedded sand and gravel of northern provenance. Overlain by thick pumice and multiple peat layers of radiocarbon dated Qob.	From below sea level to 12.5 m (41 ft)
Point Evans	Near Gig Harbor, opposite Point Defiance in Tacoma	WA-41	IRSL	123+/-6	Dated material is Whidbey in age and underlies the second till. Therefore the second till is Possession in age.	29 (95 ft)
Tacoma Narrows Bridge	Tacoma Narrows, NE	WA-22	IRSL	133 +/- 6	Dated material is Whidbey in age and underlies second till, therefore the second till and outwash are Possession in age.	27 (90 ft)
Tacoma Narrows SE		WA-23	IRSL	108 +/- 9	Dated material is Whidbey in age and underlies second till, therefore the second till and outwash are Possession in age.	4.9 (16 ft)
Tacoma Narrows SW		WA-21	IRSL	110 +/- 7	Dated material is Whidbey in age and underlies second till, therefore the second till and outwash are Possession in age.	0.5 (1.5 ft)
Sandford Point	Vashon Island, West coast	WA-25	IRSL	133=?-6 to 138+/-6	Dated material is Whidbey in age and underlies second till and outwash. Therefore the second till and outwash are Possession in age.	24 (80 ft)
Pt. Defiance	Tacoma	WA-45		74 +/- 5		43 (140)
Beacon Hill	USGS Deep Boring		na	Stratigraphic correlation	Thick glaciolacustrine deposit	(52 to 16 m in depth) 170.5-51.5 ft

Site Name	Location	Site ID	Dating Method	Age Control (ka)	Notable Features	Elevation (m)
Atlantic/I-5	Seattle, under N-bound I-5 lane at Atlantic St.	WA-1	OSL	70.8+/-3.7 to 72 +/-3.8	Folded and faulted glaciolacustrine deposits	From 23 to 18 m exposed (75-60 ft)
Magnolia Bluff	Seattle	WA-30	IRSL	114 +/-6.73 to 133+/-10	Dated material is Whidbey in age and underlies second outwash and glaciolacustrine deposit. Therefore the second advance deposits are Possession in age.	3 m (10 ft)
U-Link	Downtown to UW	WA-77	Many dates	76 +/- 15	Also many limiting date along the alignment	1.5 (5 ft)
Edwards Point	South of Edmonds	WA-34	IRSL	99+/- 15	Dated material is Whidbey in age and underlies second outwash and glaciolacustrine deposit. Therefore the second advance deposits are Possession in age.	3 m (25 ft)
212th St. SW and 52nd Ave W.	Mountlake Terrace	WA-56	IRSL	75.1 +/-5.5 to 83.3 +/-7.2	Overlies silt of Whidbey Fm.	114.3 (375 ft)
Redmond Ridge	West Snoqualmie Valley Road	WA-47	IRSL	150 +/- 20	Dated material is Double Bluff in age and underlies second outwash and second interglacial deposit. Therefore the second advance deposits are Possession in age.	82 m (269 ft)
Redmond Ridge	West Snoqualmie Valley Road	WA-46	IRSL	126 +/- 15	Dated material is Whidbey in age and underlies second outwash and is in the second interglacial deposit. Therefore the second glacial deposits are Possession in age.	82.3 m (270 ft)

Site Name	Location	Site ID	Dating Method	Age Control (ka)	Notable Features	Elevation (m)
Brightwater	Transect from Woodinville to Edmonds	WA-68,69,71	IRSL	73 to 88	various	various
Powder Mill Gulch	West of Mukilteo	WA-52	IRSL	78.5+/-4.5	Above an angular unconformity	15.2
Reiner Rd., off Old Owen Rd.	Northwest portion of Sultan Quad	Dragovich 44B	IRSL	73.3 +/-2.67	Whidbey-age sand and silt. Mapped as Olympia beds. Possession age deposits in subsurface. From Dragovich et al., 2013.	~ 88 m (~290 ft)
Near 135 St. SE, off Sultan Basin Rd.	North end of Sultan Quad/South end of Lake Champlain Quad	Dragovich 13-38A	IRSL	75.44 +/-2.25; 80.44 +/-7.02	Whidbey-age liquefied sand. Possession age deposits in subsurface. From Dragovich et al., 2013.	~95 m (~310 ft)
Foulweather Bluff, NW of Hansville	Hansville Quad.	GD28	OSL	56.36 +/-5.08	Glaciomarine drift and outwash sand with liquefaction features. Marine fossils present. Mapped as Possession drift. From Polenz et al., 2015.	3.05 m (10 ft); greater than 5.2 m (17 ft thick)
Driveway west of Tolt R. and North of Tolt R. Rd. NE	Tolt R., Lake Joy Quad	11-44C-2	IRSL	79.3 +/-6.88	Whidbey age nonglacial deposits. May be overlain by Possession age deposits in the subsurface. From Dragovich et al., 2012.	~137 m (450 ft)
South of Point No Point	Hansville Quad	GD27	IRSL	71.07 +/-6.04	Mapped as “Olympia beds?” but age is too old. From Polenz et al., 2015.	21 m (63 ft)
Quarry NE of Breidablick	Big Valley, Lofall Quad	GD4	IRSL	75.12 +/-3.7	Possession till and outwash mapped on surface and in subsurface. From Contreras et al.,	90 m (275 ft)

Site Name	Location	Site ID	Dating Method	Age Control (ka)	Notable Features	Elevation (m)
					2013.	
NW Tall Fir Lane gully	Near Bangor Naval Base, Lofall Quad	GD7	IRSL	73.15 +/-4.3	Possession till and outwash mapped on surface and in subsurface. From Contreras et al., 2013.	89 m (270 ft)
Eastern tributary to Anderson Creek	West of and in Silverdale, Poulsbo Quad	GD5	IRSL	97.25 +/- 4.85	Partially bleached sample. Possession till and outwash mapped on surface and in subsurface. From Polenz et al., 2013.	49 m (150 ft)
Unnamed drainage west of Dyes Inlet, east of Newberry Hill	Silverdale, Poulsbo Quad	GD4	IRSL	103.620 +/-6.27	Partially bleached sample. Possession till and outwash mapped on surface and in subsurface. From Polenz et al., 2013.	66 m (202 ft)
Seabeck-Holly Rd.	In deep ravines east of Hood Canal, Holly Quad	6 WA-196	OSL	82.5 +/-3.89	Dated material is Whidbey in age and underlies second outwash and till deposit. Therefore the second glacial deposits are Possession in age. From Polenz et al., 2013	18.7 m (57 ft)
Possession Point						
Useless Bay						
Lagoon Point					Easterbrook, 1994, till and Qwb	
Blowers Bluff, Whidbey Is.	Oak Harbor Quad	AA Site 35; site 47 of Dragovich et al., 2005 (also	Amino Acid	80 +/- 22	Well dated Olympia beds and Whidbey Fm in this quad area help to identify Possession age deposits. From Dragovich et al.,	~ 55 (~160 ft)

Site Name	Location	Site ID	Dating Method	Age Control (ka)	Notable Features	Elevation (m)
		sites 1, 2,3, 4, & 5)			2005; and Blunt et al., 1987.	
Point Wilson	Quimper Peninsula				Easterbrook, 1994, Gmd and outwash	
Point Williams	Olympic Peninsula				Blunt et al., 1987, Gmd and till	

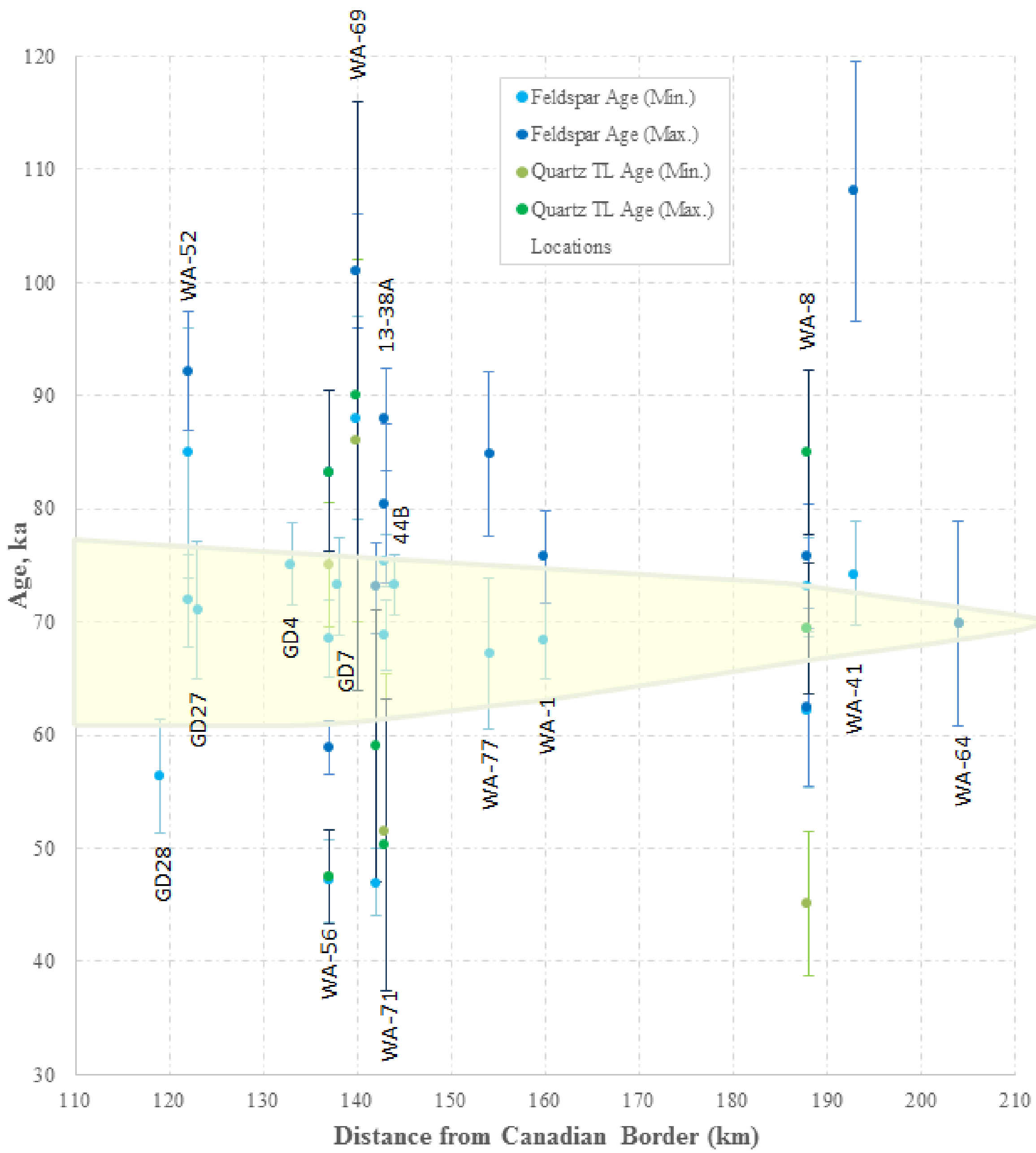


Figure 6-2. Time vs. distance graph for luminescence dates on MIS 4 deposits.
The inside of shaded triangle represents the timing of glacial deposition in the Puget Lowland, honoring the date ranges defined by 2σ (vertical lines with cross bars) of the luminescence ages. A summary of the laboratory data and information about sample locations are available (Tables A-2 and A-3).

These occurrences of Possession-age deposits have expanded the known extent of the MIS 4 glacial advance in the Puget Lowland, well beyond the Whidbey Island type section (Figure 6-3 and Table 6-1). Based on extensive mapping of correlative deposits, MIS 4 deposits have been documented throughout the Puget Lowland, with most of the identified localities in the central and eastern lowland (although perhaps only because more investigations have been conducted there). Closest to the type section at Possession Point on Whidbey Island, Possession Drift was encountered in some of the borings for the Brightwater sewer tunnel in South Snohomish County (Figure 6-3). Possession drift was also found in the far eastern and western parts of the Puget Lowland by geologists mapping for the Washington Geological Survey (Figure 6-3 and Table 6-1).

In Seattle, Possession-age deposits were confirmed at several locations. North of downtown, deep geotechnical drilling for the U-Link route encountered Possession-age deposits beneath the University of Washington and in Capitol Hill (Figure 5-11) (Mr. David McCormack and Ms. Shannon Mahan, 2008, written communication; Northlink Transit Partners, 2007 and 2008). Both Olympia and Whidbey-aged deposits have been identified beneath the south end of Magnolia Hill, and so it is likely that the intervening Possession Drift is present there too. South of downtown, folded, fine-grained glaciolacustrine deposits are exposed under the north-bound lanes of Interstate 5 on the west side of Beacon Hill opposite Atlantic Street; and Possession-age till is present in the subsurface there, based on correlation with a deep borehole drilled by the USGS (Figure 6-4 and 6-5; Odum et al., 2004).

Continuing south, the next confirmed localities are in Tacoma in the Seattle uplift along the Tacoma Narrows, Vashon Island, and Point Defiance coastlines (Figures 5-18 through 5-21).

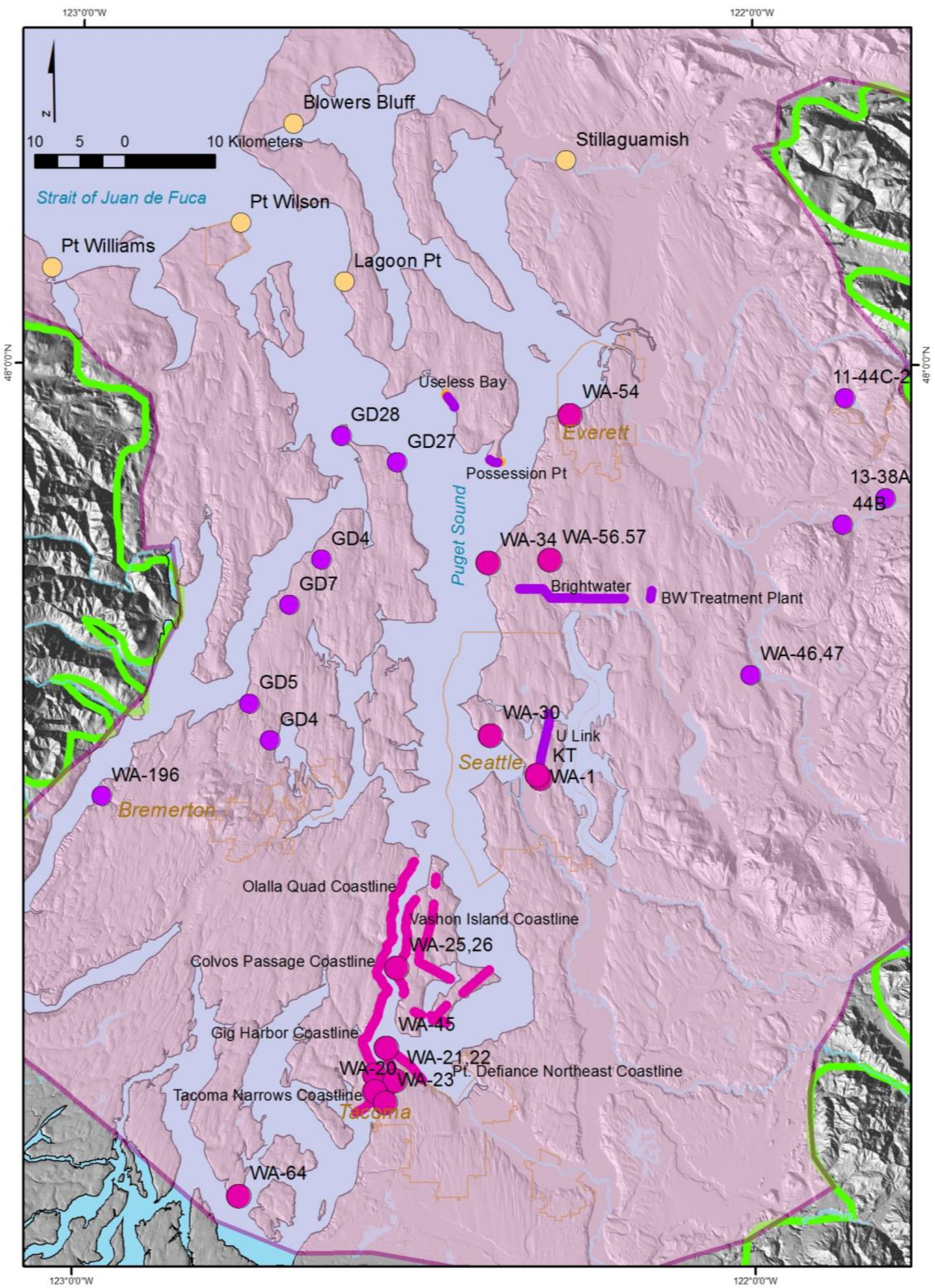


Figure 6-3. Map showings locations with confirmed Possession-age glacial deposits. Magenta indicates data from this study. Purple indicates unpublished data from consultants. Orange indicates data compiled from previously published literature.

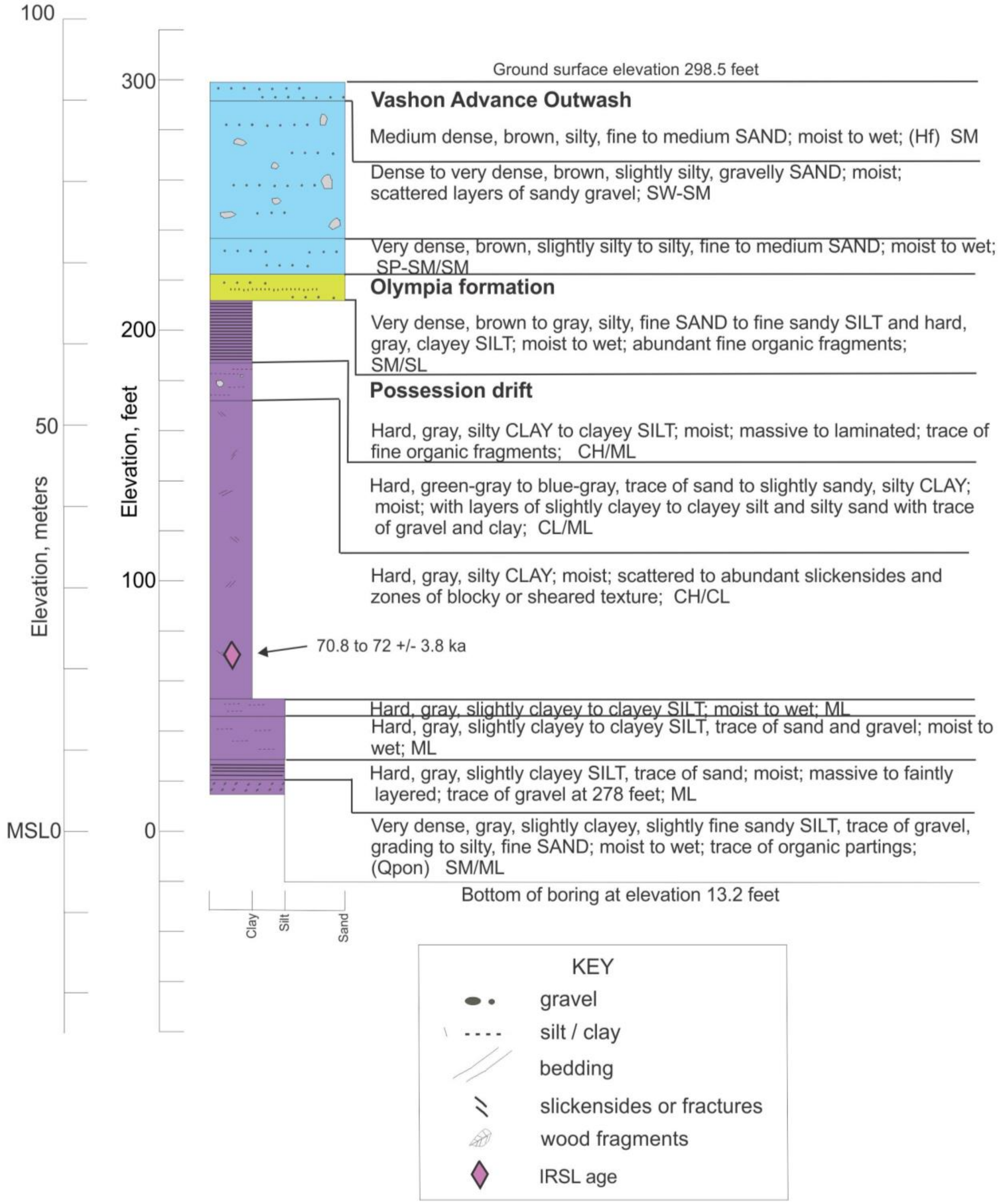


Figure 6-4. Measured section at the Atlantic/I-5 Site.
The luminescence date is sample WA-1. Deformation of the glaciolacustrine deposit is likely due to compression in the Seattle fault zone (Booth et al., 2003b). (Appendix B, Photographs 19 and 20).

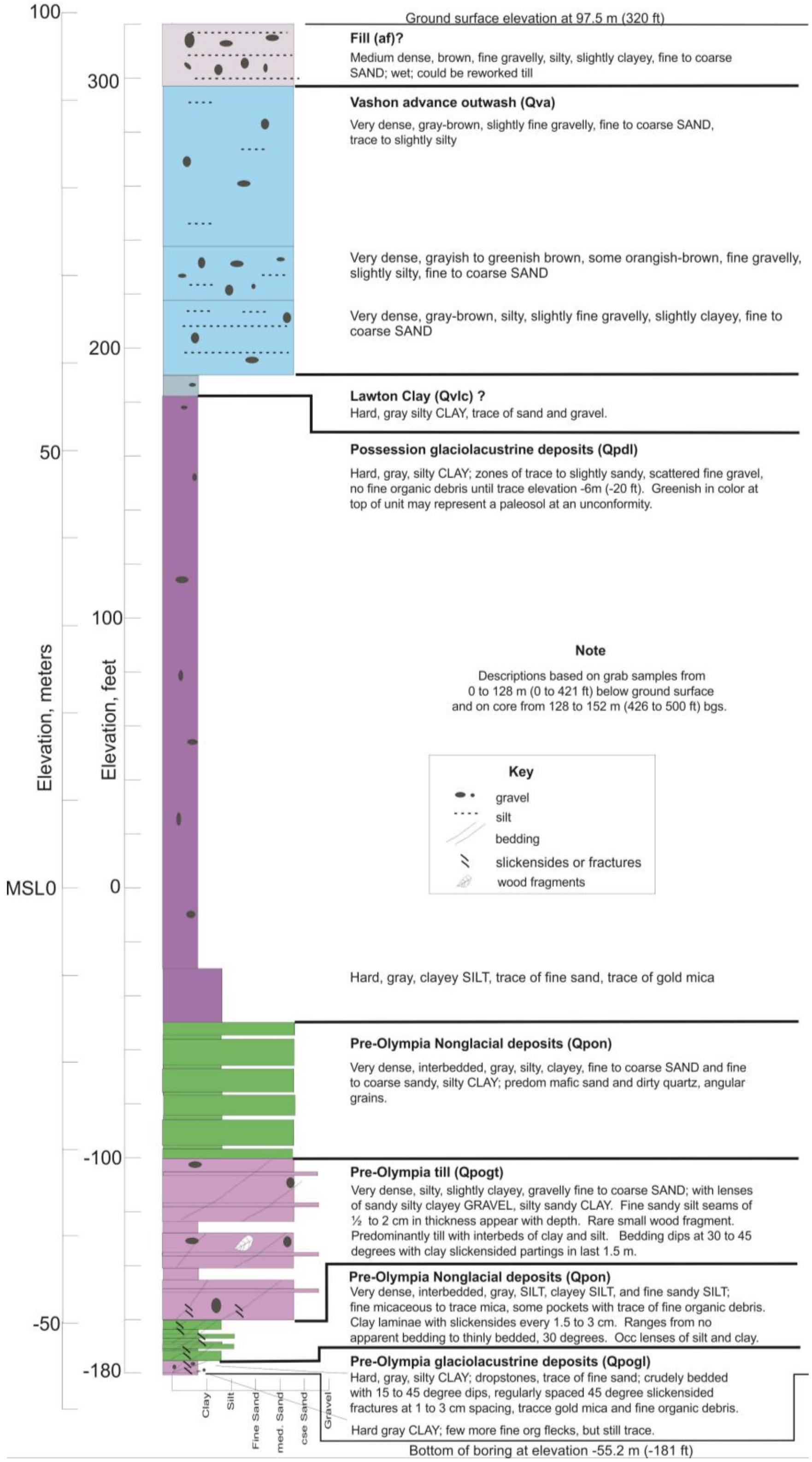


Figure 6-5. Log for the deep shear-wave boring completed by the USGS.
Boring was drilled on the top of Beacon Hill (location shown on Figure 6-3; Odum et al., 2004).

The farthest south that Possession-age deposits have been confirmed is at Devil's Head (Figure 6-6, location on Figure 6-3, sample WA-64).

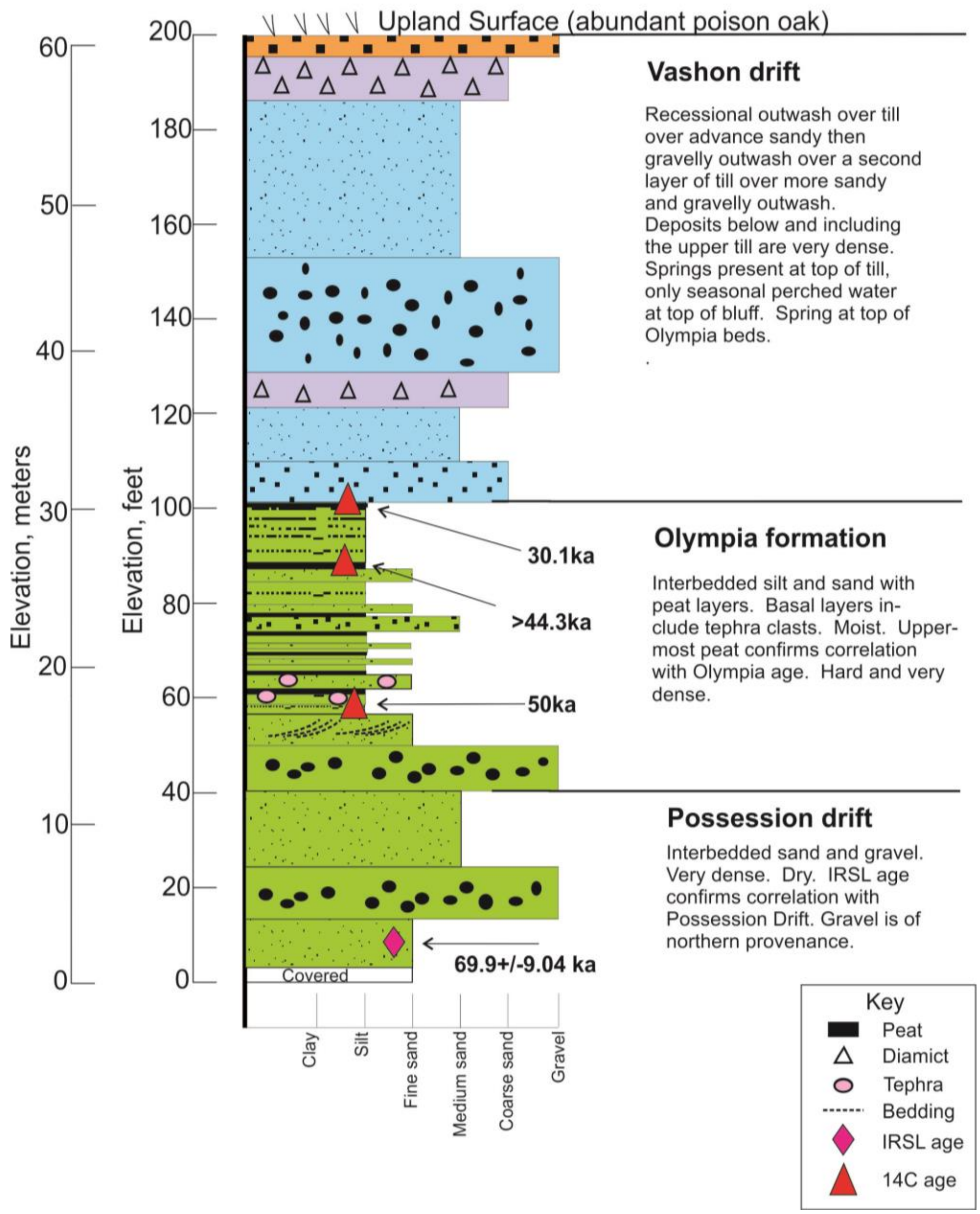


Figure 6-6. Measured section for Devil's Head site near Olympia. Luminescence date is on sample WA-64. Modified from Mr. Michael Polenz (WDNR-DGER, 2001, written communication) and Walsh et al., (2003). (Appendix B, Photograph 21).

6.1.3 Extent of MIS 4 Ice Sheet in the Puget Lowland

Given the distribution of confirmed occurrences of Possession Drift and the lateral bounding topography of the Lowland, the MIS 4 ice sheet must have had a generally similar width and length to the Cordilleran Ice Sheet during Vashon stade of the Fraser glaciation. My data put the ice sheet to within about 50 km of the LGM (Figure 6-7). The maximum extent of the Possession glaciation is not precisely known, however. In contrast, remnant moraines 1.2 km south of the southern Vashon ice margin are attributed to the earlier Double Bluff of MIS 6 glaciation by Lea (1984) based on relative weathering; based on these moraines, the Double Bluff-age ice sheet presumably advanced 2 to 12 km beyond the extent of Vashon-age ice (Figure 6-1).

Terminal moraines marking the end of the Possession glacier have not been identified on the landscape, and they are unlikely to be recognizable as such in the subsurface. Given that till was deposited as far south as the Tacoma Narrows area, it is clear that the glacier extended at least to the latitude of University Place, if not farther south. If terminal moraines existed they were likely scoured by the overriding Vashon-age ice sheet. It is highly unlikely that the ice extended beyond the extent of the Vashon ice sheet, however, because of the lack of Possession age deposits beyond the Vashon margin. If terminal moraines existed, they were likely scoured by the overriding Vashon glacier.

Given the absence of any evidence that the Possession-age ice sheet extended as far south as the Vashon-age ice sheet, the size of this earlier ice sheet was shorter and presumably with a somewhat lower surface elevation, consistent with ice volume indicated by MIS curves (Figure 6-8; Winograd, et al., 1997). We know that Possession-age deposits are found at elevations as high as 131 m (400 ft), similar to but lower than Vashon-age deposits.

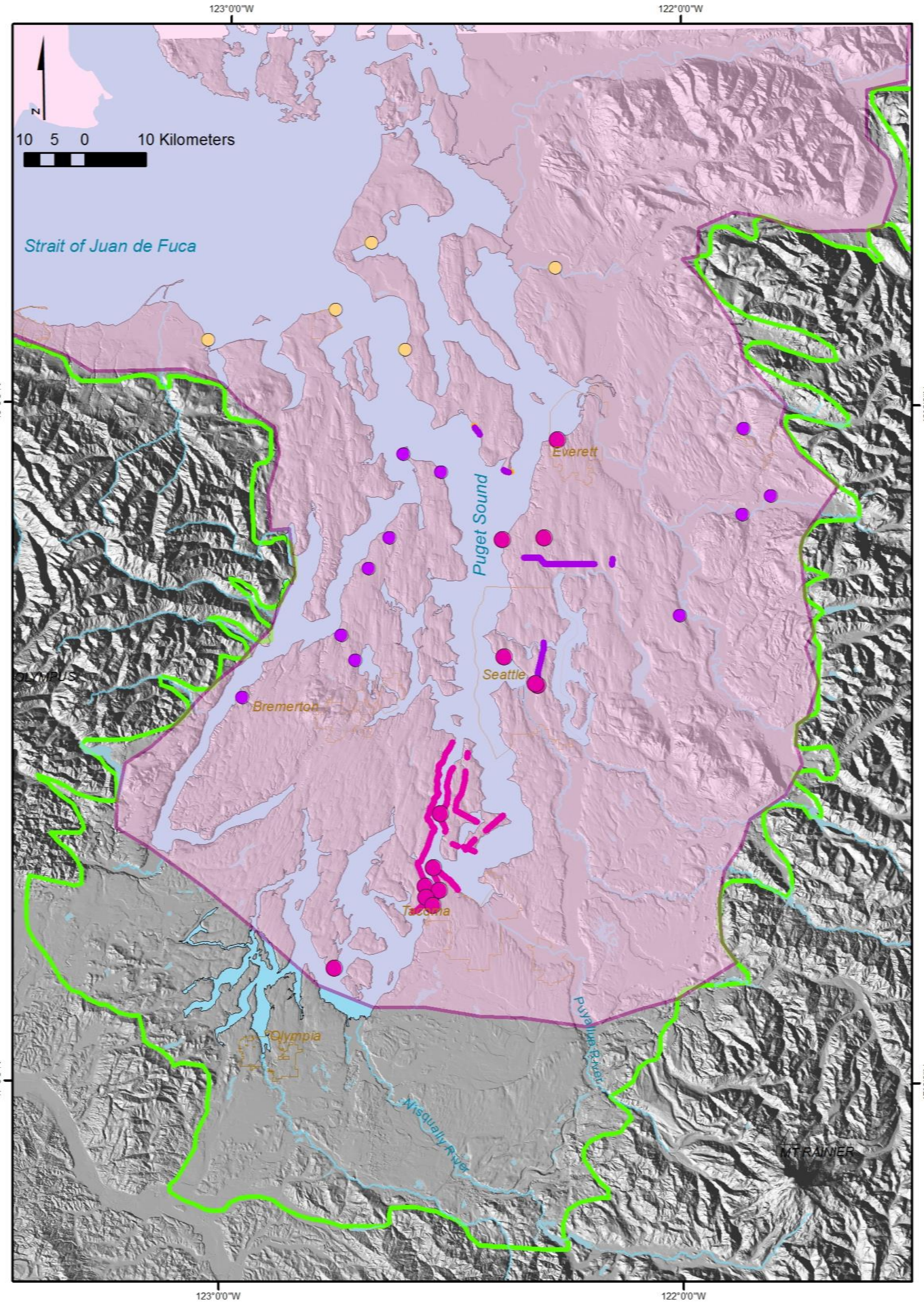


Figure 6-7. Comparison of MIS 2 and MIS 4 ice limits in the Puget Lowland. The green line marks the MIS 2 ice limit and the magenta line marks the approximate MIS 4 ice limit.

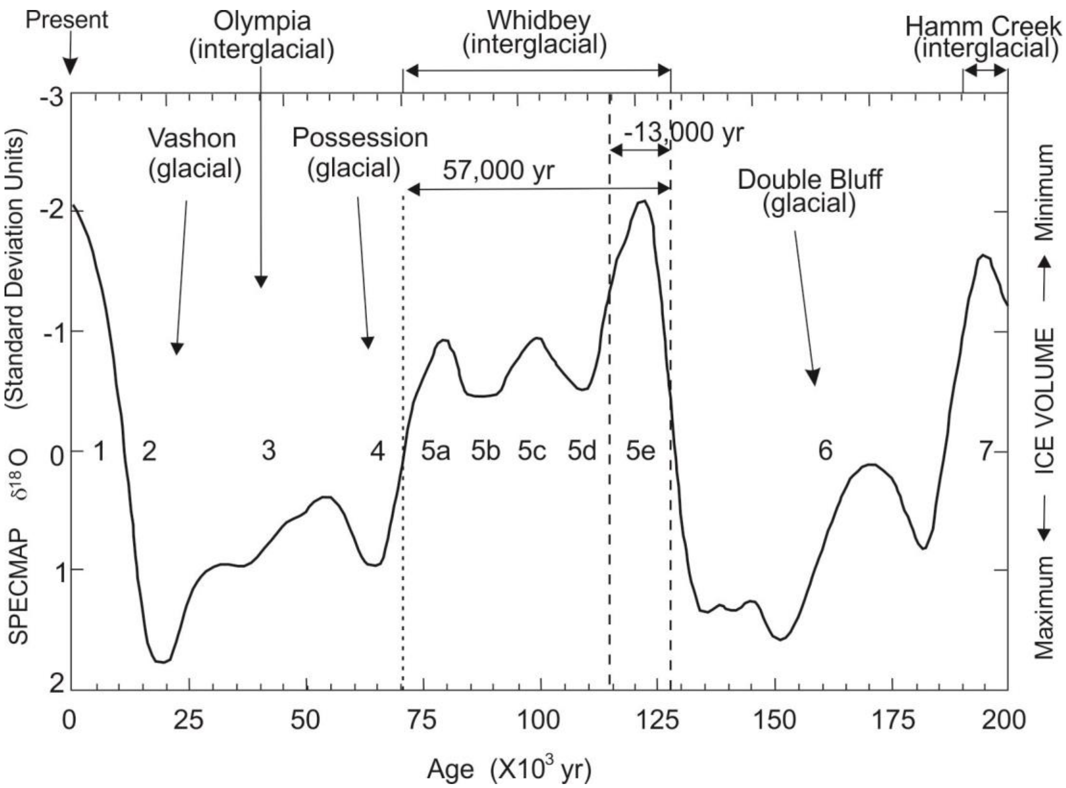


Figure 6-8. Global ice volume vs. age, marine isotope stages, and stratigraphic units. From Winograd et al., 1997.

Based on size constraints based on outcrop distributions, the ice sheet must have been about 450 km long measured from the ice divide and about 100 km wide to have left the pattern of deposits we see today. Given the relatively modest differences in length and width, the Possession ice sheet profile was likely similar to that of the Vashon (Figure 6-9).

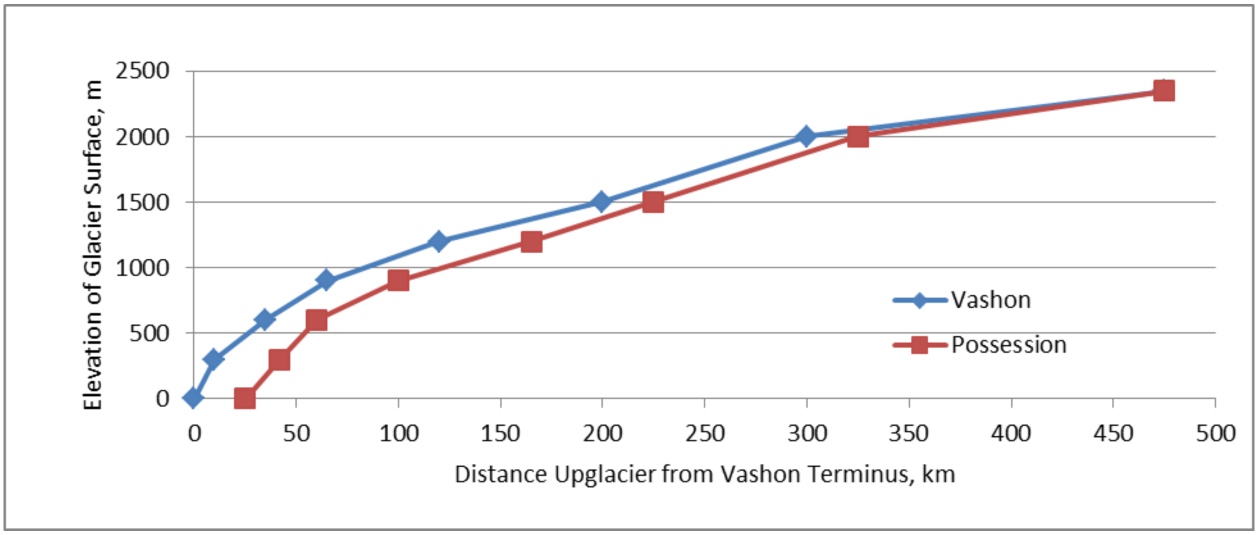


Figure 6-9. Inferred surface profiles of the MIS 2 and MIS 4 ice sheets.
MIS 2 profile after Booth, 1986.

6.1.4 Mass balance and ELA

Based on my reconstruction of the extent of the Possession ice sheet, its approximate equilibrium line altitude (ELA) can be calculated following the same procedure as Booth (1986) for the Vashon-age ice sheet. After reconstructing the ice sheet, I drew plausible contours across the reconstructed ice surface, determined the surface area between each pair of contours, used the mass balance factors of Booth (1986) developed for maritime glaciers, and ran trials using various postulated ELA values to determine the value that best approximated an ice sheet in mass balance. Based on these assumptions, an ELA of about 1240 m (4070 ft) brings the reconstructed ice sheet into balance at maximum extent. The ELA determined by Booth (1987) for the Vashon-age ice sheet was 1225 m (4020 ft). Given that the climate during MIS 4 was modestly warmer than during MIS 2, a higher elevation ELA is consistent with the paleoclimatic data (Shackleton and Opdyke, 1973; Helmens, 2014).

6.1.5 Marine Limit and Meltwater Outlet Elevation

Little data are available to determine the elevation or the latitude of the marine limit during the Possession-age deglaciation of the Lowland. Limited evidence of freshwater deposition, in the form of a lack of sodium and a lack of leaching (i.e., clay cation content greater than cation capacity), is present in the Possession-age recessional glaciolacustrine deposit on the west face of Beacon Hill (Mullineaux, 1967). Possession-age glaciomarine drift on Capitol Hill above sea level (Northlink Transit Partners, 2007 and 2008) suggests that the marine limit was at least at the latitude of Interstate 90 in Seattle. Shells found in Possession-age glaciomarine deposits in the subsurface in the Bothell area, along the Brightwater tunnel alignment, are consistent with this reconstruction (Appendix B, Photographs 22, 24 and 25). Per global sea level curves (Lambeck et al., 2002), eustatic sea level was about 50 m lower during MIS 4 than today compared to -120 m during MIS 2. Given a modestly smaller ice sheet and shallower sea level, the marine limit during MIS 4 would be shallower than during MIS 2.

Presumably an outlet for impounded meltwater in front of the retreating ice sheet, like the Black Hills outlet that was active during the Vashon stade (Thorson, 1980), was similarly controlling water levels in glaciolacustrine environments during the Possession glaciation prior to the opening of a northern outlet to the Strait of Juan de Fuca. Although the configuration and geographic location of the outlet are unknown, some control on its elevation is available. The top of Possession glaciolacustrine deposits ranges from 65 m (200 ft) in elevation at Point Evans in Tacoma, to 120 m (375 ft) on Capitol Hill in Seattle, to 130 m (400 ft) in Lake Forest Park. Therefore, the outlet elevation must have been about 150 ft higher than the corresponding outlet during the Vashon stade, when the top of glaciolacustrine deposition was about 220 ft in Seattle (Troost and Booth, 2008). These monotonically north-increasing elevations may be an artifact of limited, scattered deposits, but they may also reflect post-depositional isostatic rebound, where more northerly localities, presumably adjusted to a greater ice load, would subsequently rebound by a greater amount (as is well-documented for the Vashon-age recessional lake deposits; Thorson, 1980).

6.2 Spatial Distribution of Facies

The full complement of glacial facies associated with Possession-age deposits has not been seen at any single exposure. However, glaciomarine, advance glaciolacustrine, advance outwash, till, recessional outwash, recessional glaciolacustrine, and recessional glaciomarine deposits have all been confirmed within the Possession Drift. From these various exposures, a simple pattern is reflected in the facies distribution across the Puget Lowland (Figure 6-10). Glaciomarine drift, till, outwash, and glaciolacustrine deposits are prevalent within the Possession Drift in the northern part of the Lowland, north of Beacon Hill in Seattle. Glaciolacustrine, till, and outwash deposits are prevalent in the central and south-central part of the Lowland between Beacon Hill, in south Seattle, and Fox Island east of Tacoma. Only outwash is prevalent south of Fox Island (Figure 6-10).

Possession-age till is not as extensively exposed or encountered as Vashon till, but Possession-age glaciolacustrine deposits appear to be more extensive than the Vashon-age lacustrine equivalent, Lawton Clay. This may simply be a sampling bias, but it is consistent with a Possession-age ice sheet that advanced into a water-filled basin, advanced rapidly with a wet base, and decayed rapidly as an ice sheet containing little debris. Throughout the Brightwater tunnel alignment in south Snohomish County, 60% of the deposits of Possession age are glaciolacustrine in origin (some bearing shells), 20% are glaciofluvial, and 20% are till. The

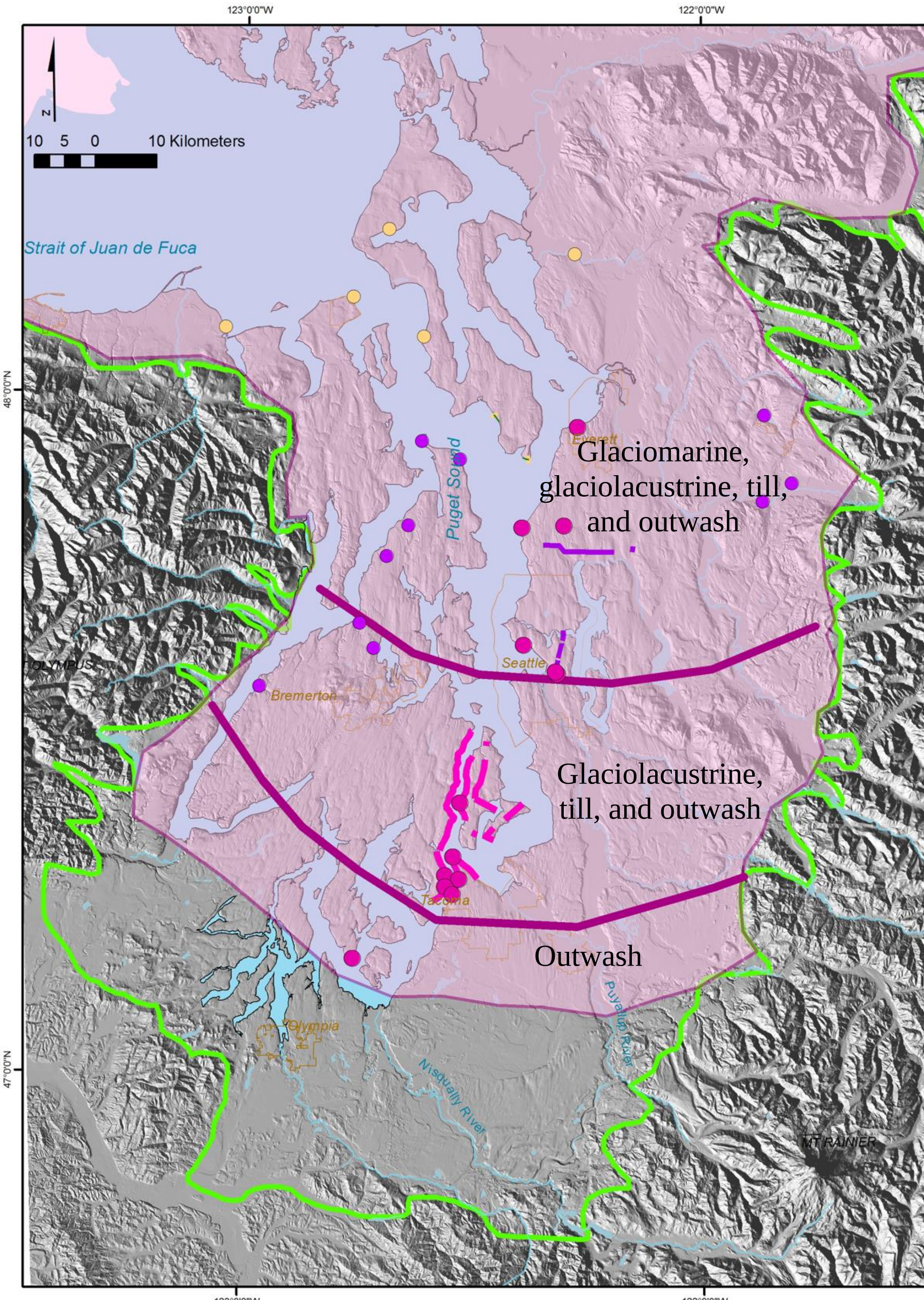


Figure 6-10. Facies distribution for Possession-age deposits.
The estimated extent of the Possession glacier is shown by the pink shading.

Possession-age glaciolacustrine deposits are similar in overall texture and structure to the Lawton Clay, except that the former seems to have more gravel-sized dropstones than the Lawton Clay (Mr. David McCormack, Aspect Consulting, 2016, personal communication).

The temporal order of facies in the Possession drift is predictable (glaciomarine drift, glaciolacustrine deposits, advance outwash, till, recessional outwash, glaciomarine drift); however the locations of lateral facies changes are gradational and not predictable.

6.3 Paleotopography of the Possession Drift

The amount of relief on the paleotopographic surface of the Possession Drift is as much as 180 m (550 ft). Modern topography appears to be a reasonable analog for the paleotopography of the Possession, at least with respect to aggregate properties of the range of elevations and the magnitude of topographic relief. The highest occurrence of Possession Drift is 135 m (450 ft) on the east side of the Puget Lowland, but most deposits are below 95 m (300 ft); the lowest identified Possession-age sediment is -65 m (-200 ft).

Deep troughs and steep unconformities are present in the surface of the Possession Drift, best displayed by extensive subsurface explorations in south Snohomish County along the Brightwater tunnel route (Figures 5-6 and 5-7) and in Seattle along the U Link transect (Figures 5-10 and 5-11), and along extensive sea-cliff exposures in Tacoma along the Gig Harbor coastline (Figures 5-18 through 20). The steep truncations near the west ends of the tunnel alignments could be former bluff edges of a paleo-Puget Sound. The Possession Drift fills deep troughs and has deep troughs scoured into its surface. The steepness and depths of these troughs mimic the overall relief of the modern Puget Lowland suggesting that controls on subsequent erosion of this deposit were similar during MIS 5 through the present.

Folding of Possession Drift is apparent in several locations. Along the Brightwater tunnel alignment (Figure 5-7), the top pf the Possession-age deposits drops toward the west; small magnitude folds are noticeable near the center of the route (McCormack and Troost, 2016). Along the U-Link route, the Possession Drift appears to be slightly warped over Capitol Hill (Figure 5-11) which is consistent with the gentle folding, seen in geophysical surveys of the subsurface, north of the leading edge of the Seattle fault (Pratt et al., 2015). Although, the drift may simply be draped on a pre-existing topography of Capitol Hill. Gentle folding of pre-Olympia deposits, including area of dated Possession-age sediment, is also seen in the Tacoma area with dips on the order of 5 to 10 degrees (Booth et al., 2004b).

6.4 Climate of MIS 4

Understanding how the climate in a region reacts to global changes has taken on increasing importance for our society (Elsner et al., 2010). The Puget Lowland is of particular interest because of the interplay of weather patterns and complex topography across a landscape that is home to 1.5 percent of the US population. Those complexities make weather prediction here under modern conditions particularly difficult (Mass, 2008). Trying to interpret an incomplete paleo-climate record adds further uncertainty.

Little is known about the climate in the lowlands of southern British Columbia and western Washington during most of the Pleistocene, with the exception of MIS 2 and MIS 3 (Heusser et al., 1980; Heusser, 1977; Hansen and Easterbrook, 1974; Mathewes and Heusser, 1981; Hicock et al., 1999; Whitlock and Grigg, 1999), MIS 2 and 3 (Barnosky, 1981 and 1985; Troost, 1999; Grigg et al., 2001), and MIS 5 (Heusser and Heusser, 1981; Muhs et al., 1994; Whitlock et al., 2000). From these studies, we know that climate during MIS 3 (Olympia nonglacial interval) was somewhat cooler and sea level was lower than today. The climate of MIS 5 (Whidbey interglaciation), with a much more incomplete record, was likely similar to that of today.

6.4.1 Temperature during MIS 4

Based on global climate proxies (Winograd et al., 1997; Lisiecki and Raymo, 2005), the mean annual temperature (MAT) during MIS 4 was cooler than most of MIS 5, somewhat cooler than MIS 3, and slightly warmer than MIS 2. This pattern is consistent with the record of glacial and interglacial periods as recorded in deposits of the Puget Lowland. Global ice volume was less during MIS 4 than in MIS 2 (Shackleton, 1987), and in many localities in the northwestern US and Canada dry climate prevailed and glaciers were absent in some areas that were subsequently glaciated during MIS 2 (Ward et al., 2007). However, July insolation was lower during MIS 4 than during MIS 2 (Berger and Loutre, 1991), suggesting that the source region for an ice advance into the Puget Lowland may have been wetter to account for development of an ice lobe that was only modestly smaller than other, more globally extensive ice advances.

No quantitative climatic reconstructions for the Cordilleran Ice Sheet during MIS 4 have been reported, but a potential near-analog is available from modeling of the summer MAT during MIS 2 by Sheerer and Hallet (2012), who determined that the MAT must have been about -7.8 ^{o}C for an ELA of 1200 m. Similarly, Seguinot (2014) predicted a summer MAT of -7 ^{o}C based on modelling efforts on the MIS 2 Cordilleran Ice Sheet. Given the relatively similar ELA's of the MIS 2 and MIS 4 Puget lobe, near-equivalent temperatures were likely reached during the time of an MIS 4 ice sheet as well.

Pollen studies provide further insight on the MAT during MIS 4 in the Puget Lowland, albeit with only minimal direct evidence. Pollen data from Carp Lake, in the southwestern Columbia basin, suggest that the climate was colder and drier during MIS 4 than today but not as cold and dry as MIS 2 (Whitlock et al., 2000). Heusser (1995) found that the temperature during the LGM (MIS 2) was about 5^{o}C cooler than present. My pollen work at the measured sections and other Possession-age outcrops in the Puget Lowland does not yield specific temperature data, because most of the Possession-age glaciolacustrine deposits had little or no pollen. What pollen I did find, however, was generally of cool-climate species such as *pinus* and *graminae*.

Climate conditions were conducive to alpine glaciation during MIS 4. Pollen evidence on the Olympic Peninsula of Washington confirms alpine vs. montane climate during MIS 2 and 4 (Heusser, 1972); the latter named the Lyman Rapids glaciation by Thackray (2001) (Appendix B, Photograph 30). His evidence also confirms alpine advances during MIS 3 for which Thackray (2001) had identified and dated glacial deposits. Porter and Swanson (2008) also recognized alpine advances in the northeastern Cascade Range during MIS 2, 4, and 6, coinciding with prominent insolation minima. Deposits of their informally named "Mountain Home advance" in the Icicle Creek drainage had a mean age 71 +/- 1.5 using ^{36}Cl exposure dating on boulders in moraines.

6.4.2 Climate controls

To address climate controls during MIS 4, we look to what controls our modern climate. The position of the jet stream is perhaps the most influential factor responsible for temperature and precipitation (Mass, 2008). The next most important factor is the position of the Aleution Low (AL) (Figure 6-11). During MIS 2, a glacial anticyclone, produced by the Cordilleran and Laurentide ice sheets, changed atmospheric circulation patterns in the Pacific Northwest (Sweeney et al., 2004). The glacial anticyclone brought prevailing easterlies to the region, instead of moisture bearing westerlies. Likely this occurred during MIS 4 as well. The Jet

Stream split producing dryer conditions in the Pacific Northwest and colder conditions to the midcontinent (Thompson et al., 1993). But in order for the ice sheets to grow, enhanced moisture supply is needed in the Arctic regions without lowering temperature (Lambeck et al., 2002). Cooling begins when the thermohaline circulation slows down. So for glaciation in the Pacific Northwest, increased moisture and temperature reduction in the arctic are likely both causes.

The linkage between oceanic and terrestrial climate indicators is important in understanding how future climate change might affect the Pacific Northwest. The literature contains an abundance of oceanic records and less terrestrial records. Recent studies are working on the connection between land and ocean using radiolarian and pollen (i.e., Pisias et al., 2001). They concluded that millennial-scale climate changes are related to changes in atmospheric circulation in the mid to high latitudes and changes in coastal upwelling.

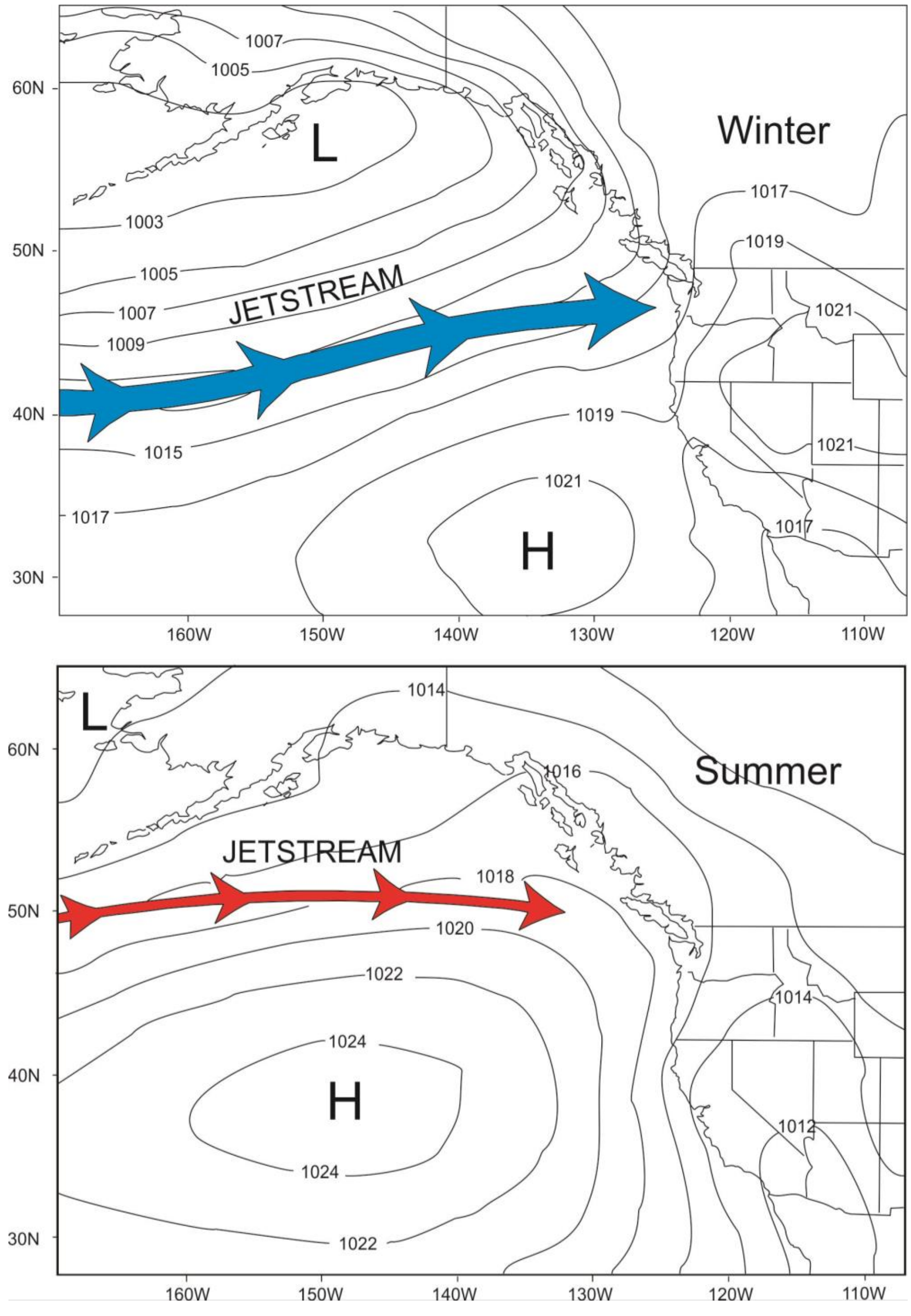


Figure 6-11. Typical positions of the Jetstream in winter and summer in the Pacific Northwest. Modified from Mass, 2008. H=high pressure. L=low pressure. The "L" is considered the Aleution Low.

6.5 Glaciation elsewhere during MIS 4

Looking at the ^{18}O record, MIS 4 peaks at a less extreme level than either MIS 2 or 6, indicating that globally averaged conditions were not as cold as MIS 6 or MIS 2, or that ice volumes were not as great as during MIS 2 or 6 (Figure 6-8). In most areas across the Northern Hemisphere, this trend holds for documented extents of MIS 4-age ice sheets. Based on long pollen records and ice-rafted debris records, Central and Northern Europe and the North Atlantic did experience full glacial conditions during MIS 4 and 2, albeit with MIS 2 having a greater ice volume (Helmens, 2014). In Scandinavia, the MIS 4 ice sheet was short lived but present (Arnold et al., 2002). MIS 3 is represented in these records with milder conditions than either the period that preceded or followed it (Helmens, 2014).

The northern latitudes of North America were glaciated throughout both MIS 4 and 3. Clark et al. (1993) concluded that the extent of MIS 4 glaciation was restricted, and that no evidence of MIS 4 glaciation exists at or beyond the southern margin of the MIS 2 Laurentide ice sheet. Marshall et al. (2000), modeling the Laurentide ice sheet in North America, noted maximum ice sheet coverage between 70 and 60 ka.

Multiple glacial advances through the late Pleistocene are also recorded in the valleys west of the Olympic Mountains (Thackray, 2001). He concluded that one of the advances, the informally named Lyman Rapids advance, likely correlates to MIS 4 based on stratigraphic position and a limiting radiocarbon date. This alpine glaciation extended farther than any subsequent glaciation, even though it did not occur during the coldest part of the pollen record. Thackray (2001) concluded that moisture was severely limited during MIS 2 on the Olympic Peninsula and in the Pacific Northwest. He further concluded that precipitation, not summer temperature, was the strongest control on the magnitude of Pleistocene glaciations.

Additional evidence of MIS 4 glaciation in the Pacific Northwest is found in loess and turbidite records. Lobes of the Cordilleran Ice Sheet advanced into eastern Washington during MIS 4, causing glacial outburst floods (McDonald et al., 2012) that were presumably analogous to the better known Missoula floods during ice-sheet retreat following the LGM. Luminescence dates on loess indicate that Lake Missoula flood systems were active during MIS 4, and that loess accumulation began as early as about 77 +/- 9.2 ka (Berger and Busacca, 1995) and continued to about 41.5 +/- 4.4 ka (McDonald et al., 2012). Some turbidites off the west coast of Washington and Oregon dating to MIS 4 have been linked to outburst flooding in eastern Washington, based on sediment accumulation rates (Normark and Reid, 2003). Cosma et al. (2008), correlating terrestrial glacial deposits with offshore glaciomarine sediments, reported ice-rafted debris in marine sediments that they related to the collapse of the Cordilleran Ice Sheet during MIS 4.

Farther north, evidence for widespread ice advance during MIS 4 has slowly been accumulating over the last decade. In the Coast Mountains and St. Elias lobe of the Cordilleran Ice Sheet, the "Gladstone glaciation" is correlated with MIS 4 and is identified as the penultimate ice advance in the region (Ward et al., 2007; Turner et al., 2016). Likewise in Alaska, the MIS 4 glaciation is considered the penultimate ice advance based on extensive cosmogenic exposure dating (Briner et al., 2005). In contrast, the MIS 6 "Reid glaciation" in the central Yukon Territory is considered the penultimate (Ward et al., 2008), with no evidence of an intervening MIS 4 ice advance prior to the LGM. Ward et al. (2007) attribute the differing histories of ice advance to climate forcing, particularly differences in available moisture, in various areas along the northern Cordilleran Ice Sheet. They further concluded that the climate during glacial periods was sufficiently cold to support ice-sheet formation, but that the region as a whole is precipitation-limited and so ice sheets could not form everywhere.

Evidence for an MIS 4 glaciation in British Columbia was only recently reported (Lesemann et al., 2013; Mathewes et al., 2015), contradicting the conclusion of Clark et al. (1993) that found evidence for an MIS 4 glaciation lacking. Mathewes et al. (2015) used palynology and optical dating to correlate deposits at a bluff on Haida Gwaii (formerly Queen Charlotte Islands) to MIS 4. They concluded that the region near the bluff hosted a treeless tundra-like landscape dating to 57.3 +/- 5.7 ka. Lesemann et al. (2013) reevaluated a stratigraphic section at Okanagan Center in the southern interior of British Columbia and defined it as an MIS 4 stratotype based on a limiting optical date. They found that the MIS 4 sequence consists of successively deposited "subaqueous and subaerial outwash, a subglacial till, and glaciolacustrine sediments."

Chapter 7 - Conclusions

"The farther backward you can look, the farther forward you are likely to see." - *Winston Churchill.*

My research reveals many new findings related to multiple advances of the Cordilleran Ice Sheet in the Puget Lowland of Washington. I developed a robust stratigraphic sequence and placed it into a global climate framework. I discovered new stratigraphic units and correlated glacial and interglacial deposits with distinct climatic events. Most specifically, I developed new information about the extent, chronology, lithology and paleoenvironmental conditions of the penultimate ice-sheet advance into the Puget Lowland of Washington State. In all, deposits from seven glaciations have been identified in the central Puget Lowland; one previously identified over a limited extent, has been confirmed (Possession), and one previously unrecognized has been discovered (Defiance glaciation, MIS 8) as a result of these studies. All of these geologic units express multiple depositional facies, and all are discontinuously expressed across the Puget Lowland.

7.1 New stratigraphic units

Two new stratigraphic units were identified during my research, one glacial and one interglacial, and deposits that had been identified in the northern Puget Lowland were identified in the southern Puget Lowland. The Hamm Creek formation is informally named for interglacial deposits from MIS 7, including a thick pumice and ash layer at a high elevation in south Seattle dating to 200,000 years ago. The Defiance Drift is informally named for glacial drift identified near Point Defiance in Tacoma, Washington dating to MIS 8, at 250,000 year ago. Deposits correlating with the Whidbey Formation (MIS 5) and the Double Bluff Drift (MIS 6) are also present in the Tacoma area.

7.2 MIS 4 Ice Sheet Glaciation in the Puget Lowland

I have shown that the MIS 4 ice sheet, the "Possession glaciation", extended much farther south than had been previously assumed, with subglacial till deposited south of the City of Tacoma and outwash deposited close to the City of Olympia. The ice sheet was somewhat smaller in size than the MIS 2 ice sheet, the Vashon glaciation, and must have had similar ice-sheet dynamics.

Deposits of the Possession glaciation are widely distributed but discontinuous across the Puget Lowland. Facies distribution across the Puget Lowland suggests that the MIS 4 ice sheet was a wet-based glacier, similar to that of MIS 2, with topographic and stratigraphic expression of extensive scouring, drumlin formation, advance and recessional lakes, and deposition of outwash.

7.3 Challenges with Unconformities

Integrating of multiple dating techniques and lithologic analyses is required to confidently assign deposits to a certain glacial or interglacial stage. The first step for identification is to determine if sediments are from glacial or interglacial periods; then, absolute dating is needed to assign to a particular glacial or interglacial period because of the similarity of the lithology and texture of deposits, and the absence of distinguishing characteristics, from each period.

The topographic relief on the surface of MIS 4 deposits is similar to that seen today on the surface of MIS 2 deposits, suggesting that the ice sheets responsible for scour and deposition were likely of similar size and with similar ice-sheet dynamics. Deep troughs were excavated, deep valleys were carved, and thick deposits accumulated on older hills and in older valleys, amounting to over 400 m of total relief. One apparent difference between the last two ice-sheet advances is that the advance glacial lacustrine outlet elevation was apparently higher during MIS 4, since glaciolacustrine deposits of this age are present at higher elevations than are the highest corresponding deposits from MIS 2. The 46-m difference could be a combination of tectonic uplift, or deepening of the outlet sometime between the close of MIS 4 and the conclusion of the ice advance during MIS 2.

The multiple advances of the Cordilleran Ice Sheet have left a series of unconformity-bounded sequences because of extensive erosion, and a semi-random alignment of stacked paleotopographic surfaces, leaving some troughs of different ages overlapping one another and others truncating prior highlands. These multiple unconformities make the sequential assignment of stratigraphic units on the basis of superposition often wrong. When accurate stratigraphic assignment is warranted, as is particularly important for long infrastructure projects, absolute dating is necessary to avoid unanticipated geologic conditions and hence greater economic risk. Paleotopography plays a major role in the ability to predict subsurface conditions from one site to the next or from one hill to the next. About half of the hills in the Puget Lowland will be cored with pre-Vashon deposits, and the remainder with thick Vashon deposits. Those hills cored with pre-Vashon deposits will likely have deposits from Olympia formation, Possession Drift, or Whidbey Formation near their tops.

7.4 Climate Implications

Paleoclimate in the Puget Lowland appears to track well with major global patterns, at least from the present back through MIS 8 (~300 ka). Glaciers and ice sheets were here when global climate proxies reflect cool summer temperatures, and interglacial conditions align with global proxies showing warm temperatures. Glaciation in the Puget Lowland during MIS 4 persisted from 60 to about 76 ka, compared to the range of 57 to 71 ka reported by Lisiecki and Raymo

(2005) and the range of 59 to 74 ka reported by Martinson et al. (1987). The poor resolution of dating beyond radiocarbon range, and the paucity of outcrops here, does not at present allow for more precise evaluation of correlations or disparities with the finer scale perturbations in global climate.

Temperature data indicate that the July MAT during MIS 4 was about 5 to 7^{o}C cooler than today. My estimated ELA for MIS 4 is 1240 m, slightly higher than the 1225 m for MIS 2, most likely indicating a slightly warmer climate than MIS 2 (which has also been reported to be between 5 to 7^{o}C cooler than today).

For glaciation to have occurred during MIS 4, changes in atmospheric circulation and insolation are required. Possible splitting and/or a more southerly position of the jet stream would bring cooler air to the Pacific Northwest. A glacial anticyclone would help to keep colder temperatures in place to grow an ice sheet to its maximum extent. Likewise, added moisture in the higher latitudes would help to extend an ice sheet. Whether temperature or moisture was the dominant factor for MIS 4 is unknown at this time.

Understanding of climate trends and resulting environmental changes is critical to the longevity of the world's inhabitants; thus, predicting how a region will respond to climate changes is a priority for research, planning, and sustainability. My research presents an opportunity to explore how a geographic region, the Puget Lowland, has responded to past global climatic conditions and changes. By comparing global climate to regional climate, we can start to develop predictive tools for changes and help society plan for future climate changes. By understanding the range of natural variability in the penultimate glaciation, this research can contribute to a growing understanding of the range of variability prior to global-scale human influence.

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Appendix A

Table A-1 Radiocarbon Results

Quad	Site Name	Sample No.	Location	Approx. Elev. (ft MSL)	Approx. Elev. (m MSL)	Sample Type	Lab. No.	Convent. 14C Age, yr. B.P.	AMS?	14C cal B.P. (2 sigma)	13C/12C Ratio o/oo	Source	Geo Unit	Pretreatment
BE	Crowell Property, East Bremerton	KT-169-05 S-1				Wood, part of tree	Beta-207994	>45880	AMS		-28.1		ng	1st tried Cellulose extraction, but no cellulose, so, worked on a 2nd sample; acid/alkali/acid
BO	Norway Hill nose	DB-98-01 S-1				wood	Beta-162623	138.2 ± 0.7	AMS; pMC		-28.3	SGMP	Qls	acid/alkali/acid
BO	HW 522 at HW 9	KT-108-00 S-7		210		wood	Beta-145432	40,070 ± 1050			-25.0*	SGMP	Qob	Acid/alkali/acid, extended counting
BW	Ross Point (at large slide)						Beta-129617	29090 ± 460			-27.0	Haeussler	Qob	Acid/alkali/acid
BW	Bremerton Bridge (under N side)	99PH116A				Wood		>45,920				Haeussler		
BW	Bremerton Bridge (under S side)	99PH118A				Peat		>43330				Haeussler		
BW	Bremerton Bridge (NW of bridge)	99PH122A				Peat		>43420				Haeussler		
BW	Ross Point (at large slide)	99PH16C		2.8 m below				27900 ± 300				Haeussler	Qob	
BW	Ross Point (SSW, near bend in road)	99PH20A				Peat		23380 ± 170*				Haeussler	Qob	
BW	Ross Point (SW of bend in road)	99PH21B				Peat		33530 ± 450*				Haeussler		

BW	Lost Creek bank	DB-110-02, S-1		180		peat	Beta-167601	>43,930			-29.3			Acid/alkali/acid
DM	McMicken Heights (SWD) SeaTac well		4018 S 164th St	179		Peat and wood		19000 ± 500				WDOE Robinson and Roberts, 1962	Qob	
DM	Sea Tac test pit	KT-47-98 S-1				Plant material within diatomite	Beta-162209		AMS	670 ± 40 See lab data	-30.6	SGMP	Qd	acid/alkali/acid
EDW	Deer Creek	KT-181-01 S-4		85		Wood	Beta-162213	43950 ± 1310	AMS		-28.6	SGMP	Qob	acid/alkali/acid
EVT	E. Pigeon Creek #2	KT-405-03 S9		140		Wood	Beta-182976	>44140			-28.2	SGMP		acid/alkali/acid
FTL	Boring MW-12b	60 feet deep	NE 1/4 SW 1/4 Sec 19 T19N R2E	176	53.6	Peaty silt	Beta-52222	13,630 ± 90				Walsh, written comm 1995	Basal Vashon Drift	None
FTL	Boring 4/6	62 feet deep	SW 1/4 NE 1/4 Sec 28 T19N R2E	210	64	Wood	I-15437	25,100 ± 600				Borden and Troost (2001)	Qob	"treated for removal of carbonate and humic acid"
GIG	Magnolia Hts. (Pt. Fosdick W)	DB-101-99 S-1	47.2666 N 122.5956 W	25	8	peat	Beta-137975	>40620			-25.0*	SGMP		Acid/alkali/acid, low C req'd special handling
GIG	Pt. Dalco, VI	DB-123-00	47.3348 N 122.5190 W	2	1	peat	Beta-142520	>45,070			-25.0*	SGMP		acid/alkali/acid, low C
GIG	Bayview South	DB-51-00 S-2	47.2754 N 122.5976 W	45	9	Organic sediment	Beta-140644	>45,240			-25.0*	SGMP		Acid washes, low C
GIG	Tacoma Yacht Club	DB-80c-99	47.3038 N 122.5107 W	35	10	Peat (lower)	Beta-137206	40,220 ± 1300			-25.0*	SGMP	Qob	acid/alkali/acid
GIG	Wollachet North	DB-81-00 S-2	47.2781 N 122.5891 W	20	6	Organic sediment	Beta-141203	>42,720			-25.0*	SGMP		acid/alkali/acid, low C
GIG	Dearth (S of Wollochet)	DB-83-00 S-1	47.2673 N 122.5951 W	20	6	Organic sediment	Beta-145430	22,570 ± 310			-25.0*	SGMP	Qob	acid/alkali/acid, low C req'd special handling

GIG	Gig Harbor Quarry	EP-3	47.3393 N 122.6084 W	<300	<90	Organic sediment	Beta-75435	15,110 +/- 130			-25.0*	Lepp and Koger, written comm, 1999	Qob	Acid washes, low C req'd special handling
GIG	Drummond Dr NW	KT-135-01 S-1	47.3536 N 122.5674 W	240	72	Fibers within peat	Beta-162211	41940 ± 2550			-29.5	SGMP	Qob	acid/alkali/acid
GIG	Pt. Evans Light	KT-158-00, S-2	47.2853 N 122.5472 W	5	2	peat	Beta-168205	42,950 ± 2430			-27.9	SGMP, USGS (Mahan)	Qob	Acid/alkali/acid extended counting
GIG	Tacoma Narrows Gully	KT-159-97, S-1	47.2604 N 122.5430 W	90	27	Peat	Beta-120061	44,880 ± 3050			-25.0*	Troost (1999)	Qob	acid washes
GIG	Pt. Evans MS	KT-255-99 S-1	47.2901 N 122.5497 W	220	67	Needles	Beta-136969	13,430 ± 60	AMS	16,135 (16,555-15,825)	-25.6	SGMP	Qob??	acid/alkali/acid/cellulose
GIG	Pt. Evans MS	KT-411-99, S-11	47.2902 N 122.5492 W	50	15	peat	Beta-168206	>44,740			-27.6	SGMP, USGS (Mahan)		Acid/alkali/acid extended counting
GIG	Pt. Evans MS	KT-91-00 S-1	47.2900 N 122.5497 W	220	67	Pine cone	Beta-145431	13,360 ± 40	AMS	16,030 (16,410-15,750)	-26.7	SGMP	Qob ??	Acid/alkali/acid
GIG	Tacoma Boathouse	KT-95-1	47.3067 N 122.5146 W	27	8.2	Peat	Beta-80938	>46,750			-25.0*	Borden and Troost (2001)	Qpon	acid/alkali/acid low C req'd special handling
GIG	Salmon Beach (lot 51)	KT-96-16, S-2	47.2965 N 122.5301 W	35	11	Peat	Beta–105923	>47,360			-25.0*	Troost (1999)	Qpon	acid/alkali/acid
GIG	Owen Beach (1st oc)	KT-96-23	47.3163 N 122.5311 W	40	12	Organic sediment	Beta–105924	26,610 ± 410			-25.0*	Troost (1999)	Qob	acid washes low C req'd special handling
GIG	Salmon Beach (S.end landslide)	KT-97-1, S-1	47.2952 N 122.5291 W	105	32	Carbonaceous rip-ups	Beta–105918	>47,300*	AMS		-22.4	Troost (1999)	Qpon	acid/alkali/acid
GIG	Salmon Beach (N. of houses)	KT-97-50, S-1	47.3025 N 122.5337 W	5	2	Wood	Beta–128802	>44,530			-25.0*	Troost (1999)	Qds?	acid/alkali/acid

GIG	Pt. Defiance Lighthouse	KT-97-58, S-3	47.3181 N 122.5460 W	15	4	Wood	Beta–128803	>43,200		-25.0*	Troost (1999)	Qos	acid/alkali/acid
GIG	Pt. Defiance (3rd Owen o/c)	KT-97-67, S-7	47.3166 N 122.5467 W	40	12	Organic sediment	Beta–105921	>50,000*	AMS	-19.9	Troost (1999)	Qpog	acid/alkali/acid
GIG	Pt. Defiance (4th Owen o/c)	KT-97-68, S-8	47.3164 N 122.5466 W	15	4	Wood	Beta–105922	>38,190*	AMS	-23.3	Troost (1999)	Qos	acid/alkali/acid
GIG	Spring Beach	UW-12	47.3467 N 122.5283 W	3?	1?	Peat	UW–12	27,900 ± 1200			Dorn et al., 1962	Qob	Presumed none
GIG	Salmon Beach (app. location)	UW-20	47.2967 N 122.5300 W	NA	NA	Peat	UW–20	34,500 +/- 1000			Dorn et al., 1962	Qob	Presumed none
ISS	Vasa Park	KT-123-01 S-1				Wood	Beta-162210	43650 ± 2470		-16.8	SGMP	Qob	acid/alkali/acid cellulose extraction
KRK	Norway Hill gully	DB-11-02, S-1		170		wood	Beta-167600	>46,190		-26.5			Acid/alkali/acid
LB	Devil's Head Peat # 2	KT-144-05 S-7				Wood below 30.1ka peat	Beta-207132	>46560	AMS	-27.3			acid/alkali/acid
LNG	Camano Island Beach o/c	KT-212-01, S-1				Wood	Beta-162219	38,840 ± 700	AMS	-27.7	SGMP	Qob	acid/alkali/acid
McN	Fox Island (NW of Gibson Pt.)	KT-97-29	47.2389 N 122.6296 W	25		Peat	Beta–105920	>47,750		-25.0*	Troost (1999)	Qpon	acid/alkali/acid
McN	Solo Point	KT-97-60 UW-19	47.1377 N 122.6310 W	60		Peat	UW–19	33,000±1000			Dorn et al., 1962	Qob	Presumed none
McN	Solo Point	KT-97-60, S-3	47.1377 N 122.6310 W	80	25	Peat	Beta–120064	41,380±1940		-25.0*	Troost (1999)	Qob	acid washes
McN	Solo Point	UW-67	47.1377 N 122.6310 W	60		Peat	UW–67	> 44,000			Fairhall et al., 1966	Qob	Presumed none
MI	Bellevue City Center bldg.			130		wood	Beta-112019	14890±70	AMS	-24.4	S&W (1998)	Qva	Acid/alkali/acid

MUK	Powder Mill Creek	KT-408-03 S-1		112		wood	Beta-182977	>44540			-25.3	SGMP		Acid/alkali/acid
MV	Lakeside Pit on S 256th	KT-151-05 S-1				Wood from buried debris	Beta-207133	>45440			-24.1		ng	No cellulose remaining; acid/alkali/acid
NE	U-District					Wood		15370 ± 60				Sound Transit; Hopkins (S&W)	Qva	
NE	Greenlake Reservoir		47.6820 N 122.3069 W			wood	UW-55	21200 +/- 300				Fairhall et al. 1966	Qob	
NE	Matthews Beach (subsurface)		47.6961 N 122.2809 W	67	20	wood	W-1892	18920 +/- 600				Marsters et al. 1969	Qob	
NE	Thornton Creek	DB-42-03 S-1		165		Wood	Beta-179207	>46450			-27.9	SGMP		Acid/alkali/acid
NE	117th Burke Gilman Trail	DB-47-03 S-1		40		Peat	Beta-179208	>44820			-28.3	SGMP		Acid/alkali/acid
NE	Mercer approach to I-5 (high)	KT-36-04	47.6293 N 122.3239 W	115		Wood	W-1227	15000 +/- 400		13050 B.C.		Levin et al. 1965	Qob	
NE	Mercer approach to I-5 (low)	KT-37-04	47.6259 N 122.3246 W	80		Wood	W-1305	15100 +/- 300				Levin et al. 1965	Qob	
NE	North end Capitol Hill (subsurface)	ST NB-105, S-7	47.6382 N 122.3199 W	145		roots	Beta-119399	20500 ± 220	AMS		-29.6	Sound Transit, writ. comm. Hopkins (S&W)	Qob	acid/alkali/acid
NSQ	Dupont MW	KT-211-01 S-1				Peat	Beta-162218	>45060			-27.4	SGMP	Qpfn	acid/alkali/acid
NSQ	Dupont Pit	KT-234-99, S-9				Wood	Beta-133322	38,710 ± 780			-25.0*	SGMP	Qob	acid/alkali/acid/cellulose extraction
NSQ	Dupont Pit	KT-235-99, S-7				Wood	Beta-133323	>31,960			-25.0*	SGMP	Qob	acid/alkali/acid/cellulose extraction
NSQ	Dupont Pit	KT-235-99, S-7 dup				Wood	Beta-136968	38,640 ± 950			-25.0*	SGMP	Qob	acid/alkali/acid/cellulose extraction

NSQ	Sequalitchew Creek	Sta. D-15	NW 1/4 SE 1/4 Sec 22 T19N R1E	~90		Peat	Beta–5175	28,110 +/- 310		Lepp and Koger, written comm, 1999	Qob	Presumed none
NW	West Point Sewage Treatment Plant		EPS F1*	-9	-3	Charcoal/wood	ß-53736		3455 (3653-3311)	Larsen and Lewarch, 1995	Qm	Standard
NW	West Point Sewage Treatment Plant		B 2*	-8.5	-3	Charcoal/wood	ß-58026		4018 (4237-3852)	Larsen and Lewarch, 1995	Qm	Standard
NW	West Point Sewage Treatment Plant		IM F9*	-1	-0.3	Charcoal/wood	ß-58038		1238 (1337-1009)	Larsen and Lewarch, 1995	Qm	Standard
NW	West Point Sewage Treatment Plant		SB 1*	5	2	Charcoal/wood	ß-61325		280 (310-0)	Larsen and Lewarch, 1995	Qb	Standard
NW	West Point Sewage Treatment Plant		SG F1*	2.7	1	Charcoal/wood	ß-64761		776 (926-703)	Larsen and Lewarch, 1995	Qm	Standard
NW	West Point Sewage Treatment Plant		CL2 F3*	6	2	Charcoal/wood	ß-64769		43 (150-10)	Larsen and Lewarch, 1995	Qb	Standard
NW	West Point Sewage Treatment Plant		CL2 F1*	3.9	1	Charcoal/wood	ß-64771		470 (510-320)	Larsen and Lewarch, 1995	Qm	Standard
NW	South Beach, West Point		47.657 N 122.425 W	3	1	Wood	W-1091	20,350 ± 600		Ives et al., 1964; Yount et al., 1980	Qob	Not reported

NW	South Beach, West Point		47.657 N 122.425 W	3	1	Peat	W-1181	22,400 ± 800		Ives et al., 1964; Yount et al., 1980	Qob	Not reported
NW	South Beach, West Point		47.657 N 122.425 W	33	10	Peat	W-1186	18,100 ± 700		Ives et al., 1964; Yount et al., 1980	Qob	Not reported
OL	Maplewood South (Corbett's Garage)	DB-212-98 KT-13-98	47.3940 N 122.5531 W	70		Peat	Beta-131069	>41,420	-25.0*	Troost (1999)	Qpon	acid/alkali/acid
OL	Fragaria Road	DB-235-97	47.4617 N 122.5372 W	80		Peat	Beta–128806	40,660 ± 970	-25.0*	Troost (1999)	Qob	acid/alkali/acid
OL	Olalla Creek Quarry	KT-11-98 DB-78-98	47.4265 N 122.5542 W	70		Peat	Beta–128805	39,050 ± 940	-25.0*	Troost (1999)	Qob	acid/alkali/acid
OL	Haug's Driveway (upper peat)	KT-170-99, S-5	47.3870 N 122.5489 W	140		Organic sediment	Beta–131071	38,790 ± 790	-25.0*	Troost (1999)	Qob	acid/alkali/acid low C req'd special handling
OL	Haug's Driveway (lower peat)	KT-170-99, S-7	47.3870 N 122.5489 W	133		Peat	Beta–131072	>44,290	-25.0*	Troost (1999)	Qob	acid/alkali/acid
OL	Maplewood coast (Kitsap Type Section)	UW-25	47.3989 N 122.5533 W	125(?)		Peat	UW-25	Probable tritium contamin a-tion		Dorn et al., 1962; Fairhall et al. 1966	Qob	Unknown; suspect too young, see Detter, 1979, p. 62; 32,700 +/- 1000
OL	Crescent Coast (near Haug)	W-1515	47.3872 N 122.5488 W	80	24	Peat	W-1515	>38,000		Deeter (1979)	Qpon	Presumed none
OL	Maplewood coast (Kitsap Type Section)	W-1982 (dup? of UW-25)	47.3989 N 122.5533 W	65(?)		Peat	W-1982	>42,000		Yount et al., 1980	Qob	Unknown
OL	Crescent Coast (near Haug)	W-2028	47.3872 N 122.5488 W	~80		Peaty silt	W-2028	>42,000		Deeter (1979)	Qpon	unknown

PB	Hylebos Overlook	EP-6	S1/2 SW1/4 Sec 25 T21N R3E	160-200?		Organic sediment	Beta–57731	36,690 +/- 650				Lepp and Koger, written comm, 1999	Qob	Presumed none
PB	Manke Quarry	KT-95-13	47.2642 N 122.3532 W	137	41.8	Paleosol	Beta–87981	36,650 ± 720			-25.0*	Borden and Troost (2001)	Qob	acid washes low C req'd special handling
PB	Woodworth Quarry (exterior)	KT-95-4	47.2729 N 122.3728 W	164	49.9	Organic sediment	Beta-80937	32,040 ± 690			-25.0*	Borden and Troost (2001)	Qob	acid washes low C req'd special handling
PB	Woodworth Quarry (exterior)	KT-95-4	47.2729 N 122.3728 W	164	49.9	Organic sediment	ISGS-3301	27,530 ± 390				Borden and Troost (2001)	Qob	None
PB	Woodworth Quarry (interior)	KT-95-9	47.2746 N 122.3712 W	240	73.2	Organic sediment	Beta-86842	>41,710			-25.0*	Borden and Troost (2001)	Qob	acid washes low C req'd special handling
PB	Foran Quarry	KT-96-1	47.2620 N 122.3536 W	130	39.6	Peat	Beta–89875	>46,450			-25.0*	Borden and Troost (2001)	Qob	acid washes low C req'd special handling
PB	Woodworth Quarry (interior)	KT-96-13	47.2746 N 122.3712 W	193	58.8	Charcoal	Beta-95340	>53,480	AMS		-27.5	Borden and Troost (2001)	Qva	acid/alkali/acid
PTN	Ft. Worden	KT-210-01 S-1				Peat	Beta-162217	>44370			-25.0*	SGMP	Qpfn	acid/alkali/acid
PY	Quarry near Puyallup	KT-03-05 S-4		285		Wood in diamict	Beta-208201	134.15 ± 1.03 pMC		Age is post 0 BP; Living in the last 50 yrs	-25.8			acid/alkali/acid
PY	Palmer Woods	W-3011	47.1648 N 122.2521 W	<400	<120	peat	W-3011	>45,000				Yount et al. 1980 Kelley et al. 1978	Qpfn (reversed)	
PY	Palmer Woods	W-3012	47.1648 N 122.2521 W	<400	<120	peat	W-3012	>45,000				Yount et al. 1980 Kelley et al. 1978	Qpfn (reversed)	

RED	OBW-7, Redmond Ridge				Beta-88121	30270 ± 1290				Koger, 2003	Qob	
RED	Redmond Ridge panhandle				Beta-176355	32960 ±300				Koger, 2003	Qob	
RED	OBW-6, Redmond Ridge				Beta-87787	33930 ±540				Koger, 2003	Qob	
RED	G-1, Redmond Ridge				Beta-148205	35210 ±200				Koger, 2003	Qob	
RED	EB-4, Redmond Ridge				Beta-142195	36760 ±1230				Koger, 2003	Qob	
RED	Redmond Ridge				Beta-148206	38400 ±200				Koger, 2003	Qob	
RED	Redmond Ridge				A H-2	38430 ±200				Koger, 2003	Qob	
RED	Pegasus				Beta-164095	39750 ±1060				Koger, 2003	Qob	
RED	Trilogy, EP-116				Beta-178029	43920 ±2600				Koger, 2003	Qob	
RED	Redmond Ridge, OW-13				Beta-151589	45540 ±1930				Koger, 2003	Qob	
RED	154th Place gully	DB-137-02 S-1	175	Wood	Beta-179209	>47150			-26.2	SGMP		Acid/alkali/acid
RED	SR 908 Kirkland gully	DB-203-03 S-1	140	Wood	Beta-179210	>46450	AMS		-28	SGMP		Acid/alkali/acid
REN	Fairwood Larry	KT-213-01 S-1		Wood	Beta-162209			290 ± 30 See lab data	-25.0*	SGMP	Qmw	acid/alkali/acid
SE	ST HW-518 @ S 154th St. AB58 S-20		35	Wood	Beta-180373	23950+/-150	AMS		-26.6	AMEC, written Comm., 2003		Acid/alkali/acid

SE	E Marginal Way @ Boeing Access AB84 S-38			-131	Wood	Beta-179371	10040 +/- 50		11440 (11940-11280)	-26.3	AMEC, written Comm., 2003		Acid/alkali/acid
SE	Bell & 5th	KE00307T-44		82	Peat	Beta-156220	>44090			-25.0*	Koger, written comm.. 2001	Qob	acid/alkali/acid
SE	AWV-EB-23 S-6	KT-100-03 S-6			Peat	Beta-179212	>46450	AMS		-28.2	SGMP		Acid/alkali/acid
SE	Westcrest Park NE	KT-157-03 S-1		260	Peat, tree under powerlines	Beta-179213	>42810			-28.7	SGMP		Acid/alkali/acid
SE	Westcrest Park SE	KT-163-03 S-3		190	Peat, tree	Beta-179214	30430+/-270			-28.2	SGMP	Qob	Acid/alkali/acid
SE	Holly Park re-dev.	KT-194-02 S-1			Peat	Beta-179215	>45080			-28.3	SGMP		Acid/alkali/acid
SE	Madison & 8th	KT-207-01 S-1			Fibers within peat	Beta-162214	>44750			-27.9	SGMP	Qpfn	acid/alkali/acid
SE	Elliott & Clay	KT-208-01 S-1			Wood	Beta-162215	>46970			-24.6	SGMP	Qpfn	Extended counting acid/alkali/acid
SE	Little Hamm Creek Pumice	KT-262-03 S-5		192	Wood	Beta-179216	>46450	AMS		-27.0	SGMP		Acid/alkali/acid
SE	Lower Little Hamm Creek	KT-273-03 S-2		110	Wood	Beta-179217	>46450	AMS		-29.5	SGMP		Acid/alkali/acid
SE	Icon Batch Plant	KT-275-03 S-3		95	Wood	Beta-179218	>46500	AMS		-28.1	SGMP		Acid/alkali/acid
SE	Near Pigeon Point	KT-30-04; CENEK EP-2, 7'	47.5669 N 122.3645 W	105		Beta-163692	260 +/-40		300 (430-0)		aesi	Qmw	
SE		KT-31-04; ST NB-203 S-15	First Hill, Seneca, between Terry and Boren	228		Beta-125674	38360 +/- 780			-25	Sound Transit	Qob	

SE		KT-32-04; ST NB-205 S-17	Capitol Hill, Broad, between E Denny and E John	253		Beta-125675	>44,630			-25	Sound Transit	Qpf
SE		KT-33-04; ST NB-215 S-22	First Hill, Boylston, between Marion and Madison	248		Beta-125676	43030 +/- 2470			-25	Sound Transit	Qob
SE	Seola Beach ravine	KT-34-04	47.4931 N 122.3594 W	100	Peat	W-1622	>42000				Ives, Levin, Oman	Qpfn
SE	1st Natl Bank Bldg, 3rd & 4th & Spring & Madison Sts.	KT-35-04	47.9056 N 122.3319 W	75-140	Cedar branch	W-1979	>42000				Marsterns, Spiker, Rubin	Qpogm
SE	N end Beacon Hill @ I-5	KT-38-04	47.6010 N 122.3233 W	190		W-1388	24300 +/- 700		22350 B.C.		Levin et al. 1965	Qob
SE	N end Beacon Hill @ I-5	KT-39-04	47.6009 N 122.3231 W	190		W-1638	24200 +/- 700		22250 B.C.		Ives et al. 1967	Qob
SE	N end Beacon Hill @ I-5	KT-40-04	47.6008 N 122.3230 W	190		W-1641	24000 +/- 700		22050 B.C.		Ives et al. 1967	Qob
SE	Lake WA; west of Medina	KT-41-04	47.6153 N 122.2666 W	-210	peat	L-330	14000 +/- 900				Broecker et al. 1957	Qvrl
SE	Lake WA; west of Medina	KT-42-04	47.6150 N 122.2667 W	-210	peat	L-346 (A)	13650 +/- 550				Broecker et al. 1957	Qvrl
SE		KT-43-04; ST SB-310 S-22	S. Lander St, bet. 16th & 17th Ave S	181		Beta-130629		>49,280			Sound Transit	Qpogm
SE		KT-43-04; ST SB-310 S-37	S. Lander St, bet. 16th & 17th Ave S	113		Beta-130630	>45,510				Sound Transit	Qponf
SE		KT-44-04; AWV EB-7B	Alaskan Way@ Blanchard St	-60			35,800 +/- 500				Sound Transit	Qob

SE		KT-45-04; ST SB-321 S-19	shldr I-5 NB, S of S Forest St	24			Beta-148860	2770 +/- 60		2860 (2990-2760)		Sound Transit	Qls	
SE		KT-45-04; ST SB-321 S-8	shldr I-5 NB, S of S Forest St	52			Beta-148859	1130 +/- 50		1050 (1170-945)		Sound Transit	Qls	
SE		KT-47-04; ST SB-329 S-28	15th Ave S, bet. S Lander & S McClellan St	179			Beta-148938		47570 +/- 1650			Sound Transit	Qob	
SE		KT-48-04; ST SV-301 R-17	S. Lander St, bet. 16th & 17th Ave S	178			Beta-131450	33,890 +/- 190				Sound Transit	Qob	
SE	Upper Hamm Creek	KT-54-03 S-3	47.5185 N 122.3352 W	183		Woody peat	Beta-179211	43550 +/- 1510	Yes		-28.0	SGMP	Qob	Acid/alkali/acid
SPN	Boring DA-2	97 feet deep	NW 1/4 NW 1/4 Sec 24 T19N R2E	203	61.9	Wood	I-15705	>40,000				Borden and Troost (2001)	Qpog	“treated for removal of carbonate and humic acid”
SPN	Ft. Lewis EGDY	KT-209-01 S-1				Peat	Beta-162216	>45140			-25.0*	SGMP	Qpfn	acid/alkali/acid
ST	Boring DA-12e	140 feet deep	47.1272 N 122.5182 W	132	40.2	Wood	Beta-81801	>41,300			-25.0*	Borden and Troost (2001)	Qpog	acid/alkali/acid
ST	Sunset Beach	KT-96-12	47.2231 N 122.5643 W	140	42.7	Flattened wood	ISGS-3343	12,960 ± 180			NA	Borden and Troost (2001)	Basal Vashon Drift	None
ST	Sunset Beach	KT-96-5	47.2232 N 122.5643 W	140	42.7	Flattened wood	Beta-89876	13,620 ± 80			-25.0*	Borden and Troost (2001)	Basal Vashon Drift	acid/alkali/acid
ST	Gordon Point	KT-97-14, S-7	47.1700 N 122.6094 W	15		Organic sediment	Beta–120063	>43,090			-25.0*	Troost (1999)	Qob	acid washes
ST	Gordon Point	KT-97-14, S-7 dup	47.1700 N 122.6094 W	15		Peat in organic sediment	Beta–128799	41,190 ± 570	AMS		-31.6	Troost (1999)	Qob	acid/alkali/acid
ST	Sunset Beach	KT-97-2	47.2232 N 122.5643 W	140	42.7	Flattened wood	Beta-105919	13,310 ± 110*	AMS		-23.4	Troost (1999)	Basal Vashon Drift	acid/alkali/acid

ST	Boring DA-12e	S-10a, 92’	47.1272 N 122.5182 W	180	54.9	Wood	Beta-79885	13,510 ± 80			-25.0*	Borden and Troost (2001)	Basal Vashon Drift	acid/alkali/acid
STN	Kayak Pt. Park So.	KT-146-05 S-1A WG-31505-1A		50			Beta-207135	>45670	AMS		-27.8		ng	acid/alkali/acid
SW	AlLki Trunk and West Seattle Tunnel	B-207 S20	47.575719 N 122.395879 W	1727	8.2	Silt/organics Organic sediment	Beta-58853	30200 ± 1500			-25.0*	KogerConverse Cons., 1993	Qob	acid washes, extended counting
SW	AlLki Trunk and West Seattle Tunnel	B-207 S-24a	47.5759 57571 N 122.3959 39813 W	155	4.6	Organic fragments	Beta-58854	31100 ± 1000			-25.0*	KogerConverse Cons., 1993	Qob	acid washes, extended counting
SW	AlLki Trunk and West Seattle Tunnel	B-208 S-17	47.574425 N 122.398132 W	2325	7.6	Peat	Beta-58855	27100 ± 883			-25.0*	KogerConverse Cons., 1993	Qob	acid washes, extended counting
SW	AlLki Trunk and West Seattle Tunnel	B-211 S-18b	47.57251 N 122.40330 W	2025	7.6	peat	Beta-58856	25500 ± 400			-25.0*	KogerConverse Cons., 1993	Qob	acid/alkali/acid extended counting
SW	Beach at Me Kwa Mooks	DB-79-99	47.56431 N 122.40629 W	-1	-0.3	Wood	Beta-136967	27,810 ± 130	AMS		-24.0	SGMP	Qob	acid/alkali/acid/ cellulose extraction
SW	4706 Beach Dr: Dippery Res., West Seattle	KE00218G EB220	47.56086 N 122.40208 W	24	7.3	Organic sediment	Beta-142519	23,370 ± 170			-25.0*	Koger, 2000, written comm..	Qob	Acid washes, low C
SW	47th Ave SW	KT-12-00 S-1	47.50860 N 122.38837 W	215	65.5	needles	Beta-140643	>47,750	AMS		-28.5	SGMP	Qpon	acid/alkali/acid
SW	Mildred’s on Alki	KT-12-99 S-1	47.59110 N 122.39047 W	40	12.2	wood	Beta-128800	21,116 ± 170			-25.0*	SGMP	Qob	acid/alkali/acid, extended counting
SW	Alki Ave (below Bonair)1238 Alkii Ave SW	KT-167-00 S-1		-6	-1.8	Fibers within peaPeat	Beta-162212	26080 ± 400			-27.7	SGMP	Qob	acid/alkali/acid

SW	Lincoln Park (pool)	KT-270-99 S-3		80	24.4	Charcoal	Beta-162221	37040 ± 670	AMS	-26.3	SGMP	Qob	acid/alkali/acid
SW	Beach at MMee Kwa Mooks Beach	W-1182	47.5634 N 122.4047 W	-10	-0.3	Peat	W-1182	24,100 ± 900		na	Mullineaux et al, 1965	Qob	unknown
TL	Spee-Bi-Dah So.	KT-149-05 WG-31705-2				wood	Beta-207136	>46960		-26.8			acid/alkali/acid
TN	Garfield Park Hypo Gully	KT-130-97, S-2	47.2735 N 122.4589 W	80		Peat	Beta–120059	44,370 ± 2970		-25.0*	Troost (1999)	Qob	acid washes
TN	Garfield Park Hypo Gully	KT-130-97, S-2 dup.	47.2735 N 122.4589 W	79		Peat	Beta–122230	32,740 ± 410		-25.0*	Troost (1999)	Qob	acid/alkali/acid low C req'd special handling
TN	Garfield Park Gully, SE Side	KT-131-97, S-1	47.2692 N 122.4562 W	130		Peat	Beta–120060	41,310 ± 2020		-25.0*	Troost (1999)	Qob	acid washes
TN	Schuster Prkwy (E end pullout)	KT-133-97, S-1	47.2723 N 122.4537 W	97		Paleosol	Beta-122231	39,190 ± 870		-25.0*	Troost (1999)	Qob	acid/alkali/acid low C req'd special handling
TN	Schuster Prkwy (grnbelt trail end)	KT-135-97, S-1	47.2671 N 122.4454 W	45		Peat	Beta–128804	42,210 ± 2310		-25.0*	Troost (1999)	Qob	acid/alkali/acid
TN	Garfield Park Gully, NW Cor.	KT-22-99, S-5	47.2746 N 122.4601 W	15		Organic sediment	Beta–131070	34,900 ± 350	AMS	-27.1	Troost (1999)	Qob	acid/alkali/acid
TN	Garfield Park, NW Cor	KT-310-99 S-1	47.2775 N 122.4182 W	50	15	Peat	Beta-136970	27,180 ± 110	AMS	-25.3	SGMP	Qob	acid/alkali/acid
TN	Marine View Drive, Tac	KT-32-99 S-2	47.2737 N 122.4586 W	80	24	Organic sediment	Beta-128801	3430 ± 50	AMS	-26.3	SGMP	H	acid/alkali/acid
TS	Swan Creek	KT-170-97, S-1	47.2210 N 122.3934 W	150		Peat	Beta–120062	44,160 ± 3100		-25.0*	Troost (1999)	Qob	acid washes
TS	Route 7 Canyon	KT-96-14	47.2285 N 122.4262 W	210	64	Organic sediment	Beta–89256	17,110 ± 290		-25.0*	Borden and Troost (2001)	Qob	acid washes low C req'd special handling

*	= estimated $^{13}C/^{12}C$ ratio.
Beta	= Beta Analytic, Inc.
BO	= Bothell Quad
BP	= Before present
BE	= Bremerton East Quad
BW	= Bremerton West Quad
DB	= Sample collected by Derek Booth.
DM	= Des Moines Quad
EDW	= Edmonds West Quad
EVT	= Everett Quad
FTL	= Fort Lewis Quad
GIG	= Gig Harbor Quad
I	= Teledyne Isotopes
ISGS	= Illinois State Geological Survey, served as an independent QA lab for two samples dated by Beta
ISS	= Issaquah Quad
KRK	= Kirkland Quad
KT	= Sample collected by Kathy Troost
LNG	= Langly Quad
LB	= Longbranch Quad
McN	= McNeil Island Quad
MI	= Mercer Island Quad
MSL	= Mean sea level.
MUK	= Mukilteo Quad
MV	= Maple Valley Quad
NA	= Not available
NE	= Seattle Northeast Quadrant
NW	= Seattle Northwest Quadrant
NSQ	= Nisqually Quad
PTN	= Port Townsend Quad
QA	= Quality assurance
OL	= Olalla Quad
PB	= Poverty Bay Quad
PY	= Puyallup Quad
RED	= Redmond Quad
REN	= Renton Quad
S	= Sample number
SE	= Seattle SE Quadrant
SPN	= Spanaway Quad
ST	= Steilacoom Quad
STN	= Stanwood

SW	= Seattle SW Quadrant
TL	= Tulalip Quad
TN	= Tacoma North Quad
TS	= Tacoma South Quad
UW	= University of Washington
W	= U. S. Geological Survey (Reston, VA)

Ages that were calibrated were done so with INTCAL 98

Table A-2 Sample Information

Point ID	Lab ID	Lat	Long	OSL Age	Error	Site Name	Material	Site No	Elev, m	Elev, ft	Geo Unit	PM no	PM meas	Comment
1a	WA-01	47.5885500	-122.31919000	71	4	I-5 @ Atlantic St	silt	KT-17-99	25.0	82.0	Possession Drift	T-9013-16	N	glaciolacustrine silt w/dropstones
2	WA-02	47.5878600	-122.39398000	22	1	Mildred's on Alki	silt	KT-18-99	12.2	40.0	Olympia beds	na	na	14C=21.2
3	WA-03	47.5878600	-122.39398000	19	2	Mildred's on Alki	channel sand	KT-12-99	12.2	40.0	Olympia beds	na	na	
4	WA-04	47.6577800	-122.42395000	15	1	Discovery Park, Olympia beds TS	silty sand	KT-19-99	3.0	10.0	Olympia beds	na	na	
5	WA-05	47.6577800	-122.42395000	13	1	Discovery Park, Lawton Clay TS	silt/clay	KT-19-99	24.4	80.0	Lawton Clay	na	na	
6	WA-06	47.2708500	-122.36718000	222	18	Woodworth/ Jones Qry	sand	KT-20-99	48.8	160.0	Defiance Drift	na	na	upper ww/jones quarry, pre-V drift
7	WA-07	47.3449300	-122.31825000	203	10	Redondo	sand	KT-4-99, DB-1-99	38.7	127.0	Hamm Creek	near T-9043	T	near Dash Pt St. Pk.
8	WA-08	na	na	na	na	Garfield Park	reworked ash	KT-22-99	12.0	39.4	Olympia beds	T-7295	N	much scatter, 14C=39k
9	WA-09	na	na	na	na	Garfield Park	sand w/organics	KT-22-99	12.0	39.4	Olympia beds	T-7295	N	much scatter in OSL dates; AMS on paleosol: 34,900 +/-350
10	WA-10	47.3168331	-122.53336080	267	13	Point Defiance, east most	ow sand above lam silt	KT-23-99	6.1	20.0	Defiance Drift	na	na	
11	WA-11	47.3177773	-122.53613421	238	17	Point Defiance	ow sand	KT-23-99	9.1	30.0	Defiance Drift	na	na	170' west of WA-10

Point ID	Lab ID	Lat	Long	OSL Age	Error	Site Name	Material	Site No	Elev, m	Elev, ft	Geo Unit	PM no	PM meas	Comment
12	WA-12	47.3177773	-122.53613421	137	9	Point Defiance, near trail head	lam silt/clay	KT-24-99	1.8	6.0	Whidbey Fm	T-7033	N	aka Owens Silt
13	WA-13	47.3187268	-122.54123040	218	20	Point Defiance, west most, at arch	varved silt/clay	KT-117-97, DB-174-98	1.5	5.0	Defiance silt	T-8101	N	block sample from arch
14	WA-14	47.3262300	-122.57526000	228	21	Gig Harbor	silty clay	KT-171-01	1.5	4.9	Defiance silt	T-1300	N	south of the Tides Restaurant in Gig Harbor
15	WA-15	47.3222727	-122.57533737	235	25	Gig Harbor	coarse sand	KT-172-01	6.1	20.0	Defiance Drift	na	na	near PM reversal
16	WA-16	47.2900486	-122.54988321	133	9	Pt. Evans MS	cemented sand	KT-173-01	12.2	40.0	Whidbey Fm	na	na	oxidized
17	WA-17	47.2900486	-122.54988321	100	5	Pt. Evans MS	coarse sand	KT-173-01	29.0	95.0	Whidbey Fm	na	na	
18	WA-18	47.2900486	-122.54988321	123	6	Pt. Evans MS	peat	KT-173-01	13.7	45.0	Whidbey Fm	na	na	
19	WA-19	47.2900486	-122.54988321	150	10	Pt. Evans MS	silty clay	KT-173-01	3.0	10.0	Double Bluff Drift	T-1303	T	above Transitional pm
20	WA-20	47.2758543	-122.55487748	40	3	Tacoma Narrows NW	silt	KT-174-01,142-00	12.2	40.0	Olympia beds	T-1306	N	
21	WA-21	47.2734779	-122.55662628	110	7	Tacoma Narrows SW	cemented sand	KT-175-01, KT-141-00	0.5	1.5	Whidbey Fm	na	na	
22	WA-22	47.2651577	-122.54322597	133	6	Tacoma Narrows NE	silt	KT-176-01, 106-97	27.4	90.0	Whidbey Fm	T-7015, 7298, 7301, 7304, 8212, 8215	T, T, T, T, T, R	lac, varved

Point ID	Lab ID	Lat	Long	OSL Age	Error	Site Name	Material	Site No	Elev, m	Elev, ft	Geo Unit	PM no	PM meas	Comment
23	WA-23	47.2628900	-122.54450000	108	9	Tacoma Narrows SE	silt	KT-177-01	4.9	16.0	Whidbey Fm	na	na	
24	WA-24	47.2700071	-122.36856588	>400	na	Jones East	pumaceous sand	KT-178-01	5.0	16.4	Qpy	T-7012	R	lahars, ashes, fission track=1.1ma
25	WA-25	47.3995954	-122.52483674	127	6	Sanford Pt., Vashon Is	fine sand	KT-179-01, KT-159-00	24.4	80.0	Whidbey Fm	na	na	near fault, north side of fault
26	WA-26	47.3995203	-122.52540537	185	9	Sanford Pt., Vashon Is	silt w/dropstones	KT-180-01, KT-159-00	1.5	4.9	Double Bluff Drift	T-1321	T	south side of fault; thrust up over sand of WA-25
27	WA-27	47.5750000	-122.40028000	18	5	Schmitz Park	silt	KT-46-00, DB-142-99	37.0	121.4	Lawton Clay	T-0127	R	reversely magnetized, above 14C of 27.1 ka @ elev. 20'
28	WA-28	47.4978300	-122.45771000	>400	na	Wingehaven Park	silt	DB-43-99,147-00	24.0	78.7	>400ka	T-0145	N	normally magnetized
29	WA-29	47.4978300	-122.45771000	>400	na	Wingehaven Park	silt	DB-43-99, 147-00	1.5	4.9	>780ka	T-0142	R	reversely magnetized
30	WA-30	47.6337700	-122.40152000	123	20	S. Magnolia Bluff	silt	DB-93-01	2.0	6.6	Whidbey Fm	T-1324	N	just above low tide
31	WA-31	47.7909800	-122.38802000	11.9	0.7	Deer Creek upper sand	clayey sand	KT-181-01, DB-68-01	15.2	50.0	Qva or Qvr	T-1327	N	PM from above WA, 14C from above WA of 43.9
32	WA-32	47.7903300	-122.38877000	12.5	3.5	Deer Creek lower sand	fine sand	KT-181-01, DB-68-01	6.1	20.0	Qva or Qvr	na	na	too young, below 14C of 44 ka, is this in place, in LS face, bottom sand
33	WA-33	47.7994200	-122.39098000	13	1	Edwards Pt.	fine sand	KT-141-01	16.8	55.0	Qva or Qvr	na	na	fine sand near top
34	WA-34	47.7994200	-122.39092000	104	15	Edwards Pt.	silt w/shells	KT-141-01	3.0	9.8	Whidbey Fm	T-1330	N	estuarine, w/mollusks

Point ID	Lab ID	Lat	Long	OSL Age	Error	Site Name	Material	Site No	Elev, m	Elev, ft	Geo Unit	PM no	PM meas	Comment
35	WA-35	47.7994300	-122.39082000	212	13	Edwards Pt.	silt	KT-141-01	1.0	3.3	Hamm Creek (or Defiance Drift)	na	na	below bioturbation; mix of ages of grains
36	WA-36	47.9118651	-122.31941172	37	4	Big Gulch	silt	KT-183-01, KT-162-01, DB-94-01	21.3	70.0	Olympia beds	T-1333	N	above a till
37	WA-37	47.9001300	-122.32451000	162	17	Chenault Bch Ck	silt	KT-184-01	9.1	30.0	Double Bluff Drift	T-1336	N	below WA-36, below a till
38	WA-38	47.9680735	-122.54661628	na	na	Dbl Bluff TS, WI; West end	diamict	KT-186-01	0.6	2.0	na	T-1339	N	below presumed Double Bluff till
39	WA-39	47.9682505	-122.54140207	na	na	TS Whidbey, WI	silt	KT-188-01	3.7	12.0	na	T-1342	N	sampled below lowest peat bed
40	WA-40	47.9755569	-122.51805075	na	na	Dbl Bluff, WI; East end	silt	KT-190-01	51.8	170.0	na	T-1345	N	adjacent to Useless Bay
41	WA-41	47.2862200	-122.54834000	104	13	Pt. Evans MS	sand	KT-420-03	57.9	190.0	Whidbey Fm	na	na	underlies a till
42	WA-42	47.2861800	-122.54854000	35	3	Pt. Evans MS	silt	KT-420-03	68.6	225.0	Olympia beds	na	na	silt above sand above diamcit
43	WA-43	47.2894263	-122.54949697	132	16	Pt. Evans MS	thin gray clay	KT-421-03	0.0	0.0	Whidbey Fm	na	na	beneath "jelly roll" in till, overlies more till, then Gig Habor gravel
44	WA-44	47.3167956	-122.53484138	146	15	Pt. Defiance, lower part of bluff	sand	KT-422-03	12.2	40.0	Double Bluff OW	na	na	in place? verify this age!, mod ox.
45	WA-45	47.3167956	-122.53484138	74	5	Pt. Defiance, top of bluff	sand	KT-422-03	42.7	140.0	Possession Drift	na	na	~50' below top of bluff w/thin Qvt
46	WA-46	47.6821600	-121.98812000	126	15	Redmond Ridge E, AC2 ravine	silt	KT-423-03	76.2	250.0	Whidbey Fm	na	na	laminated, brown, very hard, ML/CL

Point ID	Lab ID	Lat	Long	OSL Age	Error	Site Name	Material	Site No	Elev, m	Elev, ft	Geo Unit	PM no	PM meas	Comment
47	WA-47	47.6821600	-121.98812000	150	20	Redmond Ridge E, AC2 ravine	sand	KT-423-03	76.2	250.0	Double Bluff OW	na	na	Sand could be as old as 200,000, micaceous, fine sandy ML to SP
48	WA-48	47.9049665	-122.38023886	148	15	Possession Pt, WI	silt	KT-425-03	0.6	2.0	Double Bluff Drift	na	na	in between peat beds at Dbl Bluff type section
49	WA-49	47.9745322	-122.51957961	18.7	3	Dbl Bluff TS, east end, WI	fine sand	KT-426-03	21.3	70.0	Should be Whidbey Fm	na	na	age says Qob, too young! Liquefaction caused?
50	WA-50	47.9720700	-122.52846000	23.5	3	Dbl Bluff TS, east end, WI	silt	KT-427-03	48.8	160.0	Olympia beds	na	na	glaciotectonic fold
51	WA-51	47.9722300	-122.52865000	23	1.6	Dbl Bluff TS, east end, WI	sand	KT-427-03	61.0	200.0	Olympia beds	na	na	expected Qva, above WA-50
52	WA-52	47.9546800	-122.27112000	75	5	Powder Mill Gulch	silt	KT-429-03, 408-03	15.2	50.0	Possession Drift	na	na	glaciolacustrine silt w/dropstones; 60-75 cm above the unconf.
53	WA-53	47.9560800	-122.27221000	>145	na	Powder Mill Gulch	sand	KT-429-03, 408-03	6.1	20.0	saturated, older	na	na	vertically dipping, interbedded ML/SP/SM; 200' upstream of WA-52
54	WA-54	47.6564920	-122.42115327	11.5	0.9	Qva TS, Fort Lawton	fine sand	KT-428-03	61.0	200.0	Esperance Sand	na	na	younger than expected
55	WA-55	47.7995000	-122.39062000	13.9	1.2	Edwards Pt.	silt	BC	21.3	70.0	Lawton Clay	na	na	young age
56	WA-56	47.8061300	-122.30213000	78	8	Mountlake Terrace	silt	BC	114.3	375.0	Possession Drift	na	na	confirm which sample is MT vs LFP
57	WA-57	na	na	52	8	Lake Forest Park	silt	BC	61.0	200.0	Olympia beds	na	na	
58	WA-58	na	na	43.1	5.3	Holy Rosary School	sand	KT-85-04	na	na	Olympia beds	na	na	view boring log

Point ID	Lab ID	Lat	Long	OSL Age	Error	Site Name	Material	Site No	Elev, m	Elev, ft	Geo Unit	PM no	PM meas	Comment
59	WA-59	na	na	174	10	Ft. Lewis sonic core	sand	LC-82d-S-1	50.3	165.0	Double Bluff Drift	na	na	well nw of Garcia blvd and Blaine ave; surf elev @~280', from115-116' deep?
60	WA-60	na	na	>160	na	Ft. Lewis sonic core	ox, org, silt	LC-82d-S-9	35.7	117.0	Double Bluff Drift	na	na	poor sample data, older than 160ka, 163' deep?
61	WA-61	na	na	180	15	Ft. Lewis sonic core	silty sand	LC-82d-S-18/19	12.2	40.0	Double Bluff Drift	na	na	240' deep?
62	WA-62	na	na	115	5	Toe Jam Hill Fault/Cedar Trench	na	KT-411-03?	na	na	Whidbey Fm	na	na	For Alan Nelson
63	WA-63	na	na	9.9	1.6	Carlson-Thompson Residence, VI	sand under thrust fault	KT-86-04 S-4	na	na	Vashon	na	na	appears too young, perhaps this is Qvr?, not likely, seems overridden
64	WA-64	na	na	69.9	9	Devils Head	ow sand	KT-145-05	7.6	25.0	Possession Drift	na	na	
65	WA-65	na	na	105	5	Brightwater Tunnel	silt	E-309-469'	4.0	13.0	Whidbey Fm	na	na	gs at 482
66	WA-66	na	na	110	6	Brightwater Tunnel	silt	E-311-155'	6.1	20.0	Whidbey Fm	na	na	gs at 175
67	WA-67	na	na	120	6	Brightwater Tunnel	silt	E-321-197'	-12.8	-42.0	Whidbey Fm	na	na	gs at 155
68	WA-68	na	na	77	7	Brightwater Tunnel	silt	E-337-308'	-17.7	-58.0	Possession Drift	na	na	gs at 250
69	WA-69	na	na	95	6	Brightwater Tunnel	silt	E-212-302.5'	-8.4	-27.5	Whidbey Fm	na	na	gs at 275
70	WA-70	na	na	145	10	Brightwater Tunnel	silt	E-213-116'	33.2	109.0	Whidbey Fm	na	na	gs at 225
71	WA-71	na	na	65	8	Brightwater Tunnel	silt	E324-299'	-14.9	-49.0	Possession Drift	na	na	gs at 250

Point ID	Lab ID	Lat	Long	OSL Age	Error	Site Name	Material	Site No	Elev, m	Elev, ft	Geo Unit	PM no	PM meas	Comment
72	WA-72	na	na	25	3	Brightwater Tunnel	silt	E-407-455'	-9.1	-30.0	Olympia beds	na	na	gs@425'
73	WA-73	na	na	143	11.4	U-Link	sandy silt	UL-507-148'	40.2	132.0	Double Bluff Drift	na	na	some oxidation
74	WA-74	na	na	25.5	3	U-Link	sand, some silt nodules	UL-513-59'	80.8	265.0	Olympia beds	na	na	
75	WA-75	na	na	131	15.7	U-Link	silt w/stones	UL-535-109'	1.5	5.0	Whidbey Fm	na	na	
76	WA-76	na	na	138	9	U-Link	sandy silt	UL-539-150'	27.1	89.0	Whidbey Fm	na	na	
77	WA-77	na	na	76	15	U-Link	sand w/dropstones	UL-549-63'	1.5	5.0	Possession Drift	na	na	

Table A-3 Summary of Results from Luminescence Dating

Sample Information	Moisture (%)	Feldspar Dose Rate (Gy/Ka)	Equivalent Dose (Gy)	Feldspar Age – Minimum (ka)	Equivalent Dose (Gy)	Feldspar Age – Maximum (ka)	TL Age (ka)	Quarts Age (ka)	Best Fit Age – Minimum (ka)	Best Fit Age – Maximum (ka)	Method	TL Age – Minimum	TL Age – Maximum	Total Bleach[r] (TL Age)	Total Bleach[r] (IRSL Age)	K (%)	Th (ppm)	U (ppm)	Cosmic Dose Rate (Gy/ka)[l]	Total Dose Rate (Gy/ka)[m]	De (Gy)[n]	n[o]	Age (ka)	Footnotes
WA-1 I-5 @ Atlantic St silt	22 (73)	2.05 ± 0.05	137 ± 0.93 153 ± 2.07	66.9 ± 3.34 74.7 ± 4.10	140 ± 0.92 155 ± 2.01	68.3 ± 3.40 75.7 ± 4.13	58.2 ± 6.82 51.7 ± 9.70		68.3 ± 3.40	75.7 ± 4.13	Feldspar													(a) (b) (c) (d)
WA-2 Mildred's on Alki silt	23 (65)	1.50 ± 0.03	30.5 ± 0.26 32.2 ± 0.28 36.5 ± 0.40	20.3 ± 1.00 21.5 ± 1.06 24.4 ± 1.16	33.8 ± 0.25 33.7 ± 0.26 38.7 ± 0.22	22.6 ± 1.09 22.5 ± 1.10 25.9 ± 1.22	16.9 ± 1.42 19.4 ± 1.34		22.6 ± 1.09	25.9 ± 1.22	Feldspar													(a) (b) (c) (d)
WA-3 Mildred's on Alki channel sand	23 (52)	1.59 ± 0.04	30.6 ± 0.24 30.3 ± 0.22	19.3 ± 0.94 19.1 ± 0.92	31.7 ± 0.24 32.8 ± 0.22	19.9 ± 0.97 20.6 ± 0.99	16.9 ± 1.22		19.9 ± 0.97	20.6 ± 0.99	Feldspar													(a) (b) (c) (d)
WA-4 Discovery Park, Olympia beds TS silty sand	28 (50)	1.79 ± 0.04	26.6 ± 0.35 26.7 ± 1.01 25.9 ± 0.17	14.9 ± 0.69 14.9 ± 1.08 14.5 ± 0.58	27.5 ± 0.33 27.6 ± 0.82 27.5 ± 0.17	15.4 ± 0.69 15.4 ± 1.09 15.3 ± 0.61			15.4 ± 0.69	15.4 ± 1.09	Feldspar													(a) (b) (c) (d)
WA-5 Discovery Park, Lawton Clay TS silt/clay	6 (35)	2.73 ± 0.04	35.6 ± 0.63 32.0 ± 0.48	13.0 ± 0.62 11.7 ± 0.52	37.4 ± 0.63 34.7 ± 0.50	13.7 ± 0.64 12.5 ± 0.53	14.0 ± 5.51 19.7 ± 5.54 14.4 ± 1.44		14.0 ± 5.51	19.7 ± 5.54	Quartz TL													(a) (b) (c) (d)
WA-6 Woodworth/	18 (46)	1.59 ± 0.04	345 ± 10.8 395	217 ± 17.1 248	369 ± 11.3 405	232 ± 17.8 254			217 ± 17.1	254 ± 16.0	Feldspar													(a) (b) (c) (d)

Jones Qry sand			± 8.14	± 15.7	± 8.26	± 16.0																		
WA-7 Redondo sand	12 (45)	1.85 ± 0.04	375 ± 4.98 335 ± 3.75 429 ± 6.26	203 ± 10.1 181 ± 8.61 232 ± 11.8	37 ± 5.00 344 ± 3.77 438 ± 6.42	203 ± 10.1 186 ± 8.80 236 ± 12.1			181 ± 8.61	203 ± 10.1	Feldspar													(a) (b) (c) (d)
WA-8 Garfield Park reworked ash	22 (79)	1.96 ± 0.04	155 ± 5.21 196 ± 6.68	79.4 ± 6.13 100 ± 7.81	154 ± 5.20 209 ± 6.90	78.9 ± 6.12 107 ± 8.11	45.1 ± 6.32 85.0 ± 7.27		45.1 ± 6.32	85.0 ± 7.27	Quartz TL													(a) (b) (c) (d)
WA-9 Garfield Park sand w/organics	28 (42)	2.09 ± 0.06	131 ± 6.24 364 ± 6.98	62.5 ± 6.95 174 ± 11.8	130 ± 6.27 381 ± 7.05	62.2 ± 6.94 183 ± 12.3	159 ± 73.6 158 ± 73.6		62.2 ± 6.94	62.5 ± 6.95	Feldspar													(a) (b) (c) (d)
WA-10 Point Defiance, east most ow sand above lam silt	24 (52)	1.36 ± 0.03	387 ± 3.31 358 ± 1.68	284 ± 14.0 263 ± 12.4	395 ± 3.48 363 ± 1.67	291 ± 14.3 267 ± 12.6	206 ± 24.9 216 ± 19.1 247 ± 20.7		206 ± 24.9	216 ± 19.1	Quartz TL													(a) (b) (c) (d)
WA-11 Point Defiance ow sand	26 (43)	1.51 ± 0.01	325 ± 6.79 352 ± 3.34	215 ± 17.2 233 ± 16.5	331 ± 6.81 360 ± 3.38	219 ± 17.4 238 ± 16.8			215 ± 17.2	238 ± 16.8	Feldspar													(a) (b) (c) (d)
WA-12 Point Defiance, near trail head lam silt/clay	19 (80)	1.99 ± 0.06	275 ± 2.36 360 ± 1.65	139 ± 8.91 181 ± 11.4	288 ± 2.39 362 ± 1.66	145 ± 9.32 182 ± 11.4			139 ± 8.91	145 ± 9.32	Feldspar													(a) (b) (c) (d)
WA-13 Point	23 (60)	1.79 ± 0.06	391 ± 12.6 384	219 ± 20.4 215	412 ± 12.7 396	230 ± 21.2 222			215 ± 20.0	230 ± 21.2	Feldspar													(a) (b) (c) (d)

Defiance, west most, at arch varved silt/clay			± 12.1 350 ± 7.10	± 20.0 196 ± 16.1	± 12.1 360 ± 8.10	± 20.3 201 ± 16.4																		
WA-14 Gig Harbor, 1.5 m above beach, silt	28 (67)	2.13 ± 0.06	656 ± 21.5 440 ± 12.0 486 ± 4.81	308 ± 28.8 207 ± 16.4 228 ± 14.0	674 ± 24.2 456 ± 12.0 483 ± 4.88	316 ± 29.2 214 ± 16.8 227 ± 13.9	261 ± 34 164 ± 54 162 ± 16		214 ± 16.8	316 ± 29.2	Feldspar													(b) (c) (f) (g) (i) (j)
WA-15 Gig Harbor sand	5 (24)	1.73 ± 0.06	411 ± 6.20 549 ± 10.8	237 ± 20.3 317 ± 28.2	429 ± 6.26 574 ± 1.89	248 ± 21.1 332 ± 29.3	143 ± 18 172 ± 30	120 ± 8.91	237 ± 20.3	332 ± 29.3	Feldspar													(b) (c) (f) (g) (i) (j)
WA-16 cemented sand below WA-17	6 (32)	1.96 ± 0.06	265 ± 3.47 246 ± 3.27	135 ± 8.83 125 ± 8.22	273 ± 3.52 258 ± 3.30	139 ± 9.07 131 ± 8.57		35.3 ± 3.06	125 ± 8.22	139 ± 9.07	Feldspar													(b) (c) (f) (g) (i) (j)
WA-17 above peat layer	5 (26)	1.69 ± 0.03	165 ± 1.27	97.8 ± 4.56	174 ± 1.29	103 ± 4.77		45.6 ± 1.93	97.8 ± 4.6	103 ± 4.77	Feldspar													(b) (c) (f) (g) (i) (j)
WA-18 peat layer, sand from peat	33 (70)	2.39 ± 0.04	304 ± 2.22 283 ± 4.30 284 ± 5.48	127 ± 4.93 118 ± 5.57 119 ± 6.27	308 ± 2.22 294 ± 4.32 290 ± 5.48	129 ± 4.99 123 ± 5.71 121 ± 6.35	101 ± 4.08 63.2 ± 7.21 83.4 ± 13 .1		118 ± 5.57	129 ± 4.99	Feldspar													(b) (c) (f) (g) (i) (j)
WA-19 bottom of sequence Owens Silt?	24 (71)	1.74 ± 0.03	289 ± 3.55 252 ± 8.84	167 ± 7.81 145 ± 11.7	293 ± 4.16 286 ± 8.92	169 ± 8.29 164 ± 12.2	103 ± 12 79.3 ± 8.15		145 ± 11.7	169 ± 8.29	Feldspar													(b) (c) (f) (g) (i) (j)
WA-20 Sam Folly Gulch Owens Silt?	21 (59)	2.05 ± 0.03	72.8 ± 2.32	35.6 ± 2.53	90.1 ± 2.33	44.1 ± 2.86	21.2 ± 7.06[e]		35.6 ± 2.53	44.1 ± 2.86	Feldspar													(b) (c) (f) (g) (i) (j)

WA-21 Tacoma Narrows Bridge sand	6 (25)	1.75 ± 0.05	176 ± 3.87	101 ± 7.05	221 ± 3.98	126 ± 6.33	139 ± 13	40.0 ± 2.23	101 ± 7.05	126 ± 6.33	Feldspar													
			185 ± 1.57	106 ± 6.58	194 ± 1.59	111 ± 7.10	101 ± 10																	(b) (c) (f) (g) (i) (j)
WA-22 Tacoma Narrows Bridge silt	27 (54)	2.07 ± 0.04	245 ± 1.66 280 ± 2.21	118 ± 5.63 136 ± 5.09	280 ± 4.14 305 ± 2.29	135 ± 6.09 147 ± 5.47	75.5 ± 8.17		118 ± 5.63	147 ± 5.47	Feldspar													(b) (c) (f) (g) (i) (j)
WA-23 Tacoma Narrows	23 (64)	2.06 ± 0.03	190 ± 9.48 256 ± 8.35	92.1 ± 9.66 124 ± 9.03	211 ± 9.09 278 ± 7.92	102 ± 9.39 135 ± 8.33	96.4 ± 13.1 97.6 ± 5.45		92.1 ± 9.66	135 ± 8.33	Feldspar													(b) (c) (f) (g) (i) (j)
WA-25 Vashon Island Sandford Point sand	5 (28)	1.74 ± 0.04	230 ± 1.86	133 ± 6.21 133 ± 6	239 ± 1.86	138 ± 6.44 138 ± 6	97.8 ± 12.6 98 ± 12 to 116 ± 13		133 ± 6.21	138 ± 6.44	Feldspar													(b) (c) (f) (g) (i) (j)
WA-26 Vashon Island Sandford Point silt	16 (46)	2.19 ± 0.04	310 ± 4.22 345 ± 9.38	142 ± 6.18 158 ± 10.1	353 ± 4.34 365 ± 9.45	161 ± 6.78 167 ± 10.3			142 ± 6.18	167 ± 10.3	Feldspar													(b) (c) (f) (g) (i) (j)
WA-27 Schmitz Park West Seattle	22 (65)	2.38 ± 0.05	38.9 ± 0.52 49.1 ± 0.77 29.9 ± 0.14	16.4 ± 0.88 21.0 ± 1.15 13.0 ± 0.85	47.6 ± 0.53 56.4 ± 0.78 30.2 ± 4.12	20.0 ± 1.02 24.0 ± 1.28 13.0 ± 3.52	23.8 ± 2.84[e]		16.4 ± 0.88	20.0 ± 1.02	Feldspar													(b) (c) (f) (g) (i) (j)
WA-28 Wingehaven Park silt	21 (55)	1.64 ± 0.03																						(b) (c) (f) (g) (i) (j)
WA-29	9	2.26	268	119	301	133	194		119	135	Feldspar													(b)

Wingehaven Park lower silt	(68)	± 0.04	± 7.48 297 ± 5.08	± 7.77 131 ± 6.35	± 7.65 304 ± 5.11	± 8.16 135 ± 6.44	± 83		± 7.77	± 6.44														(c) (f) (g) (i) (j)
WA-30 S. Magnolia Bluff silt	10 (53)	2.44 ± 0.06	324 ± 8.42 279 ± 4.35 326 ± 3.13	133 ± 9.59 114 ± 6.73 134 ± 7.18	326 ± 8.41 285 ± 3.89 338 ± 3.18	134 ± 9.62 117 ± 6.82 138 ± 7.40																		(b) (c) (f) (g) (i) (j)
WA-31 Deer Creek, top sand	25 (42)	1.73 ± 0.04						10.6 ± 0.67 11.3 ± 0.07	10.6 ± 0.67	11.3 ± 0.07	Quartz TL													(b) (c) (f) (g) (i) (j)
WA-32 Deer Creek, bottom sand	3 (34)	3.89 ± 0.08	47.3 ± 0.29 39.1 ± 0.06	12.1 ± 0.91 10.0 ± 0.74	47.9 ± 0.61	12.3 ± 0.92 13 ± 1.0	9.24 ± 0.72 16 ± 1.3	10.7 ± 0.68	10 ± 0.7 9.24 ± 0.72	13 ± 1.0 16 ± 1.3	Feldspar Quartz TL													(b) (c) (f) (g) (i) (j)
WA-33 Edwards Point, top sand	12 (37)	2.39 ± 0.08	29.4 ± 0.27 30.9 ± 0.28 25.9 ± 0.70	12.3 ± 0.82 12.9 ± 0.86 10.9 ± 0.91	30.7 ± 0.26 31.6 ± 0.26	12.9 ± 0.85 13.3 ± 0.88	8.85 ± 0.9 6.36 ± 0.56		12.3 ± 0.82	13.3 ± 0.88	Feldspar													(b) (c) (f) (g) (i) (j)
WA-34 Edwards Point middle silt	19 (35)	2.80 ± 0.21	278 ± 2.84 278 ± 8.45	99.4 ± 15.2 99.3 ± 16.3	280 ± 2.52 283 ± 8.46	100 ± 15.4 101 ± 16.6	129 ± 20.2[e]		99.3 ± 16.3	101 ± 16.6	Feldspar													(b) (c) (f) (g) (i) (j)
WA-35 Edwards Point bottom silt	9 (34)	2.16 ± 0.04	438 ± 7.88 455 ± 11.2 380 ± 7.52	203 ± 10.3 211 ± 12.9 176 ± 9.40	441 ± 7.89 462 ± 11.3 387 ± 7.55	204 ± 10.4 214 ± 12.9 179 ± 9.50	119 ± 17 224 ± 17 145 ± 15		176 ± 9.40 119 ± 17	214 ± 12.9 224 ± 17	Feldspar Quartz TL													(b) (c) (f) (g) (i) (j)
WA-36 Big Gulch silt	23 (66)	1.90 ± 0.03	63.3 ± 2.06	33.3 ± 2.43	76.6 ± 2.08	40.2 ± 2.54	41.1 ± 3.8 4[e]		33.3 ± 2.43 41.1 ± 3.8	40.2 ± 2.54 41.1 ± 3.8	Feldspar Quartz TL													(b) (c) (f) (g) (i) (j)

									4	4														
WA-37 Chenault Creek silt	19 (69)	1.94 ± 0.07	314 ± 6.37	162 ± 13.3	321 ± 6.84	166 ± 13.3	157 ± 16.9[e]		162 ± 13.3 157 ± 16.9	166 ± 13.3 157 ± 16.9	Feldspar Quartz TL													(b) (c) (f) (g) (i) (j)
WA-41 Pt. Evans section Revisited sand	5 (39)	1.57 ± 0.04	116 ±5.65 117 ±3.81	73.7 ± 9.29 74.3 ± 4.62	169 ± 5.23 152 ± 3.88	108 ± 11.5 96.9 ± 5.76	122 ± 10.2	>101 ± 18.5	74.3 ± 4.62 122 ± 10.2	108 ± 11.5 122 ± 10.2	Feldspar Quartz TL													(b) (c) (e) (f) (g) (h)
WA-42 Gig Harbor silt Olympia Beds?	19 (52)	2.19 ± 0.04	74.5 ± 4.38	34.0 ± 3.55[e]	78.9 ± 4.05	36.2 ± 2.34[e]			34.0 ± 3.55	36.2 ± 2.34	Feldspar													(b) (c) (e) (f) (g) (h)
WA-43 Gig Harbor silt Double Bluff?	11 (47)	1.99 ± 0.04	251 ± 15.2	126 ± 10.1[e]	276 ± 12.1	139 ± 11.8[e]			126 ± 10.1	139 ± 11.8	Feldspar													(b) (c) (e) (f) (g) (h)
WA-44 Pt. Defiance sand	9 (40)	1.94 ± 0.07	277 ± 3.86 287 ± 3.44	143 ± 11.0 148 ± 11.3	281 ± 3.85 288 ± 3.44	145 ± 11.2 148 ± 11.4	150 ± 17.3	>99.0 12.4	143 ± 11.0 150 ± 17.3	148 ± 11.4 150 ± 17.3	Feldspar Quartz TL													(b) (c) (e) (f) (g) (h)
WA-45 Pt. Defiance sand Possession?	15 (23)	1.86 ± 0.05	136 ± 4.76	73.1 ± 4.39[e]	141 ± 5.08	75.8 ± 4.62[e]		69.4 ± 5.83	73.1 ± 4.39 69.4 ± 5.83	75.8 ± 4.62 69.4 ± 5.83	Feldspar Quartz TL													(b) (c) (e) (f) (g) (h)
WA-46 W. Snoqualmie Road silt	24 (54)	3.06 ± 0.09	384 ± 21.1	125 ± 13.8[e]	388 ± 22.3	127 ± 15.2[e]			125 ± 13.8	127 ± 15.2	Feldspar													(b) (c) (e) (f) (g) (h)
WA-47	25 (41)	1.88 ± 0.08	240 ± 11.2	128 ± 14.1	242 ± 11.4	129 ± 14.2	184 ± 26.8		120 ± 10.9	157 ± 13.6	Feldspar													(b) (c)

W. Snoqualmie Road sand			226 ± 8.83	120 ± 10.9	295 ± 7.04	157 ± 13.6	134 ± 60.4		134 ± 60.4	184 ± 26.8	Quartz TL													(e) (f) (g) (h)
WA-48 Whidbey Island silt	29 (56)	3.15 ± 0.08	466 ± 33.3	148 ± 14.6[e]	472 ± 37.5	150 ± 15.28[e]			148 ± 14.6	150 ± 15.28	Feldspar													(b) (c) (e) (f) (g) (h)
WA-49 Whidbey Island sand	19 (33)	2.16 ± 0.06	56.6 ± 2.30	26.2 ± 1.59[e]	60.3 ± 2.29	27.9 ± 1.70[e]	30.6 ± 2.23[e]	18.7 ± 3.03	26.2 ± 1.59	27.9 ± 1.70	Feldspar													(b) (c) (e) (f) (g) (h)
									30.6 ± 2.23	30.6 ± 2.23	Quartz TL													
WA-50 Lawton clay	18 (73)	3.38 ± 0.09	73.8 ± 2.75	21.8 ± 1.26	82.3 ± 2.79	24.4 ± 1.40	24.2 ± 2.80		21.8 ± 1.26	24.4 ± 1.40	Feldspar													(b) (c) (e) (f) (g) (h)
									24.2 ± 2.80	24.2 ± 2.80	Quartz TL													
WA-51 sand	1 (29)	1.96 ± 0.05			73.0 ± 1.57	37.2 ± 1.95	35.7 ± 2.77	23.2 ± 1.61	37.2 ± 1.95		Feldspar													(b) (c) (e) (f) (g) (h)
			<71.8 ± 1.57	<36.6 ± 1.92	<111 ± 3.52	<56.4 ± 3.81			35.7 ± 2.77		Quartz TL													
									23.2 ± 1.61		Quartz													
WA-52 Powder Mill Gulch	18 (64)	3.18 ± 0.09	228 ± 9.07	71.8 ± 4.07	249 ± 6.22	78.5 ± 4.45	116 ± 9.34		71.8 ± 4.07	92.2 ± 5.28	Feldspar													(b) (c) (e) (f) (g) (h)
			253 ± 9.59	79.5 ± 4.56	293 ± 12.3	92.2 ± 5.28			116 ± 9.34	116 ± 9.34	Quartz TL													
WA-53 Powder Mill Gulch sand	15 (33)	2.01 ± 0.09	171 ± 10.2	84.9 ± 11.1	>250 ± 18.2	>124 ± 14.0	>145 ± 19.5	> 96.1 ± 21.5	84.9 ± 11.1	>124 ± 14.0	Feldspar													(b) (c) (e) (f) (g) (h)
									>145 ± 19.5	>145 ± 19.5	Quartz TL													
WA-54 Discovery Park, sand Esperance type section	4 (30)	1.42 ± 0.04						12.6 ± 1.01	12.6 ± 1.01	12.6 ± 1.01	Quartz													(b) (c) (e) (f) (g) (h)
WA-55	19 (49)	2.76 ± 0.05	36.9 ± 1.11	13.5 ± 0.78	39.2 ± 1.13	14.4 ± 0.80			12.8 ± 1.21	14.4 ± 0.80	Feldspar													(b) (c)

Edwards Point				12.8 ± 1.21																				(e) (f) (g) (h)
WA-56 Lake Forest Park silt	28 (53)	2.25 ± 0.04	156 ± 6.20 115 ± 4.53 97.6 ± 3.88	68.5 ± 3.43 51.3 ± 2.91 43.4 ± 3.17	161 ± 5.64 194 ± 4.97	70.5 ± 2.70 86.2 ± 4.08	83.3 ± 7.12 75.1 ± 5.51		68.5 ± 3.43 75.1 ± 5.51	83.3 ± 7.12 83.3 ± 7.12	Feldspar Quartz TL													(b) (c) (e) (f) (g) (h)
WA-57 Lake Forest Park silt	25 (60)	2.28 ± 0.05	107 ± 4.64 125 ± 1.89	47.1 ± 3.63 54.9 ± 2.23	110 ± 4.61 134 ± 2.00	48.2 ± 3.64 58.9 ± 2.40	47.5 ± 4.17[e]	37.3 ± 3.93	47.1 ± 3.63 47.5 ± 4.17	58.9 ± 2.40 47.5 ± 4.17	Feldspar Quartz TL													(b) (c) (e) (f) (g) (h)
WA-58 Holy Rosary School sand	13 ± 1								43.1 ± 5.33	43.1 ± 5.33	Feldspar					1.13 ± 0.05	3.24 ± 0.15	1.37 ± 0.09	0.06 ± 0.02	1.44 ± 0.06	62.0 ± 2.71	14 (17)	43.1 ± 5.33[f]	(k) (l) (m) (n) (o) (p) (q)
WA-63 Carlson-Thompson Residence, VI sand under thrust fault	7 ± 1								9.93 ± 1.62	9.93 ± 1.62	Feldspar					1.27 ± 0.13	5.31 ± 0.42	2.20 ± 0.17	0.06 ± 0.02	1.78 ± 0.08	17.6 ± 1.19	20 (20)	9.93 ± 1.62[f]	(k) (l) (m) (n) (o) (p) (q)
WA-64 Devil's Head Outwash Sand	7 ± 1								69.9 ± 9.04	69.9 ± 9.04	Feldspar					0.83 ± 0.03	2.05 ± 0.12	0.90 ± 0.05	0.06 ± 0.02	1.01 ± 0.03	70.6 ± 4.11	7 (8)	69.9 ± 9.04[g]	(k) (l) (m) (n) (o) (p) (q)
WA-65 Brightwater Tunnel silt				105.2 ± 5.7 107.8 ± 5.7		108.8 ± 5.8 111.5 ± 5.9			105.2 ± 5.7 187.7 ± 24.6	111.5 ± 5.9 205.5 ± 25.8	Feldspar Quartz TL	187.7 ± 24.7 >68.2 ± 5.6	205.5 ± 25.8 >85.4 ± 7.6	316.8 ± 23.8	112.8 ± 6.0									(r) (s) (t) (u)
WA-66 Brightwater Tunnel silt				108.4 ± 6.5		109.6 ± 6.6			108.4 ± 6.5	109.6 ± 6.6	Feldspar	>42.8 ± 3.9	>53.4 ± 5.0											(r) (s) (t) (u)

WA-67 Brightwater Tunnel silt				119.4 ± 6.2 112.7 ± 6.8		120.9 ± 6.3 116.9 ± 7.0			112.7 ± 6.8 102.5 ± 24.8	120.9 ± 6.3 158.6 ± 9.7	Feldspar Quartz TL	150.1 ± 9.3 102.5 ± 24.8	158.6 ± 9.7 148.2 ± 27.8	210.8 ± 18.1	118.1 ± 7.0									(r) (s) (t) (u)
WA-68 Brightwater Tunnel silt				76.8 ± 4.1 68.8 ± 3.1		88 ± 4.5 74.5 ± 3.4 84.8 ± 3.8			68.8 ± 3.1 >51.4 ± 14.1	88 ± 4.5 >50.4 ± 12.9	Feldspar Quartz TL	>51.4 ± 14.1 >46.6 ± 4.8	>50.4 ± 12.9 >54.6 ± 5.3 >51,1 ± 4.5	147.7 ± 10.1	89.3 ± 4									(r) (s) (t) (u)
WA-69 Brightwater Tunnel silt				88 ± 9 98 ± 4		91 ± 9 101 ± 5			88 ± 9 86 ± 16	101 ± 5 90 ± 26	Feldspar Quartz TL	86 ± 16 60 ± 4	90 ± 26 66 ± 7											(u) (v) (w) (x) (y)
WA-70 Brightwater Tunnel silt				117 ± 7		154 ± 8 146 ± 8			117 ± 7 74 ± 5	154 ± 8 79 ± 6	Feldspar Quartz TL	74 ± 5 79 ± 6	-	129 ± 8	156 ± 9									(u) (v) (w) (x) (y)
WA-71 Brightwater Tunnel silt				47 ± 3 54 ± 4		73 ± 4			47 ± 3 40 ± 15	73 ± 4 59 ± 12	Feldspar Quartz TL	28 ± 9 40 ± 15	59 ± 9 59 ± 12	132 ± 9	102 ± 5 103 ± 5									(u) (v) (w) (x) (y)
WA-72 Brightwater Tunnel silt				29 ± 2 14 ± 1		28 ± 2 29 ± 2 22 ± 1			22 ± 1 24 ± 2	29 ± 2 26 ± 2	Feldspar Quartz TL	24 ± 2 25 ± 2	26 ± 2 25 ± 2	49 ± 4	23 ± 1									(u) (v) (w) (x) (y)
WA-73 U-Link sandy silt	15 (32)								143 ± 11.4	143 ± 11.4	Feldspar					1.14 ± 0.02	4.28 ± 0.16	1.70 ± 0.07	0.20 ± 0.02	2.44 ± 0.05 1.73 ± 0.04	348 ± 17.4		143 ± 11.4[aa]	(l) (n) (o) (z) (aa) (bb)
WA-74 U-Link sand, some silt nodules	18 (25)								24.3 ± 2.92	26.7 ± 2.94	Feldspar					1.03 ± 0.04	2.32 ± 0.19	0.70 ± 0.18	0.24 ± 0.02	1.72 ± 0.09 1.36 ± 0.07	45.9 ± 1.84 33.0 ± 2.48	30 (35)	26.7 ± 2.94[aa] 24.3 ±	(l) (n) (o) (z) (aa) (bb)

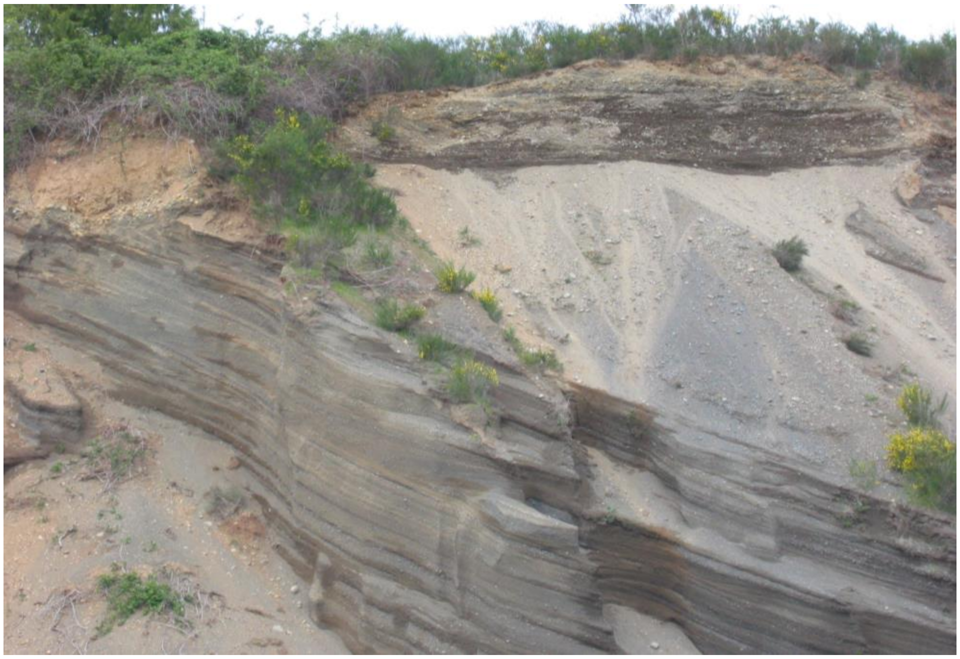
																							2.92[bb]	
WA-75 U-Link silt w/stones	25 (60)								131 ± 15.7	131 ± 15.7	Feldspar					0.98 ± 0.02	2.86 ± 0.15	1.17 ± 0.09	0.22 ± 0.02	1.76 ± 0.05 1.31 ± 0.04	232 ± 20.8		131 ± 15.7[aa]	(l) (n) (o) (z) (aa) (bb)
WA-76 U-Link sandy silt	22 (41)								138 ± 9.01	138 ± 9.01	Feldspar					0.97 ± 0.03	3.31 ± 0.16	1.24 ± 0.08	0.20 ± 0.02	1.89 ± 0.05 1.38 ± 0.04	262 ± 10.5		138 ± 9.01[aa]	(l) (n) (o) (z) (aa) (bb)
WA-77 U-Link sand w/dropstones	14 (24)								67.2 ± 6.67	84.8 ± 7.24	Feldspar					1.01 ± 0.03	3.42 ± 0.14	1.03 ± 0.07	0.24 ± 0.03	2.09 ± 0.07 1.56 ± 0.05	178 ± 9.78 105 ± 6.81	21 (24)	84.8 ± 7.24[aa] 67.2 ± 6.67[bb]	(l) (n) (o) (z) (aa) (bb)

(a) Field moisture, ages based on 57-83% of the full saturation moisture, according to sand content (more sand less moisture, more silt more moisture).
(b) Silt fraction (4-11 micron size) for IRSL as multiple aliquot additive dose technique (MAAD), obtained with a CS-3-67 orange filter 10 minute bleach.
(c) Silt fraction (4-11 micron size) for IRSL as multiple aliquot additive dose technique (MAAD), obtained with a CS-3-67 orange filter 60 minute bleach.
(d) Samples collected in February 1999.
(e) Field moisture (saturation moisture), ages based on 46-72% of the full saturation moisture, according to sand content (more sand less moisture, more silt more moisture).
(f) Lab used fine sand grains (125-90 micron size) for Blue-Light OSL as single aliquot regeneration techique (SAR). Fit to linear regression. Errors on equivalent dose and dose rate at one sigma.
(g) Weighted average of three ages (taken from weighted average of equivalent doses).
(h) Samples collected in October 2003.
(i) Field moisture (saturation moisture), ages based on 56-83% of the full saturation moisture, according to sand content (more sand less moisture, more silt more moisture).
(j) Samples collected in September 2001 (WA-38, WA-39, WA-40 not run, from Useless Bay, Whidbey Island. WA-24 Jones East Quarry, tephra, too old also not run.)
(k) Locations for samples include Holy Rosary School and Devil's Head, Olympia.
(l) Cosmic doses and attentuation with depth were calculated using the methods of Prescott and Hutton (1994).
(m) Total dose rate is measured from moisture content of 25% as an average between field moisture and full saturation moisture values, and does not include alpha component.
(n) Reported to one sigma.
(o) Number of replicated equivalent dose (De) estimates used to calculate the mean. Second number is total measurements made including failed runs with unusable data.
(p) Lab used fine sand grains (105-90 micron size), data fit to linear regression.
(q) Lab used fine sand grains (250-180 micron size), data fit to exponential + linear regression.
(r) Oldest possible age if the sample had been well bleached before deposition, most haven't
(s) Ages based on dose rates of 35% moisture content through time for E-321 and E-337 (the silty clay)
(t) Ages based on dose rates of 20%-25% moisture content through time for E-309, E-311 (the sandy silt)
(u) In all of these samples the fraction run was fine silt 4-11 micron size

(v) Ages based on dose rates of 30% moisture content through time for E-212-302.5' (the silty clay)
(w) Ages based on dose rates of 20% moisture content through time for E-213-116', E-324-299' and E-407-435' (the sandy silt)
(x) IRSL= Infrared Stimulated Luminescence Dating (on feldspars)
(y) TL= Thermoluminescence dating (feldspars and quartz)
(z) Total dose rate is measured from moisture content of 25% as an average between field moisture and full saturation moisture values, top is for IRSL fine grains, bottom is for quartz OSL.
(aa) Lab used fine silt grains (4-11 micron size), data fit to an exponential regression and obtained as infrared stimulated luminescence on feldspar by multiple aliquot additive dose.
(bb) Lab used fine sand grains (150-90 micron size), data fit to exponential + linear regression and obtained as blue light stimulated luminescence on quartz by single aliquot regeneration.

Appendix B
Photographs

All photos were taken in the State of Washington.



Photograph 1. Foreset and topset beds in Vashon recessional outwash at the Brinnon Delta on Hood Canal.

Photograph 2. Image of Vashon till at Perkins Lane, Seattle. Red bar is 2 meters in length. Voids represent where sand and groundwater had been present.

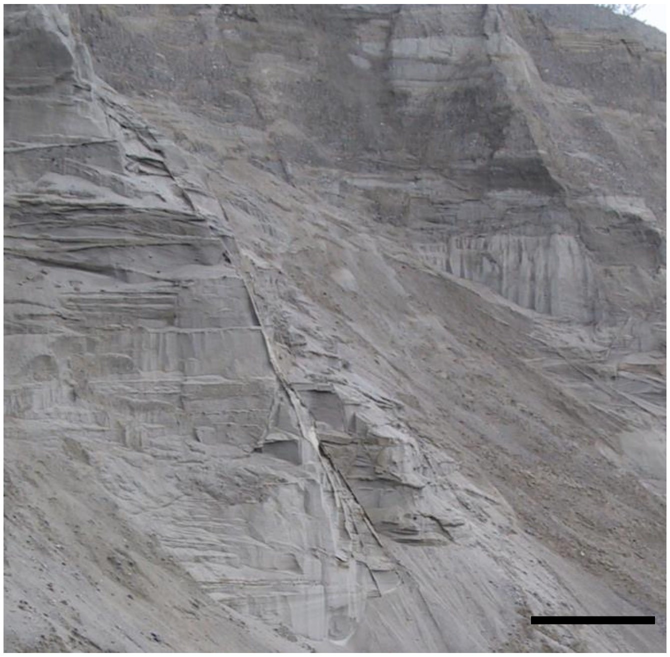

Photograph 3. Joint sets in Vashon till in Lake Washington, north end of Seward Park, Seattle.


Photograph 4. Close up of till/bedrock contact with clasts of bedrock in the till, south of Bellevue.

Photograph 5. Vashon till over Esperance Sand near Mill Creek. Sharp contact.

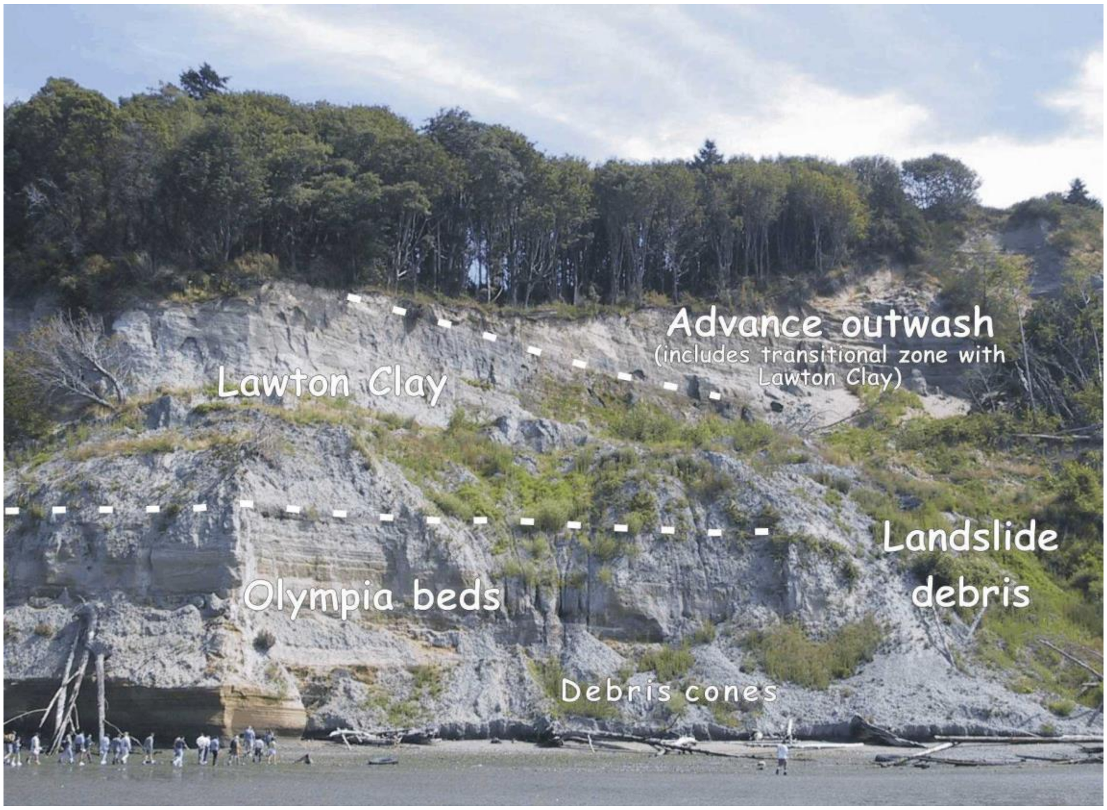
Photograph 6. Vashon till over Esperance Sand near Fife. Gradational contact.

Photograph 7. Shannon Mahan and Derek Booth collecting luminescence sample at Discovery Park, Seattle.

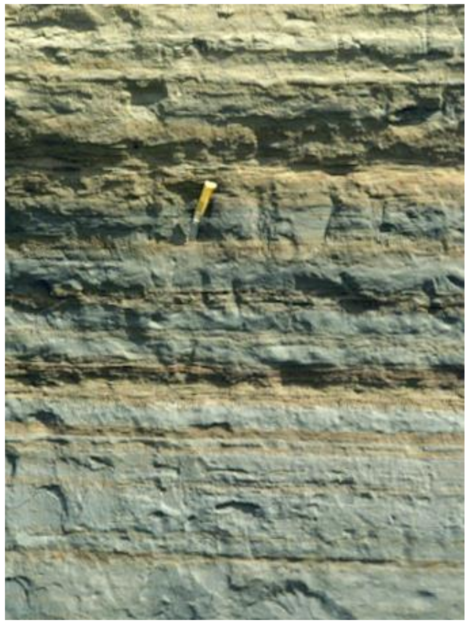


Photograph 8. Cross bedded Esperance Sand in quarry in Fife. Numerous normal faults with offsets of 2 to 3 m. Black bar is 2 m in length.

Photograph 9. Diapir of Lawton Clay injected into Esperance Sand, Possession Point, Whidbey Island. Chris Converse pictured.

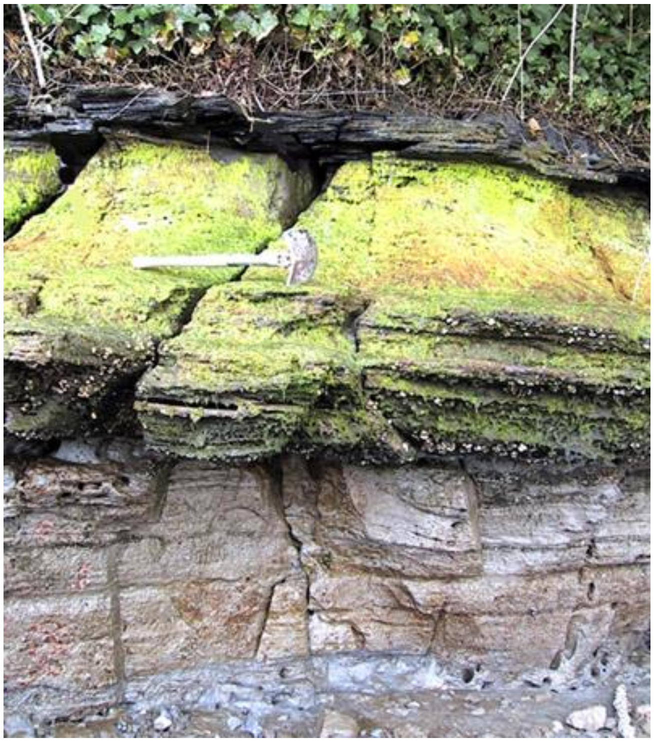


Photograph 10. View of bluff at South Beach at Discovery Park, Seattle, type section for Esperance Sand, Lawton Clay, and Olympia formation (aka Olympia beds) Photo by D. Booth.



Photograph 11. Close-up view of Olympia formation deposits at Discovery Park, Seattle.

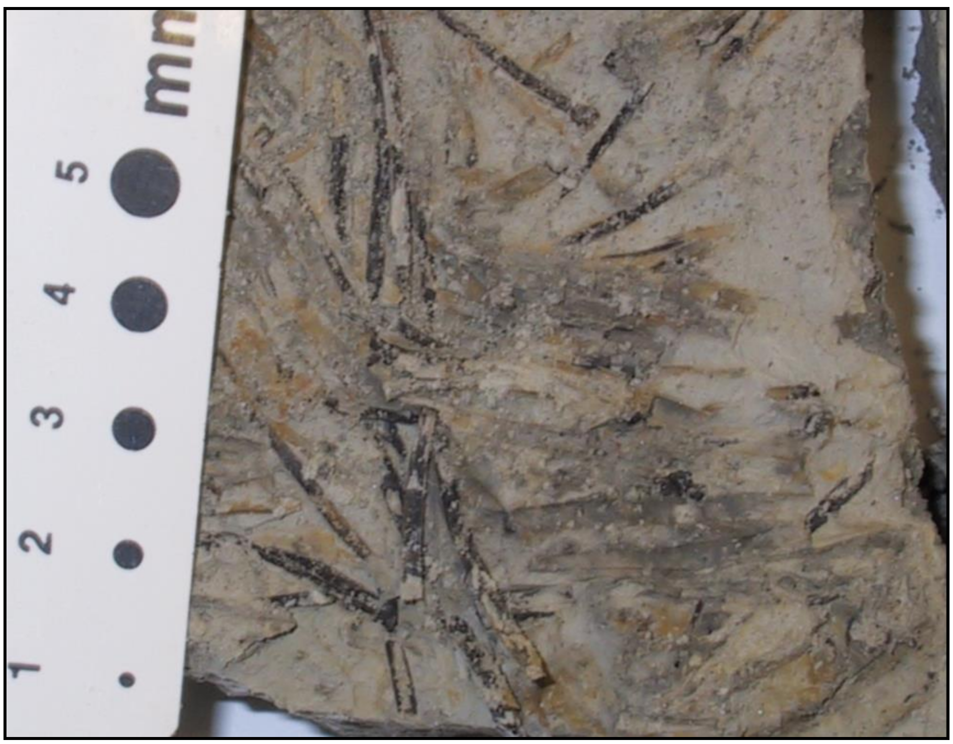
Photograph 12. Wood and cones in Olympia-age deposits near Bremerton.



Photograph 13. Peat (covered in moss) and organic silt in Olympia-age deposits near Bremerton.

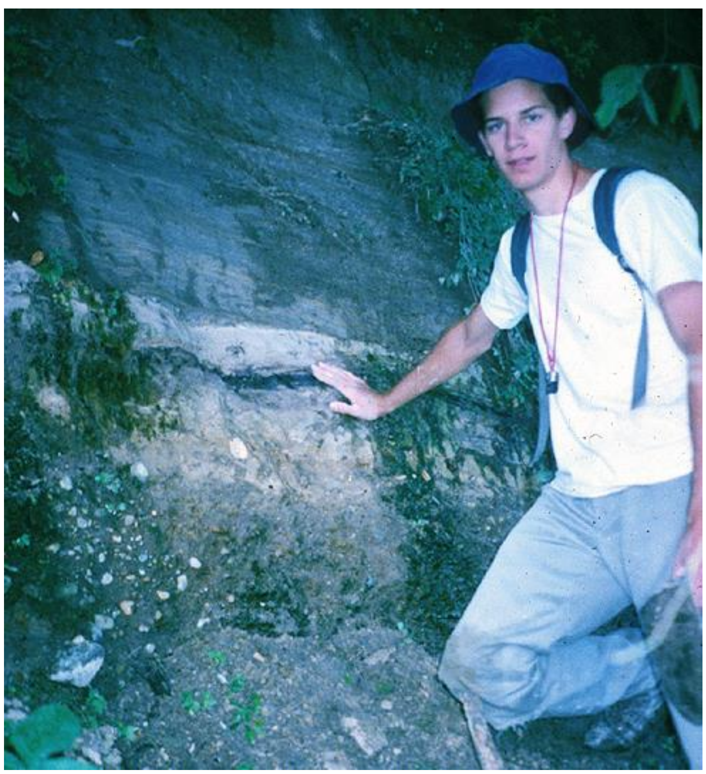
Photograph 14. Fluvial sand in the Olympia formation near Bremerton. Note finely disseminated organics near tip of knife.

Photograph 15. Image of cone from *Picea Englemannii* from Olympia formation deposits at Point Evans.



Photograph 16. Image of western white pine needles from Olympia formation deposits at Point Evans.

Photograph 17. Image of freshwater mussel fossil in Olympia formation deposits at South Beach at Discovery Park, Seattle.



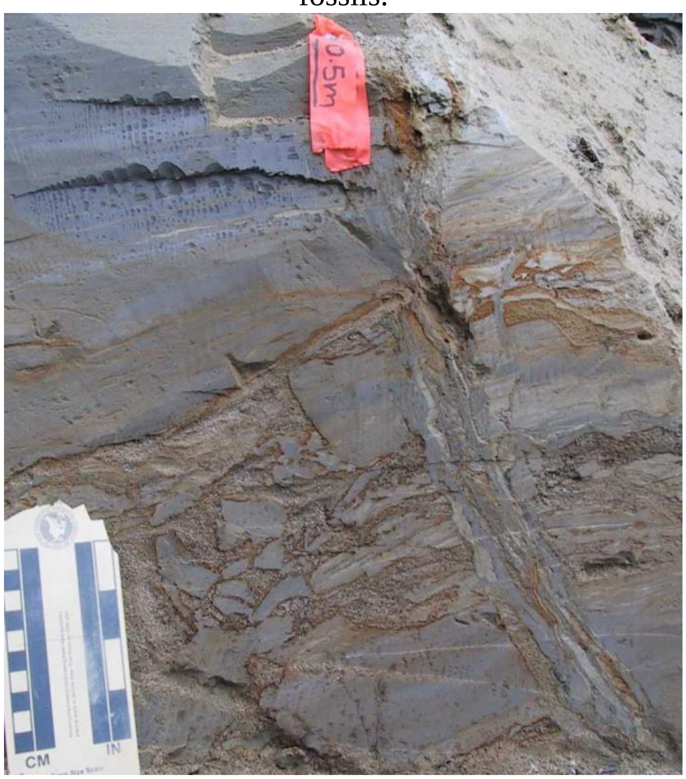
Photograph 18. Image of volcanic ash layer (above hand of Tabor Hersum), peat layer, and fluvial deposit (below hand) of Olympia-formation age, Garfield Park, Tacoma.

Photograph 19. Location of the Atlantic/I-5 type section underneath the northbound lane of I-5 on the west side of Beacon Hill. Luminescence sample location WA-1.

Photograph 20. Image of Possession-age glaciolacustrine deposits at the Atlantic/I-5 type section on the west side of Beacon Hill.

Photograph 21. View of Devil's Head type section in the southern Puget Sound showing interbedded silt, organic layers, and pumice-rich sand. Gravelly deposit at base was determined to be Possession in age based on luminescence dating.

Photograph 22. Angular unconformity near base of section at Point Edwards, south of Edmonds. Steeply dipping sand below an MIS 4 horizontally-oriented glaciomarine deposit with clam fossils.



Photograph 23. Liquefaction features in MIS 4 deposits at Edwards Point, south of Edmonds.

Photograph 24. Image of marine mussels in Possession-age glaciomarine drift encountered in boring E-212, at a depth of 310-315 ft (elevation -40 to -45 ft), for the Brightwater project.

Photograph 25. Image of marine/estuarine clam fossils in Possession-age glaciomarine drift at Edwards Point, south of Edmonds.

Photographs 26 and 27. Images of the Point Evans type section near Gig Harbor. Horizontally bedded material near top is Esperance Sand. Possession-age till at the "till" label.

Photograph 28. Whidbey-age silt over Double Bluff till at Point Evans measured section, near Tacoma.

Photograph 29. Whidbey-age fluvial deposits at Point Evans measured section, near Tacoma.

Photograph 30. View of Lyman Rapids outwash, likely correlative with MIS 4 alpine glaciation on the Olympic Coast (Photo by S. Porter).

Photograph 31. Probable liquefaction-related offsets, Franklin Ave North, north end of Capitol Hill.


Photograph 32. Image of dipping Whidbey Formation deposits north of Gig Harbor in the Tacoma Fault Zone.


Photograph 33. Collecting paleomagnetic measurement in reversely magnetized deposits near sea level on Vashon Island.


Photograph 34. Preparing hole for luminescence sampling, Vashon Island.


Photograph 35. Image of end cap of luminescence sampler embedded in silty sand at sample site.


Photograph 36. Image of pre-Vashon outwash with Curtis Koger of AESI.


Photograph 37. Glaciolacustrine deposits of the Defiance drift (MIS 8) at Point Defiance, Tacoma. Numerous small reverse faults and sand-filled dikes present. Derek Booth for scale.

Photograph 38. Glaciolacustrine deposits of the Defiance drift (MIS 8) at Point Defiance, Tacoma.

Photograph 39. Steeply dipping old (>400ka) glaciolacustrine beds overlain by horizontally bedded interglacial deposits, Powder Mill gulch, northeast of Mukilteo.

Photograph 40. Pumice-rich sand cut by channel filled with volcanic and pumice clasts. Determined to be 1.1 ma by fission track dating. North of Sumner.