SR 520, I-5 to Medina:
Bridge Replacement and HOV Project

Geomorphology and Shoreline History of Lake Washington, Union Bay, and Portage Bay Technical Memorandum

Prepared for

Washington State Department of Transportation
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Prepared by

Kathy Goetz Troost
Troost Geological Consulting

Consultant Team

Parametrix, Inc.
CH2M HILL
HDR Engineering, Inc.
Parsons Brinckerhoff
ICF Jones & Stokes
Confluence Environmental Company
Michael Minor and Associates
PRR, Inc.
Critigen
Troost Geological Consulting

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Executive Summary

The Washington State Department of Transportation retained Troost Geological Consulting under subcontract to Parametrix, Inc. to conduct a geomorphological study of Lake Washington, Union Bay, and Portage Bay along the I-5 to Medina: Bridge Replacement and HOV project corridor. The purpose of the study was 1) to determine the presence of former shorelines and 2) to determine the history of water level rise.

Samples were collected from continuously sampled borings drilled as part of the geotechnical engineering investigation. Logging and classification of the samples led to an understanding of the submerged strata in the three basins. Selected samples were subjected to analyses that aided in the identification of water depth, plant assemblages, depositional environment, landscape features, and depositional age. These analyses were used to construct the geologic history and geomorphic development for the study area.

The depositional histories of Lake Washington, Union Bay, and Portage Bay are similar. Starting at the bottom, in general the strata in Union Bay and Portage Bay consist of glacial recessional silty gravelly deposits, overlain by glacial lake silt/clay with a weathered surface, overlain by diatomaceous peat or organic silt. A sandy horizon was noted in Union Bay. Starting at the bottom in Lake Washington, the strata generally consist of glacial lake clay/silt with a weathered surface and a thin layer of marine/estuarine silt, overlain by a thick layer of gyttja (diatomaceous ooze and organic matter). Three volcanic ash layers were encountered, and two were determined to correlate with events of known ages, Glacier Peak and Mazama O.

Water depth and depositional environment for the basins add significant information about their geologic history. Union Bay, after the glacial lake environment, persisted as a shallow freshwater lake to marsh environment with periods of and areas of subaerial exposure. Streams entering and crossing the bay contributed localized sandy material. Portage Bay also persisted as a shallow freshwater lake but with less vegetation than in Union Bay. Lake Washington persisted as a deep freshwater lake after the retreat of marine water at the end of the glacial recessional phase.

Large-scale landscape features are the product of glacial scouring while some of the smaller-scale features are the result of human influences. The water bodies occupy glacially-scoured basins and depressions left by large blocks of ice. Two drumlins extend into Lake Union; one at the east side of Union Bay is totally submerged today, and the other is the submerged northern extension of Foster Island. The scoured bottoms of the basins have some topographic relief. Geomorphic characteristics of shorelines were seen in Union Bay, benches, and in the sides of Lake Washington, knickpoints and benches. Dredging and dumping in Union Bay altered the

landscape and shoreline around Foster Island, and the opening of the Lake Washington Ship Canal in 1916 altered the shoreline of the Lake and Union Bay by lowering the water level 9 feet.

A history of water level rise was compiled using the geologic history with the radiocarbon dates from this study. Parts of the submergence curve agree with previous studies. Lake Washington filled to an elevation of -40 feet by about 14,500 years calibrated before present (Cal B.P.), then it continued to rise gradually until 1916 when the abrupt lowering occurred. Union Bay followed close to the same pattern. Portage Bay filled to an elevation of about -18 feet by about 13,000 years Cal B.P., then it rose gradually to the present level. The submergence curve can be used to estimate minimum water elevation at a given time in lake history. Inflections in the curve correlate with older shorelines identified during the analyses.

Buried shorelines, i.e., paleoshorelines, are present in the study area at several elevations but only eight appear to be potentially significant to this study:

1) at -40 feet at about 14,500 years Cal B.P. in the Lake and Union Bay

2) at -32 feet at about 8,500 years Cal B.P. in Union Bay

3) at -22 feet at about 7,600 to 7000 years Cal B.P. in the Lake and Union Bay

4) at -18 feet at about 13,000 years Cal B.P. in Portage Bay

5) at -12 feet at about 5000 years Cal B.P. in the Lake and Union Bay

6) at -22 to 3 feet until 2,000 years Cal B.P. on the submerged ridge at the east side of Union Bay

7) at 25+/-4 feet and 17+/-4 feet at 980 AD around all of the basins from the Seattle fault earthquake

8) at 28+/-2 feet at September 1916 around Lake Union and Union Bay

These interpretations and conclusions are based on the available data and actual conditions may vary. Additional data may enhance or require a revision of these interpretations.

Contents

Appendices

Tables

Figures

1.0 Introduction

This report is part of Task 5.1 of the YH-8393 contract deliverables between Troost Geological Consulting (TGC) and Parametrix, Inc. The report provides a summary from findings of the geomorphology and shoreline study conducted by TGC between August 19, 2010, and early April 2011.

Lake level in Lake Washington has risen both gradually and intermittently since deglaciation over 15,000 years ago (16,850 years calibrated before present [Cal B.P.]), with shorelines developing when a particular lake level was maintained for a period of time. These older shorelines, some now submerged, are considered paleoshorelines and may be manifest in many ways, including weathering horizons, in situ land plants, land insects or animals, layers of charcoal and artifacts, and relatively flat geomorphic surfaces. Recognizing, identifying, and delineating these paleoshorelines is an important aspect for construction projects within the Lake Washington and ship canal basins yet surprisingly little is known about lake level rise and possible paleoshorelines.

1.1 Goal of the Study

The goals of this study are 1) to determine the history of lake level rise, and from that information, 2) determine where paleoshorelines exist within the Lake Washington, Union Bay, and Portage Bay basins within the proposed new SR 520 corridor. Since evidence of almost all of the paleoshorelines is likely submerged, sampling from below the water was required to address these goals. Methods employed are described below in Section 2.0. Paleoshorelines are potentially useful horizons for evaluating Native American use of the area, earthquake history, and the history of local response to regional and global climate change.

1.2 Site Description and Geologic Setting

The study area consists of the proposed new SR 520 bridge alignment, from just east of I-5 to the eastern shoreline of Lake Washington at Medina (Figure 1). This section of bridge and roadway contains 1 mile of floating bridge, about 2 miles of traditional bridge, and about 1 mile of overland road surface. Over that 4-mile distance, SR 520 crosses, from west to east, Portage Bay, Union Bay, and Foster Island, then Lake Washington (Figure 1). Low-elevation land ridges separate Portage Bay and Union Bay, and a similar, but submerged, ridge separates Union Bay from Lake Washington. Foster Island, a ridge, partly splits Union Bay, creating a smaller western basin. All of these water bodies (Figures 2 and 3) occupy natural basins, although they are now interconnected by a ship canal that was excavated in 1916.

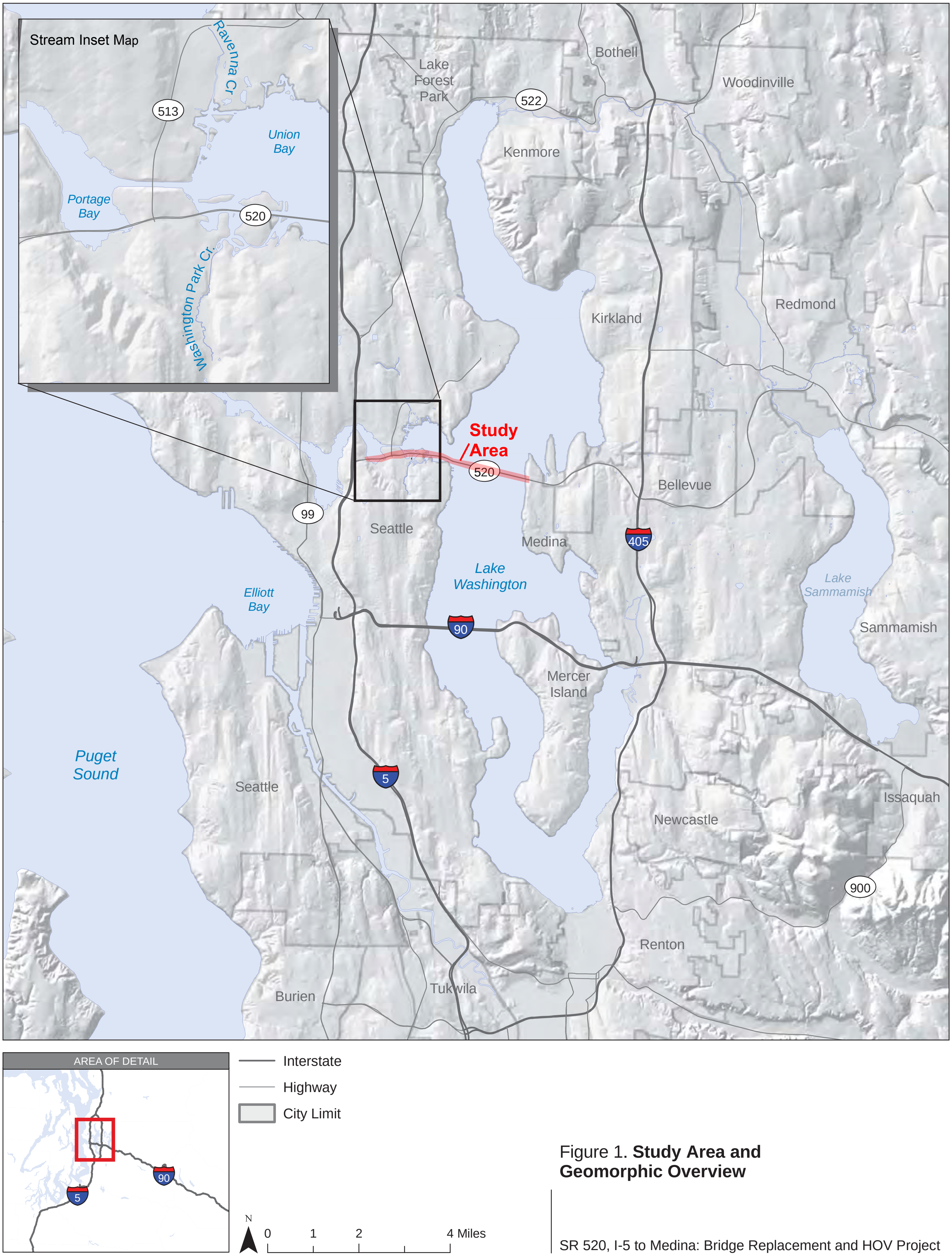

Figure 1. **Study Area and Geomorphic Overview**

SR 520, I-5 to Medina: Bridge Replacement and HOV Project

Lake Washington is the second largest natural lake in the State of Washington, with a shoreline length of nearly 72 miles and a water area of 28 square miles (Chrzastowski, 1983). Several peninsulas project into the lake and Mercer Island occupies a large portion of the southern half of the lake. Average lake depth is about 110 ft and in the SR 520 corridor, the depth is just over 200 feet; the maximum for the Lake is about 215 feet. The current primary inflows to the Lake are from the Cedar River and the Sammamish River draining Lake Sammamish and secondary inflows are from springs along the slopes above the Lake and deeper groundwater seeps. The Lake's current outflow is through the Lake Washington Ship Canal which is about 8 miles long and at least 30 feet deep, providing navigable water between the freshwater Lake and marine water of Puget Sound. Lake level, kept within a 2-foot range, is currently controlled by a dam at the Hiram M. Chittenden Locks maintained by the Corps of Engineers. Although there is some fluctuation, the elevation of the lake surface averages around 18 to 19 feet above mean sea level, with 18 feet being the reference elevation for the lake for this report.

Lake Washington occupies a north-south elongated trough that was carved subglacially during the last glaciation, Vashon Stage, of the Central Puget Lowland (Booth, 1994). The trough was scoured to an elevation of -400 feet (Lister and others, 1967) according to sonar reflection profiling. Water and sediment accumulated in the lake as the glacier melted and continues to accumulate today. The lake is surrounded by other north-south-oriented features that attest to the direction of ice flow, such as drumlins and large hills (Figure 1). The modern shoreline of the lake is characterized by a 10-foot-high bench, embayments, gentle slopes, steep slopes, and a few peninsulas. The embayments typically contain marshes growing on peaty organic sediment that were once part of the lake bottom.

The study area falls within an active tectonic area. The southern third of Lake Washington crosses the Seattle fault zone, a high-angle reverse fault intermittently active over the past 30 million years (Johnson and others 1999; Pratt and Troost 2008), while the northern two-thirds of the lake crosses the Seattle Basin (Blakely and others 2002) in the footwall of the fault. At Lake Washington, the northern strand of the Seattle Fault runs parallel to I-90 and lies under the northern end of Mercer Island (Stephenson and others 2007; Liberty and Pratt, 2008). Depth to competent bedrock is deepest under the UW vicinity where the basin is at its deepest at 6 miles. Pleistocene deposits there are on the order of 1750 feet thick (Jones 1996). Several earthquakes have occurred on strands of the Seattle fault within the Holocene; the most recent with known impacts on the Lake Washington Basin occurred 1,100 years ago (Chrzastowski, 1983; Atwater and Moore 1992; Jacoby and others 1990; Karlin and Abella 1992). Lake Washington is deepest north of the fault and the deepest peat is found north of the fault in Mercer Slough at 70 feet in depth.

Parts of the study area have been altered significantly since settlers arrived in the mid-1800s. The land was logged allowing more runoff to enter the basins. A landfill was established that filled part of the marsh south of Marsh Island. The ship canal was opened in 1916 and a channel was dredged to improve navigation. The dredge spoils were placed nearby and upwards of 15 feet of fill were placed on the marshes of Union Bay. The landfill persisted until 1935.

1.3 Previous Studies

Hundreds of papers have been written about Lake Washington, ranging from hydrologic to biologic to geologic. Several papers stand out as particularly relevant for the study conducted herein. Others, while relevant, will be referenced as appropriate throughout the report but receive no special mention here.

A report by Mr. Charles Hodges (2010), addressing the shorelines on north Foster Island for the SR 520 Project, recognized the potential for submerged shorelines that led, in part, to this study. He recognized the difficulty of establishing a clear lake level rise history for Lake Washington with just the available literature.

Several studies have partly addressed the history of lake level rise in Lake Washington. The two most significant studies are unpublished: one by Dr. Estella Leopold at the University of Washington and one by Dr. Robert Thorson at the University of Connecticut. Dr. Leopold (1982a, 1982b, 1986) has written several articles about Lake Washington based largely on pollen work from deep cores and was available for consultation during this study. The unpublished work compares the environmental implications from deep cores from Mercer Slough and offshore from Sand Point.

Thorson (1998) provided an assessment of lake level rise based on his recognition of terrestrial peat in Juanita Bay. This report has not been published and the figures are not available; therefore the validity of his results was not evaluated. Based on submerged terrestrial peat, Thorson concluded that between 13,000 and 3,000 years before present (B.P.) the lake level in Lake Washington was controlled by sea level. From 3,000 to present, the outlet of the lake was not directly influenced by Puget Sound and the lake level was separate from sea level.

Other work on Lake Washington particularly relevant to this study is that related to diatoms, the strata in Lake Union, and potential turbidity deposits. Work completed by Abella with diatoms (1982, 1986, 1988) helped to delineate some of the past depositional environments and to focus investigative methods for this study. Ms. Abella was also available for consultation during this study. McManus (1963) completed a manuscript based on the drilling prior to the initial construction of SR 520 in Lake Union. His detailed stratigraphic information proved helpful for parts of the geologic history reconstruction. Gould and Budinger (1961) reported on the bathymetry and configuration of the lake bottom and Rigg and Gould (1957) reported on the sediments in the bottom of Lake Washington. Rigg’s estimated age for the bottom of lake sediment, 14,800 years Cal B.P. (13,500 years ago) has been quoted extensively since it was published in 1958. Karlin and Abella (1996) and Karlin and others (2004) completed a sediment study and sidescan sonar view in Lake Washington identifying evidence for paleo earthquakes, landslides, and storm events. Some of these events were also seen in the deposits sampled for this study.

In 1983, Chrzastowski compiled a map and report documenting the historical changes to Lake Washington and the route of the Lake Washington Ship Canal. His work provides a thorough description of the conditions and setting before and after the locks and canal were completed. Galster and Laprade (1991) also provide historical recounting of early engineering works, including the Ship Canal, and a description of engineering geology for the Seattle area.

The most recent geologic information for the study area and region come from Troost and Booth (2008) and Troost and others (2005), while site-specific subsurface information is available in reports by Shannon & Wilson, Inc. (including 2006, 2011a, and 2011b). In addition, a marine geophysical investigation was completed by Golder Associates in 2003 that provided some insight about the bottom of Lake Washington and Union Bay.

2.0 Methods

Multiple corroborative methods were used to address the two main goals of the study, including literature search, geomorphic mapping, borehole sampling, and sample testing. A single type of analysis or single data point is generally not sufficient for drawing conclusions about shorelines and water depth because of the high probability of data gaps and potentially misleading data. By using multiple methods, trends are more likely to be seen in the data, an inconclusive finding can be confirmed by another method, or a gap in the first method may be filled in subsequent methods. The methods described in this section were designed to answer two questions:

1) What is the history of lake level rise?

2) Where are the paleoshorelines within the Lake Washington, Union Bay, and Portage Bay basins?

2.1 Literature Review

A literature search was conducted to capture not only manuscripts that address the two main goals directly, but also address the methodologies proposed to answer the questions. For example, diatom assemblages are useful for determining water depth, so literature about diatom research in Lake Washington was collected.

Literature describing history, diatoms, peat, water level, sediment, pollen, earthquakes, faulting, and vegetation for Lake Washington, Union Bay, and Portage Bay were collected. These documents were obtained from University of Washington library and Special Collections, WorldCat Libraries, King County, and private individuals. The U.S. Army Corps of Engineers, Seattle Parks and Recreation, and University of Washington Botanical Gardens were contacted to understand the history of filling and excavating in the study area.

The literature review started several months before sample acquisition and continued throughout the project as needed, although the bulk of the work was completed by the end of 2010. Some of the documents collected are listed in the references section at the end of this report. Many of the rest of the documents collected were helpful but are not actually referenced in this report.

2.2 Geomorphic Mapping

Geomorphic mapping was conducted along the SR 520 alignment to evaluate the land surface and subaqueous surfaces for shorelines. This technique consists of evaluating Lidar topographic features such as curvature, slope, and texture and other characteristics to determine landscape elements and potential origins. The bathymetry of Lake Washington, Union Bay, and Portage Bay (Figures 4 and 5) is a significant element of the analysis for possible shorelines. The results of the geomorphic mapping are integrated with the rest of the analyses to determine potential shorelines.

2.3 Borehole Sampling

While Shannon & Wilson, Inc. (S&W) was conducting geotechnical barge-mounted drilling for the new SR 520 bridge representatives from TGC collected split samples alongside the S&W representative at some of the borehole locations from September through December 2010 and January 2011. Split samples were collected only at the continuously sampled boreholes (Figures 2 and 3). These samples were subjected to several types of analyses, including diatom analyses, seed identification, peat identification, bivalve identification, radiocarbon dating, tephra analyses, organic content, dry density, and soil classification and humification. Specific borings were selected in each main basin to serve as stratigraphic and age control borings and, as such, samples from those borings received most of the analyses.

As of early May, eighty-nine borings were drilled over water for the geotechnical investigation of the new bridge and landings between Medina and I-5. Land borings and additional overwater borings were drilled by S&W after early May, when TGC drafted the report for this study; those borings were not used in TGC's analysis. TGC participated in the drilling of 31 borings as continuously sampled boreholes (Table 1, Figures 2 and 3, Appendix A). “Participation” means that a TGC representative was onsite to log the boreholes and to extrude samples. Photographs of the drilling operations, samples, and equipment used are included in Appendix B. Drilling was accomplished by WSDOT drill crews on barges with a CME-45 skid rig using the advancing-casing method (photograph pages B-1, B-2, B-3, Appendix B).

Continuous sampling was accomplished by alternately pushing Shelby tubes and driving various-sized split-spoon samplers. For most of the boreholes, the samplers and rods advanced under their own weight in the soft lake sediment. For glacially overridden material, autohammers were used to drive the split-spoon samplers. Shelby tubes were advanced by a piston sampler or using the push method. All sampling intervals were logged in the field and the samples in the split-spoon sampler were observed, logged, photographed, and collected in the field. Shelby tubes were capped in the field by the S&W representative and taken to their laboratory to be extruded and described at a later date (photograph page B-4, Appendix B). Sample recovery was occasionally impaired by the use of a split-spoon sampler in fibrous peat (photograph page B-5, Appendix B).

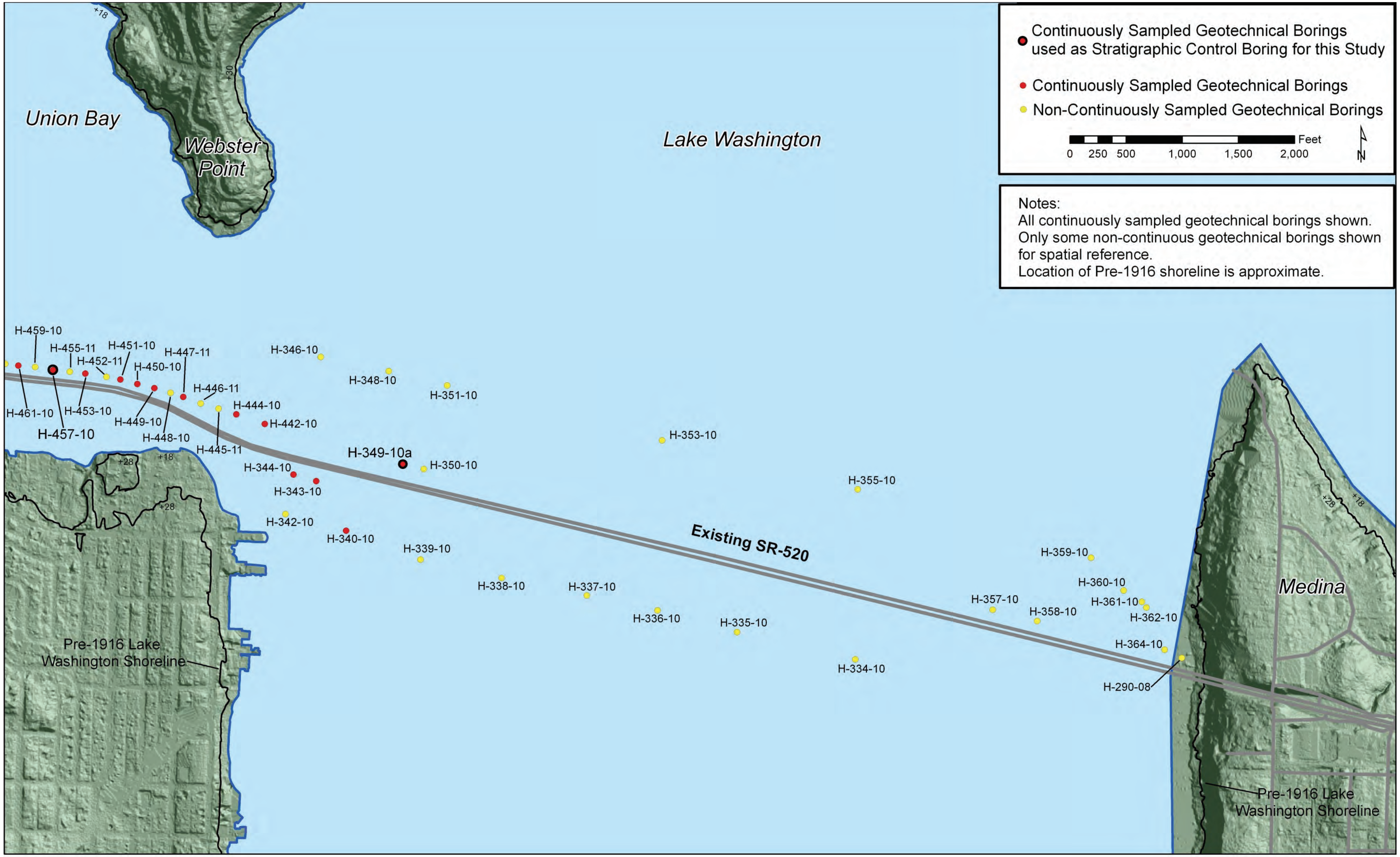

Figure 2. **Map Showing Borings Utilized in Lake Washington**

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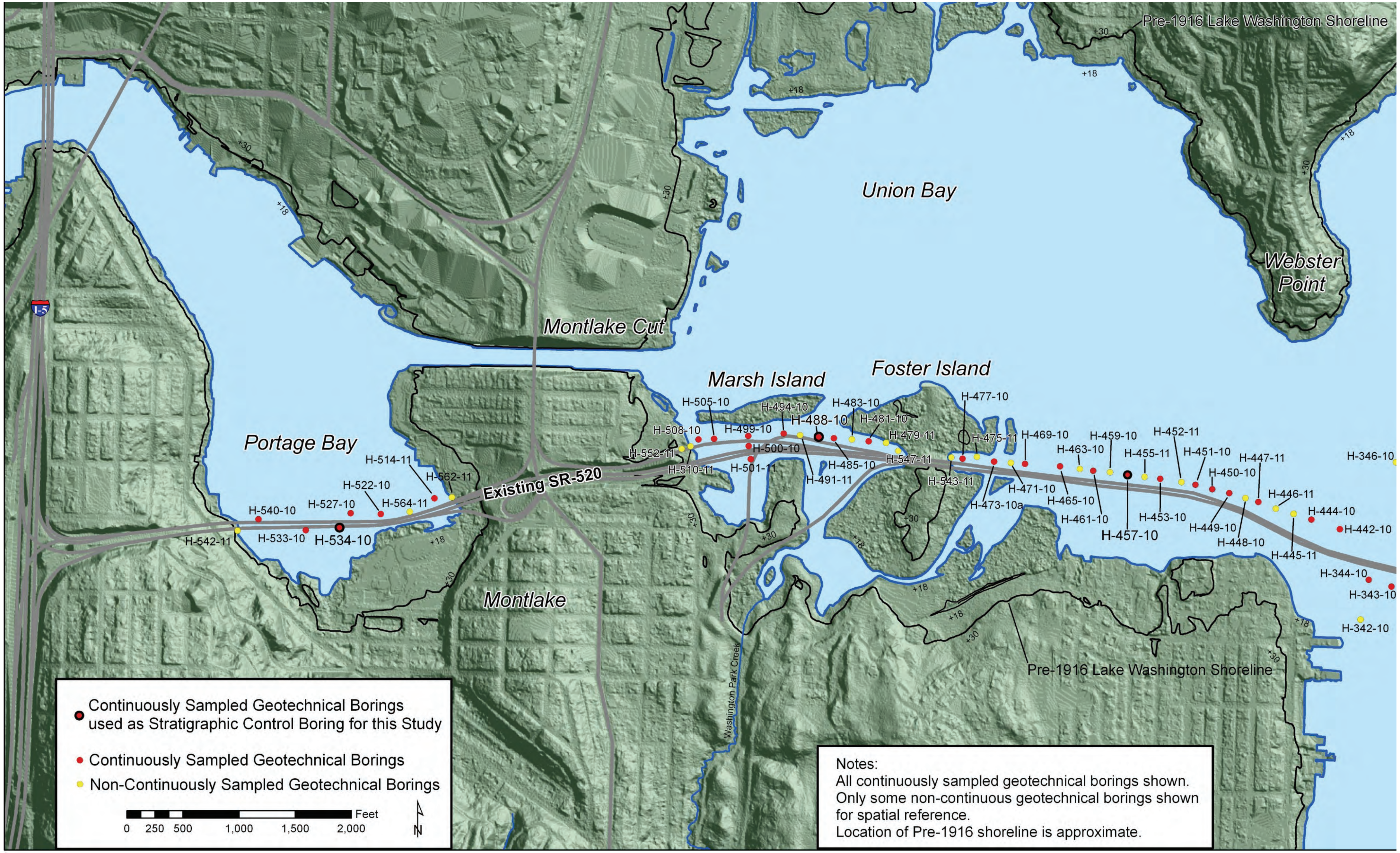

Figure 3. **Map Showing Borings Utilized in Union and Portage Bays**

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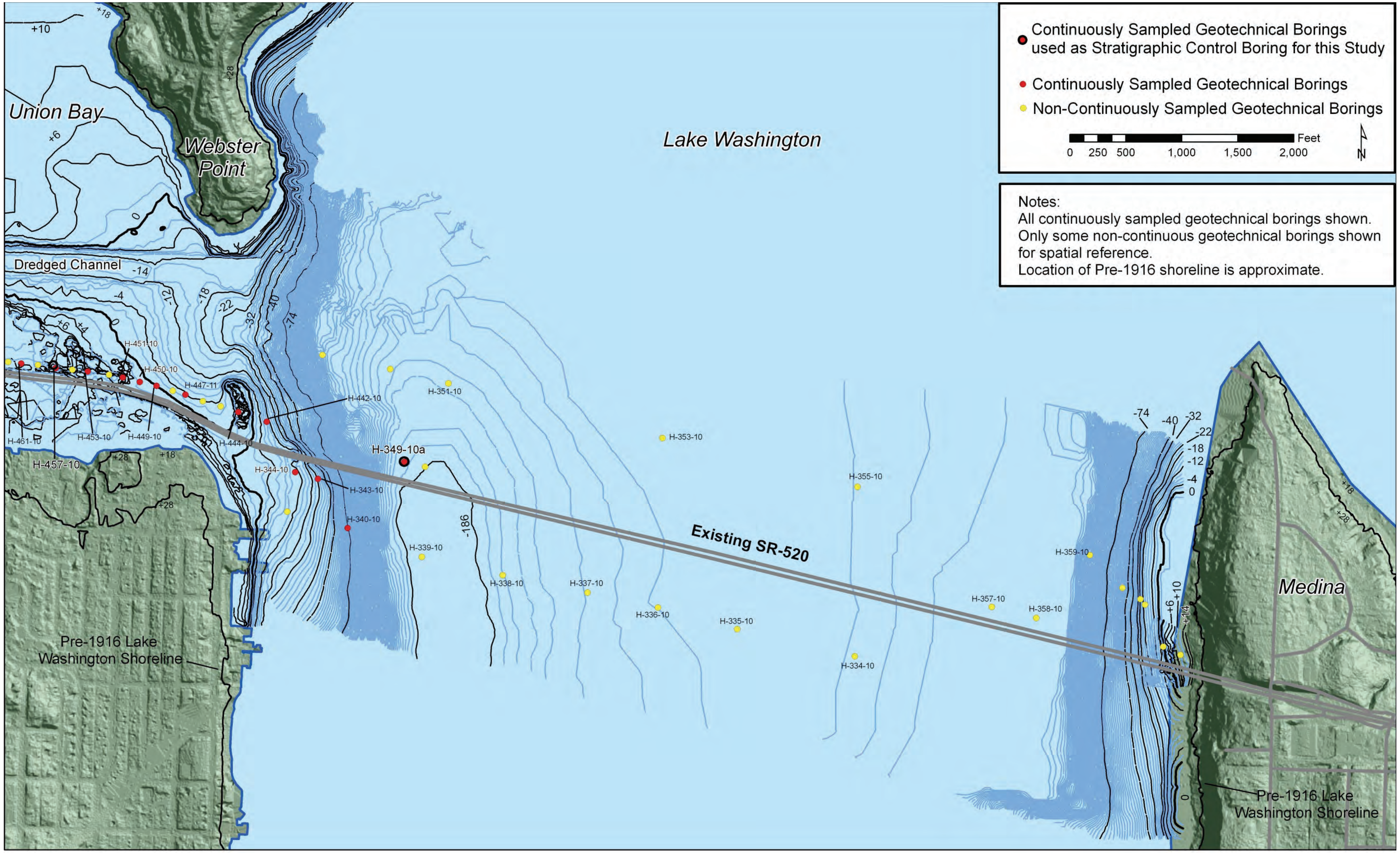

Figure 4. **Map Showing Bathymetric Contours in Lake Washington. Contours at sea level and at or near paleoshoreline elevations are shown with a darker line.**

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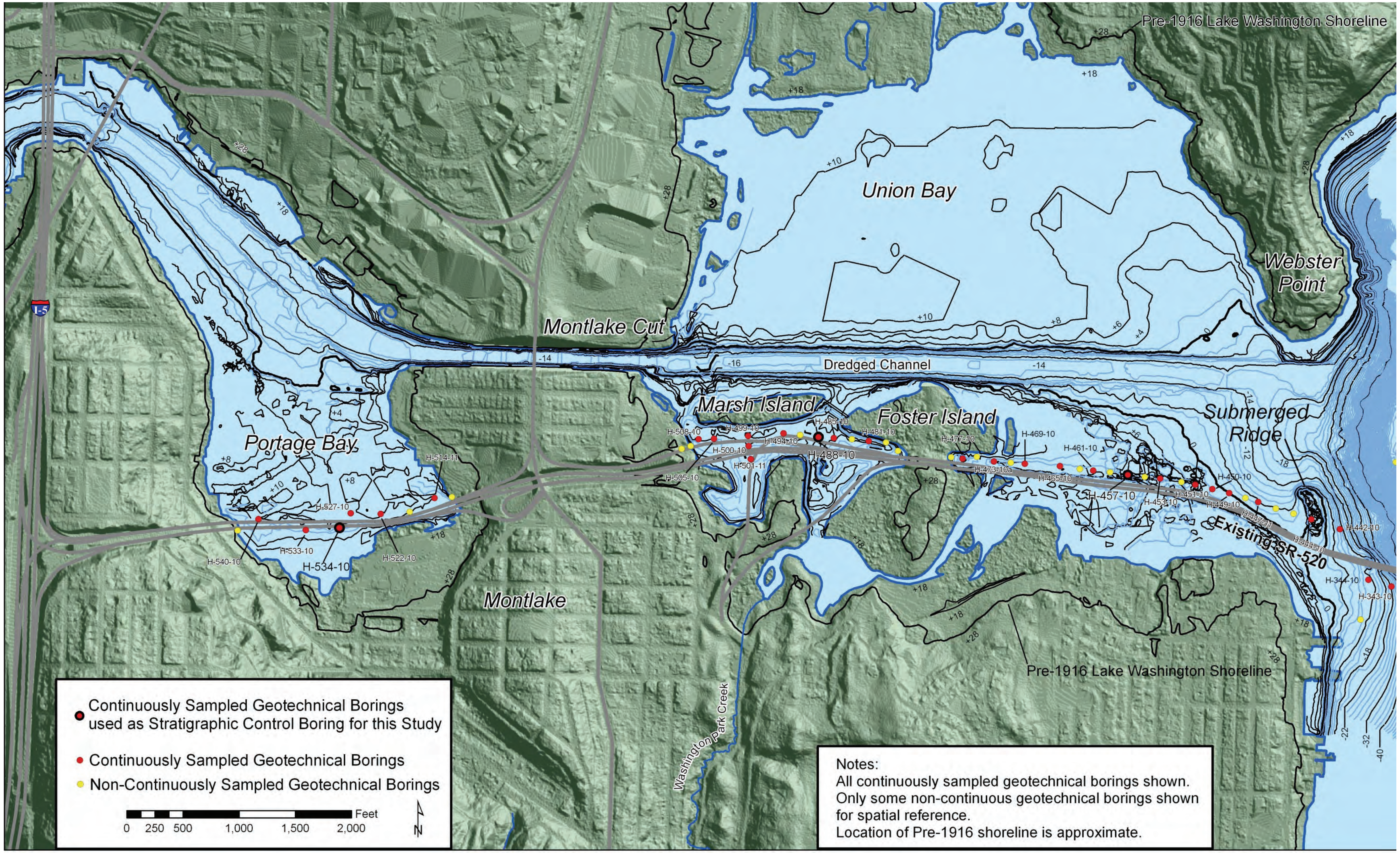

Figure 5. **Map Showing Bathymetric Contours in Union and Portage Bays. Contours at sea level and at or near paleoshoreline elevations are shown with a darker line.**

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Table 1. List of Borings Used in this Study

Boring	Use	Mudline Elevation (ft)	Boring	Use	Mudline Elevation (ft)
Lake Washington - FBL			**Union Bay – East of Foster Island**		
H-290-08	cross-section	6	H-444-10	continuous	3
H-334-10	cross-section	-175	H-445-11	cross-section	-3
H-335-10	cross-section	-173	H-446-11	cross-section	-4
H-336-10	cross-section	-174	H-447-11	continuous	-3
H-337-10	cross-section	-177	H-448-10	cross-section	-2
H-338-10	cross-section	-184	H-449-10	continuous	0
H-339-10	cross-section	-191	H-450-10	continuous	1
H-340-10	continuous	-66	H-451-10	continuous	4
H-342-10	cross-section	-9	H-452-11	cross-section	6
H-343-10	continuous	-22	H-453-10	continuous	8
H-344-10	continuous	-11	H-455-11	cross-section	9
H-346-10	cross-section	-158	H-457-10	continuous	9
H-348-10	cross-section	-179	H-459-10	cross-section	9
H-349-10	continuous	-184	H-461-10	continuous	8
H-350-10	cross-section	-186	H-463-11	cross-section	9
H-351-10	cross-section	-181	H-465-10	continuous	11
H-353-10	cross-section	-171	H-469-11	continuous	9
H-355-10	cross-section	-173	H-471-10	cross-section	11
H-357-10	cross-section	-177	H-473-10	continuous	10
H-358-10	cross-section	-180	H-475-11	cross-section	13
H-359-10	cross-section	-158	H-477-10	continuous	9
H-360-10	cross-section	-57	H-543-11	cross-section	17
H-361-10	cross-section	-23			
H-362-10	cross-section	-15	**Union Bay - West of Foster Island**		
H-364-10	cross-section	-1	H-479-11	cross-section	14
H-442-10	continuous	-9	H481-10	continuous	9
			H-483-10	cross-section	8
Portage Bay			H-485-10	continuous	8
H-514-11	continuous	9	H-488-10	continuous	6
H-522-10	continuous	7	H-491-11	cross-section	8
H-527-10	continuous	8	H-494-10	continuous	8
H-533-10	continuous	12	H-499-10	continuous	7
H-534-10	continuous	11	H-500-10	continuous	10
H-540-10	continuous	8	H-501-10	continuous	10

Table 1. List of Borings Used in this Study

Boring	Use	Mudline Elevation (ft)	Boring	Use	Mudline Elevation (ft)
H-542-11*	cross-section	20*	H-505-10	continuous	8
H-562-11*	cross-section	20*	H-508-10	continuous	13
H-564-11	cross-section	8	H-510-11*	cross-section	33*
			H-547-11	cross-section	14
			H-552-11*	cross-section	32*

Notes:

Borings designated as “continuous” were logged and sampled by TGC for this study. Those designated as “cross-section” were utilized for making cross-sections.

An asterisk after the boring designation indicates a land-based boring. All others were drilled from a barge over water.

Mudline elevations were provided by Shannon & Wilson, Inc. Mudline elevations are approximate and based on the depth of the water column measured in the field at the time of drilling. Water surface elevations were obtained by S&W from the Corps of Engineers for the day of drilling. An asterisk indicates approximate land elevation, from Shannon & Wilson, Inc.

Refer to the Shannon & Wilson geotechnical report for engineering logs of these and other borings (Shannon & Wilson, 2006, and Shannon & Wilson, 2011a and 2011b).

Samples were described using a modified Unified Soil Classification system (ASTM D 2487-10, Appendix A, Figure A-1). When possible, colors were described using the Munsell soil color chart. Attention was paid to evidence for paleosols, transitions in or indicators of depositional environments, and time markers, such as shells, manganese nodules, root mats, volcanic ash, changes in peat type, iron-oxide staining, black to dark brown horizons, and burrow fillings.

Humification tests were performed within a few seconds of opening the split spoons or extruding Shelby tubes for peat samples. Any organic matter with a potential for radiocarbon dating was wrapped in foil, sealed in Ziploc bags, and then stored under refrigeration to safeguard against contamination and further decay. Materials identified as possible volcanic ash (tephra) and shells were handled in the same manner, and then evaluated under the microscope for confirmation.

Five borings were selected to serve as stratigraphic control points for this study: H-349-10 on the west side of Lake Washington, H-457-10 in east Union Bay, H-488-10 and H-500-10 in west Union Bay, and H-534-10 in Portage Bay, shown with darker circles on Figures 2 and 3 (Appendix A, Figures A-2 through A-6). No boring was selected for the east side of Lake Washington since those borings were completed prior to the beginning of this study and the Holocene deposits on the east side are generally thin and sparse. The borings were selected on the basis of representative stratigraphy, relatively good recovery, representative locations, and being drilled early in the program.

2.4 Microscopic Identification

Microscopes were used to assist with sediment and specimen identification leading to characterization of water depth, depositional environments, and vegetation. Often small grains were viewed with a stereo microscope to help with identification of the grains as lithics, organics, or animal parts. Although microscopic viewing helped identify genus and species or plant type from fragments; the bulk of the microscopic work was with seed identification and diatom analyses. This level of analysis was focused on the five stratigraphic control borings.

2.4.1 Seed Identification

Seeds can be very useful for assessing the type of vegetation growing nearby at a given time when the seeds are preserved in host sediment. Seeds were observed in the sediment samples and used to estimate environment and water depth. Prior seed work had been conducted in Mercer Slough by Ms. Cynthia Updegrave, and her paleolimnology work provided a framework for the seed identification conducted for Union Bay, Portage Bay, and Lake Washington.

Samples were prepared at the TGC laboratory, and then taken to the University of Washington (UW) pollen laboratory for seed picking and identification. To prepare samples, 30-milliliter aliquots of peat and organic silt were collected from the split samples from the five borings. These subsamples were soaked for a minimum of 24 hours before being washed over fine and coarse sieves, 0.150-millimeter (mm) and 4.0-mm screens (no. 100 and no. 5 sieve size). Petri dishes with coarse and fine material were transported to the pollen lab at the UW for seed picking and identification work under stereo microscopes.

Laboratory staff picked seeds, sketched the seeds found, and, to the extent possible, identified the seeds by comparing them to seeds in the collection or in references, mindful of species listed for the Lake Washington area. Seeds were picked by placing a small amount of screened material in new petri dishes and floating the material in water (photograph page B-6, Appendix B). The material could then be viewed without obstructions under the microscope. Fine-point tweezers were used to pick the seeds from the petri dishes.

The UW pollen laboratory has a vast seed collection and resource materials maintained by Dr. Leopold. Both Dr. Leopold and Ms. Updegrave were available for consultation during the seed picking and identification process. Other resources included Seedimages.com (Colorado State University's virtual herbarium).

2.4.2 Diatom Analyses

Diatoms, the siliceous cell structure of brown and green algae, can be reliable indicators of water depth, salinity, and temperature. Some diatoms appear in nearly every wet environment, but obligate species are uniquely present in specific environments. Many articles have been published on the diatoms in Lake Washington and the changes in population and assemblages over time. Therefore, the diatom work for this study focused on obligate species and assemblages.

Aliquots of split samples were used to prepare two types of slides: a smear slide and a diatom counting slide. Smear slides were prepared in the TGC laboratory and the counting slides were prepared by BSA Environmental out of Beachwood, Ohio, a company with a focus on phytoplankton.

Smear slides were used for estimating the percentage of diatoms present by volume at a given depth in lake sediment. These slides consist of a small amount of sediment that is captured on the tip of a toothpick, mixed with a drop of distilled water, then smeared thinly over a microscope slide. After the smear dries, adhesive is used to attach a cover slip, and then the adhesive is cured under an ultraviolet light. The slides become a permanent record of the sediment (photograph page B-7, Appendix B). Diatoms, organic matter, and fine lithics are identifiable in the slides.

Counting slides were used to count and identify species of diatoms that had fallen into the lake sediment at given depths. These slides consist of a small amount of sediment cleaned in nitric acid to remove the organic sediment. After boiling in acid, multiple rinses, and centrifuging, the concentrate is mounted in Meltmount, a thermal plastic medium, on a glass microscope slide and covered by a glass cover slip. The diatom analyst counted and identified a minimum 400 valves (cell casings) for each sample for a statistical sampling. Ms. S. Abella reviewed the counts to interpret depositional environment, water depth, and whether the water was fresh or marine (Section 3.3.2 and Appendix C).

2.5 Peat Identification and Humification

Peat and peaty organic silt are common deposits in Union Bay, Portage Bay, and parts of Lake Washington. For this study, peat is defined as a concentration of decaying or partly decayed plant matter. Specific types of plants or plant fragments in peat can provide clues about water depth and depositional environment. Therefore, subsamples of the peat collected from the stratigraphic control holes were selected for peat identification steps.

2.5.1 Peat Identification

All samples retrieved from the continuously sampled borings were described by TGC representatives either in the field or in S&W's laboratory, and then stored in Ziploc bags; some were wrapped in aluminum foil or plastic wrap and stored in Ziploc bags to preserve moisture and structure (photograph page B-7, Appendix B). All organic-rich samples were stored under refrigeration to slow the decay process. Those samples identified as peat or peaty sediments in the stratigraphic control holes underwent further analyses to determine the percentages of different kinds of plant material present following the method described in McKee and Faulkner (2000). This classification involved washing the peat over a set of sieves, a 3.0-mm screen, a 1.5-mm screen, and a No. 200 sieve (75-micron). The coarse material was separated by material type such as wood, "grass" including blades and narrow leaves, reed fragments (sedges and bulrushes), root mats, rhizomes, broadleaves, roots, cones, moss, fine gravel, other, and unknown. The fine material was separated by material type into roots, moss, seeds, sand, muck, other, and unknown. When possible, uncommon types of plant matter were identified using the microscope, for example with equisetum sheaths. Estimates of percent by volume for each material type were made. These percentages were used to determine the peat classification following the procedure described in ASTM D4427-07, Rigg (1958), and generally following the von Post method (1992). The first step in the peat classification is to determine if the peat is fibrous, sedimentary, or granular, or if the material is considered muck (completed decomposed). Then modifiers are added that describe the most voluminous plant material(s) present in the sample, e.g., woody fibrous peat. Peat classifications are shown on the summary logs in Appendix A.

2.5.2 Humification

In addition to identifying plant types, other aspects of peat description are helpful for correlating between boreholes and evaluating depositional history such as degree of humification and organic content. Organic content is discussed below in Section 2.9.1. Humification testing, a visual/manual test, followed the procedures outlined in ASTM D5715-00, a modified version of the system developed by L. von Post (1992). Upon retrieval from the borings, humification tests were run on split-spoon samples immediately after exposing the samples to air. Peat samples collected in Shelby tubes were tested for degree of humification immediately upon extrusion in the lab. It was important to run the test upon exposure to the air because the rate of peat decay rapidly increases when exposed to oxygen. Humification is the process of biochemical decomposition, and the scale ranks percent visual composition along the continuum of transformation of plant remains to humus. The degree of humification was determined by squeezing the peat with the hand and observing the material extruded through the fingers and comparing it to what remained in the palm; classification ranged from H1, living vegetation, to H10, completely decomposed and homogeneous organic material (photograph page B-8, Appendix B). The results of humification measurements are shown on the summary boring logs in Appendix A. This test is somewhat subjective, so to maintain consistency, only those determinations made by the same person, or persons with consistent measurements, are included on the summary logs. In addition, an enhanced version of the von Post scale was used to help with consistency (Henderson and Doiron, 1982).

2.6 Macrofossil Identification

Many macrofossils were encountered in the sediment samples, but most were not identifiable due to the degree of decay or fragmentation. When possible, fossils were identified to genus and, in some cases, species. Many of these identifications are tentative because of the nature of the specimen; for example, key features may be missing. A complete list of plant and animal types encountered was not part of the scope of this project; however some identification was needed since some species are indicators of environment. For this study, "fossil" is used broadly and refers to any plant or animal specimens that were found buried in lake sediment. In all but two cases, the specimens have been dead for more than several hundred to several thousand years. Refer to Section 3.4 for the results of the identifications.

Shells were noted both in split-spoon and Shelby tube samples. Most of these shells were collected and hand delivered to Dr. Elizabeth Nesbitt, curator of invertebrate and micropaleontology at the Burke Museum, University of Washington. Dr. Nesbitt, an expert on Pacific Northwest invertebrate, provided identification to species level when possible for some of the shell samples, of which some provided information about water depth and salinity. Some shells were identified to genus and species level by TGC personnel.

2.7 Radiocarbon Dating

Forty-nine radiocarbon dates were obtained for this study to determine the timing of lake level rise and the ages of potential shorelines (Appendix D). Samples were selected based on stratigraphic position, geomorphic position, lithologic setting, material type, and obtaining vertical age control in Lake Washington, Union Bay, west Union Bay, and Portage Bay. Due to a contracted drilling schedule and sample review program, a phased approach to sample selection was not possible. Furthermore, many samples were not available for dating since some of the Shelby tubes from the continuously sampled borings were being held at the Shannon & Wilson laboratory for engineering testing and had not been extruded before the end of this study's analysis period.

All samples selected for testing were analyzed using accelerated mass spectrometry which allows for much smaller sample size and better precision than standard radiocarbon dating. Samples underwent cleaning at the TGC laboratory prior to transport to Beta Analytic in Miami, Florida. Further pretreatment was applied by Beta Analytic to remove possible contamination by humic acids and lake water. None of the samples were corrected for a reservoir effect from Lake Washington, although the amount of correction could be on the order of 700 years subtracted from the reported age.

Dates of less than about 20,000 years old were calibrated by Beta Analytic and reported here to 2 sigma (σ) range, or 95 percent probability (2nd standard deviation). The results of radiocarbon dating are normally presented as an age range. This range is a statistical margin of error which reflects the inherent uncertainty associated with the rate at which carbon-14 decays, changes in the carbon ratio over time, and lab measurement error. Radiocarbon measurements are usually reported in years B.P. with zero B.P. defined as AD 1950. If a date is calibrated, the letters "Cal" will appear after the age. Results calibration is necessary to account for changes in the global radiocarbon concentration over time. Tree rings are used to calibrate radiocarbon measurements; specific programs are available for the mathematical conversion. Beta Analytic uses the database INTCAL04 and mathematics by Talma and Vogel (1993). Carbon 14 is a naturally occurring isotope of the element carbon. It is also called "radiocarbon" because it is unstable and radioactive relative to carbon 12 and carbon 13. Carbon consists of 99% carbon 12, 1% carbon 13, and only about one part in a million million carbon 14.

2.8 Tephra Analyses

Volcanic ash layers, or tephra, were encountered in the lake and bay sediments. Upon retrieval from the core, ash and suspected ash samples were collected in foil and Ziploc bags then stored under refrigeration for further processing. Three different techniques were employed to analyze the ash and suspected ash. First, a small amount of the sample was placed on a slide and viewed under a petrographic microscope with a polarizing lens to determine the composition of the sample. Those samples that were determined to be ash were described and some were selected for the second technique, determining index of refraction.

Two methods were used to determine index of refraction, the Becke line method used by the TGC laboratory and the dispersion staining method used by MicroLab Northwest of Redmond, Washington (Appendix E). With this Index of Refraction measurement, the ash encountered in the study area could be compared to known suspected ashes, such as Mazama and Glacier Peak ash. If confirmed, the identified ash would then provide a time marker since the ashes have been dated elsewhere. The ash between Lake Washington, Union Bay, and Portage Bay could then be correlated on the basis of index of refraction, stratigraphic position, and age.

Finally, to confirm the ash identification, two samples were sent to Dr. Franklin Foit, Director of the Microbeam Lab at Washington State University in Pullman, Washington. Dr. Foit conducted chemical composition analyses of the samples using a microprobe to determine if they matched any volcanic ashes in the global database (Appendix E).

2.9 Geotechnical Testing

Shannon & Wilson, Inc. conducted geotechnical testing on many borehole samples, including organic content and dry density determinations. They classified soil using the Unified Soil Classification System (USCS) 2-letter classification symbol (ASTM D2487-00), reported herein, for samples using visual classification supplemented by soil index testing such as grain size analyses and Atterberg Limits on selected samples.

2.9.1 Organic Content

Organic content is a measurement of the percent organic matter present in a sample, by dry weight. This measurement was determined using ASTM D2974-07a which is also used to report loss on ignition. The organic content determines whether a sample will be classified as peat or organic silt. If the sample contained more than 50 percent organic matter and it appeared to be a peat, it was classified as "peat." If the sample contained less than 50 percent organic matter and the organic matter was fibrous, the sample was classified as "peaty organic silt." If the sample contained less than 50 percent organic matter and the organic matter was muck, the sample was classified as "organic silt"(or organic clay, sand, or gravel, depending on the main constituent). The results of the organic content determinations are shown on the summary logs, Appendix A.

2.9.2 Dry Density

Dry density is a measurement of the dry unit weight of the solids in a sample, measured in pounds per cubic foot (pcf). This measurement was determined using ASTM D7263-09. This determination helps identify peat and diatomaceous ooze samples because of their low unit weights. Peat can have a dry unit weight of 4 to 12 pcf and diatomaceous ooze can have a dry unit weight of 10-30 pcf, depending on the mineral content of the sediment. The results of the dry density determinations are shown on the summary logs, Appendix A.

2.9.3 Classification

Soil classifications presented in this report are the result of a multi-step process. Samples were first described in the field and in the laboratory by TGC and S&W representatives. TGC representatives were looking for stratigraphic and time markers during their descriptions. Many samples then underwent index property testing at S&W's soils laboratory, then further refinement in soil classifications were made by S&W personnel. The soil classifications presented in the summary logs in Appendix A are a combination of the S&W soil classification and the field and laboratory descriptions by TGC. The two-letter USCS symbol is based on visual classification, supplemented by laboratory tests performed on selected samples. Only draft boring logs and soil classifications were available from S&W (2011b) at the time of this report, so the reader should refer to the final geotechnical reports by S&W for final engineering boring logs.

2.10 Shoreline Identification

Shorelines and paleoshorelines were identified during this study. Paleoshorelines are former shorelines that have been permanently abandoned. They are recognized by a combination of physical and biological characteristics. For this study, a geomorphic analysis of landforms and other physical characteristics helped to identify knickpoints, benches, and platforms in the topographic surface and bathymetric surface below and within the sediment fill in the basins. Bathymetric maps (Figures 4 and 5) are particularly useful for this task. Other physical characteristics include determining depositional environment from sediment lithology. Biological characteristics helped identify water depth from diatoms, seeds, and peat and depositional environment from vegetation, seeds, macrofossils, diatoms, and peat. Age control was provided by marker horizons such as tephra layers and radiocarbon dating. With all of these types of data, shorelines were identified; for example a bench on the side of Lake Washington whose elevation corresponds with a layer in Union Bay with shoreline plants and diatoms and riverine deposits would be a candidate for a shoreline. Radiocarbon dates on wood in the sediment from that layer would provide limiting age control for that shoreline. By plotting the plausible shorelines and ages, a submergence curve can be generated.

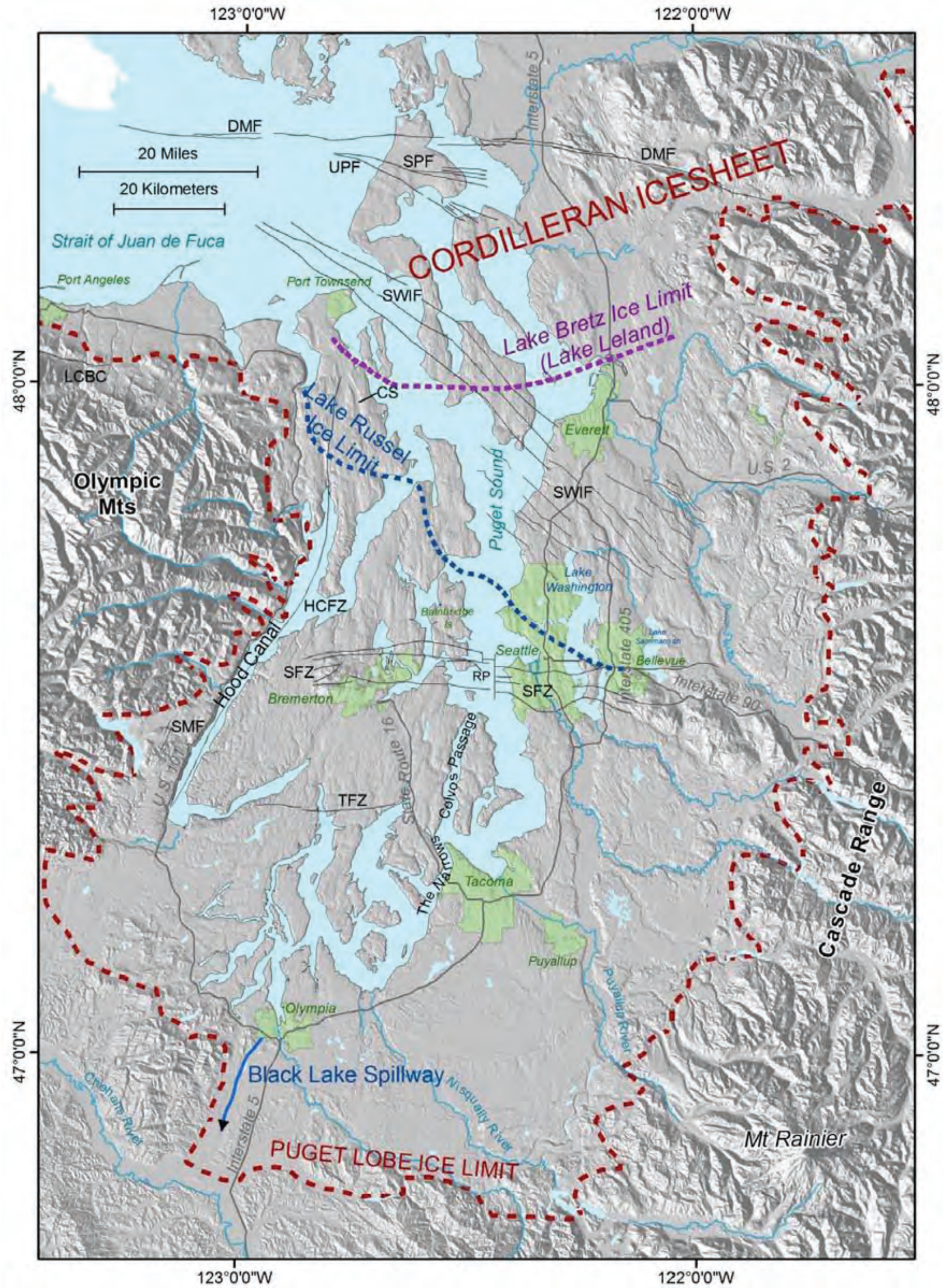
3.0 Findings

3.1 Geologic History

The Lake Washington basin and Puget Sound areas were overridden by the Vashon glacier around 17,600 years Cal B.P. (Porter and Swanson, 1998). At its maximum extent, the ice was over 3,000 feet thick in the Seattle area and extended from the foothills of the Olympics to the foothills of the Cascade Mountains and from British Columbia, Canada, to south of Olympia, Washington (Booth and others, 2004). During glacial advance, subglacial meltwater carved the Lake Washington basin and all the troughs of Puget Sound, including the Duwamish, Green, Puyallup, and Sammamish river valleys (Booth, 1994). Subglacially, these troughs were connected to Puget Sound, and when the ice receded, the troughs were still connected via water.

Ice persisted in the area until around 16,850 years Cal B.P. when recession began by collapse of the ice sheet, likely beginning in the troughs first (Porter and Swanson, 1998; Booth, 1987). As soon as the troughs were ice free, meltwater accumulated in these low-lying areas. Initial inundation of Lake Washington and the adjacent bays likely occurred during this early Vashon recessional stage. Water in the deep troughs of the lowland coalesced and formed Glacial Lake Russell (Figure 6) starting about 16,630 years Cal B.P. (Porter and Swanson 1998; Thorson, 1989). As more of the ice sheet melted and more troughs were exhumed, a larger lake was formed, Glacial Lake Bretz, dammed by ice in the Strait of Juan de Fuca (Thorson, 1989). Glacial Lake Bretz (Figure 6) covered much of the land in the region because the land was depressed below modern sea level due to isostatic loading by the Vashon glacier (Dethier and others, 1995). The early ice margin during Glacial Lake Bretz is thought to be near the alignment of the Lake Washington Ship Canal (Thorson, 1989). Other glacial recessional lakes occupied the Lowland (Haugerud, 2009; Troost and Wisher, 2005 and 2009). As glacial ice melted, sea level rose and the land rebounded at different rates.

As the sea level rose, ice blocking the Strait of Juan de Fuca thinned enough by melting that marine water could float the remaining ice and enter the Puget Sound trough, thereby draining Glacial Lake Bretz. Marine water inundated the troughs of Puget Sound, including the trough of Lake Washington, around 14,900 years Cal B.P., creating a glaciomarine environment in the central and northern Puget Sound. With continued isostatic rebound, marine water drained from Lake Washington likely followed by a retreating estuary at the interface with the Sammamish River. The lake began filling with freshwater from the Sammamish River, runoff, and groundwater seepage from the freshly exposed saturated glacial deposits around 14,800 years Cal B.P.



The area south of the Lake Russell ice limit was inundated with water to an elevation of about 330 feet in the Seattle area, rising to the north and dropping to the south because of isostatic depression and rebound. The area south of the Lake Bretz ice limit was inundated with water to an elevation of 100 feet in the Seattle area, rising to the north and dropping to the south. Intermediate glacial lake levels are not shown. SFZ = Seattle Fault Zone
SWIF = Southern Whidbey Island Fault Zone
TFZ = Tacoma Fault Zone
Modified from Troost and Booth 2008.

Figure 6. **Map Showing Locations of Ice Margins during Two Recessional Lakes**

Isostatic rebound was complete by 11,600 years Cal B.P. (Thorson, 1989; Clague and James, 2002) isolating Lake Washington from Puget Sound. With the growth of the Cedar River fan at the south end of the lake, water level rose from about 14,800 years Cal B.P. until 1916, when the Lake Washington Ship Canal was constructed and water level was henceforth mostly controlled by the U.S. Army Corps of Engineers.

An earthquake about 1,100 years ago (about 980 AD) caused offset such that land north of the Seattle fault (Figure 6) dropped 3 feet and land south of the fault raised 24 feet, generating a tsunami in Puget Sound (Atwater and Moore, 1992). Lake Washington was affected by the earthquake: large landslides slid into the lake, turbidity currents generated by these landslides left sandy deposits in the otherwise fine-grained lake mud (Karlin and Abella, 1996; Karlin and others 2004), and a spit and delta platform were submerged (Thorson, 1998). Karlin and others (2004) determined that evidence for several earthquakes since 3,500 years ago is apparent in the lake sediment. Sherrod (2002, 2005) and Sherrod and others (2001) describe ground offset related to movement on the Seattle fault, in Bellevue near Vasa Park, older than the 980 AD event but younger than 10,000 years.

3.2 Stratigraphy

The stratigraphic units encountered in the basins are described on Figure 7 and depicted on cross sections (Figures 8 through 13). Calibrated radiocarbon dates, rounded to the nearest one hundred years, are also shown on the cross sections; details about each date are provided in Table 2. Figure 14 shows all of the radiocarbon dates on one graph and Figure 15 shows just those dates from Union Bay to highlight the age/time relationship there.

All material that was overridden by the Vashon glacier is described as glacially overridden material (GOM) and not further differentiated in this study. The glacier scoured into Vashon and pre-Vashon-aged stratigraphic units, such that various types of geologic materials are present at the glacially overridden contact, depending on position and complexity in the substrate. For example, glacial scour in Union Bay, off the north end of Foster Island, revealed Vashon till, while deeper in the bay, till from a previous glaciation was exposed. GOM includes all deposits that have been overridden and compacted by the advancing Vashon ice sheet, including Vashon subglacial till (unit Qvt), Vashon advance outwash, Lawton Clay, and all deposits preVashon in age. The GOM interface is a scoured surface and will consist of different geologic materials depending on the paleotopography of these older materials and the depth of scour (Troost and others, 2005). Depth to GOM was determined by S&W during drilling or by geophysical means (Lister and others, 1967) where the borings did not extend through the thick lake deposits.

Sediment was deposited in Lake Washington and Portage and Union Bays during glacial recession, occupation by Glacial Lakes Bretz and Russell, and subsequently during post-glacial lake occupation (Troost and Booth, 2008). Glacial recession lasted several hundred to one thousand years and consisted of several stages. The first stage yielded deposition of outwash and ice-contact deposits (units Qvro, Qvi, Qvat, Qvrl-mx), shown at the bottoms of Portage Bay and west Union Bay, and along the sides of Union Bay (Figures 10-13). The differences between these units are subtle and the units are most likely gradational. They likely accumulated in kettles, basins created by large blocks of ice left behind by the glacier, when the ice melted leaving the ice-entrained debris to mix with remnant subglacial debris. If this material underwent mixing with lake sediment but has an appreciable amount of medium dense to dense coarse-grained sediment, it is called unit Qvrl-mx. If the material is relatively clean of silt, it is called unit Qvro (photograph page B-8, Appendix B). If the material is intermixed till and sand, having collected next to ice, then it is called unit Qvi. If the material is intermittently dense and composed of till and sand, then it is called unit Qvat. The thickness of any of these units varies from a few inches to 30 feet.

The next stage provided silt and clay (unit Qvrl), which accumulated rapidly in the lake and bays during occupation by recessional glacial lakes including Lakes Russell and Bretz (photograph pages B-9 and B-10). The lake mud is very soft and devoid of pollen and diatoms in all but the top few feet of the deposit. The lack of pollen and diatoms suggests cold water, and the presence of a concretion (photograph page B-9, Appendix B) and dropstone (photograph page B-9, Appendix B) suggest glacial lake conditions (Mullineaux, 1967). Following the drainage of Glacial Lake Bretz, a marine incursion in Lake Washington produced a thin layer of marine deposits in the top of unit Qvrl; marine water did not rise high enough in elevation to enter or otherwise inundate Union or Portage Bay. Estuarine deposits are associated with the marine deposits, and both are found at the top of the following unit.

Unit Qvrl underwent weathering, bioturbation, and the accumulation of some organic matter, becoming a new unit (Ql/Qvrl). This transitional process occurred in the bays as well and includes the waning deposition of fines settling out of sediment-laden water in the bays lasting well into the Holocene in Union Bay. Unit Ql/Qvrl varies from a few inches to 20 feet in thickness (photograph pages B-10, 11, 12, 13, 14, and 15, Appendix B).

Less than 1 inch of volcanic ash, most likely from Glacier Peak, is present in unit Ql/Qvrl. This ash is relatively continuous in west Union Bay (Figure 12), is present in one boring in Lake Washington (Figure 9), and is otherwise absent from the borings examined in Union Bay and Portage Bay. According to Fryxell and Loope (1965), the age of the Glacier Peak ash is 13,250 to 14,290 years Cal B.P. (BETA-WSU-155). Correlation with Glacier Peak is based on age, ash characteristics, and index of refraction (Table 3). This ash may be more widespread than reported here, since not all of the Shelby tube samples were available for examination prior to the writing of this report and poor sample recovery affected a few samples.

Following deposition of glacial lake fines, marking the transition from glacial to nonglacial conditions, the record is dominated by warmer-climate lake sediments. Organic-rich material began accumulating and continues today. In Lake Washington, the organic-rich material varies from deep-water diatomaceous ooze to diatomaceous silt, or gyttja, to organic silt (unit Qlg on Figures 8 and 9; photograph page B-15 and B-16, Appendix B). In Union Bay and west Union Bay along the alignment, peat with layers of organic silt accumulated in mostly shallow environments (units Qp and Qlo on Figures 8, 11, and 12). In Portage Bay along the alignment, shallow to deeper water organic silt with a few lenses of peat accumulated (unit Qlo with Qp on Figures 8 and 13). Thickness varies from 40 feet in Union Bay to 25 feet in Portage Bay to nearly 50 feet in Lake Washington (photograph pagesB-16, 17, 18, and 19, 20, and 21, Appendix B).

Volcanic ash positively correlated with Mazama O tephra occurs within the organic-rich deposits (Table 4). This ash is present in each basin, but is not continuous, having been eroded or not deposited. The Mazama O Tephra was dated by Kittleman (1973) as 7,580 years Cal B.P. and 8,030 years Cal B.P., 7,900 years Cal B.P. was selected for this report. His dates with laboratory numbers Tx-487 and GaK-1124, respectively, were calibrated by Beta Analytic for inclusion in this report. Correlation between boreholes is based on refractive index, position, and age (Table 3). This ash may be more widespread than reported here, since not all of the Shelby tube samples were available for examination prior to the writing of this report and poor sample recovery affected some samples in the organic-rich materials.

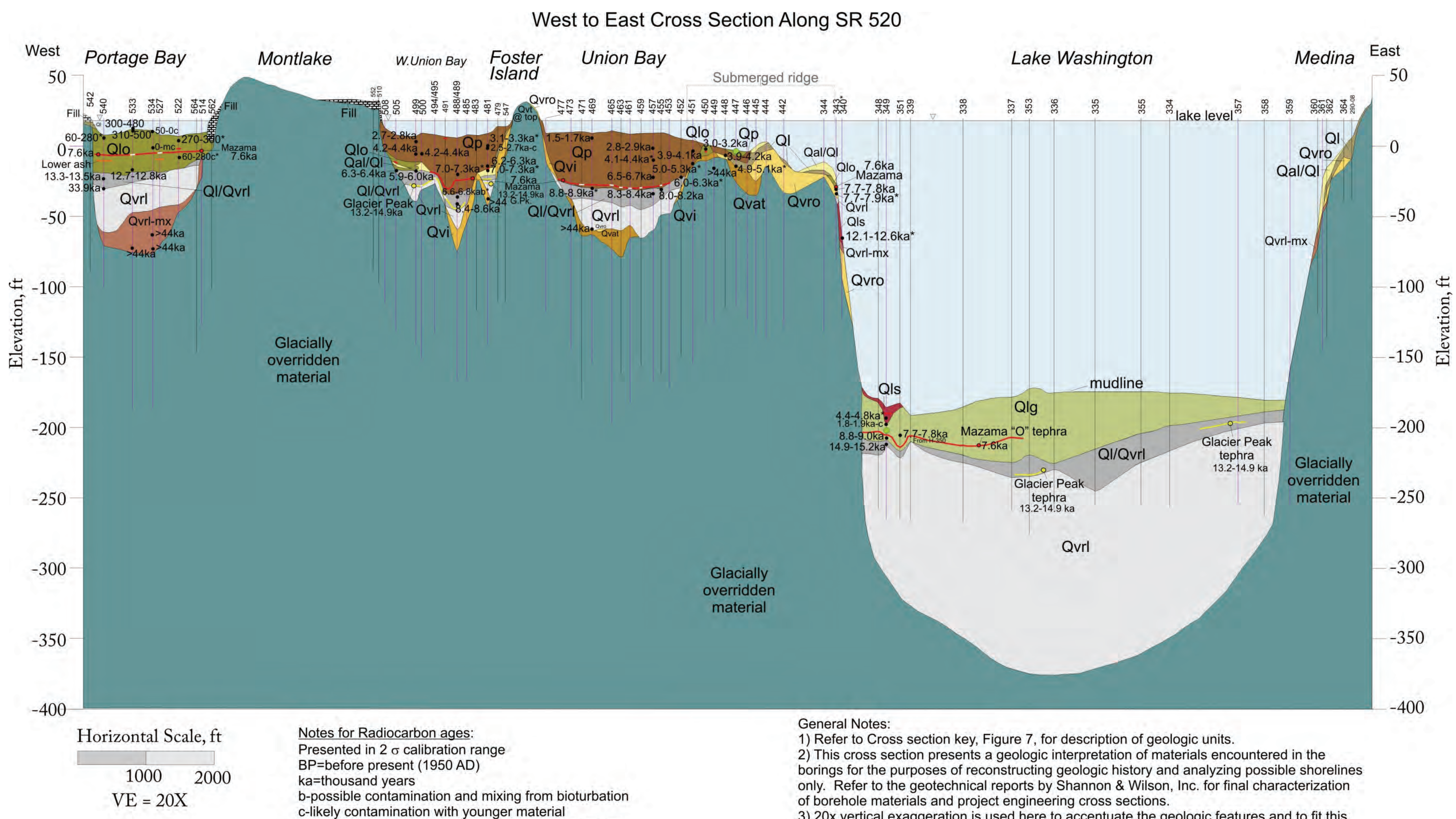
A third ash is present, identified simply as “lower ash,” and has an age somewhere between that of the Mazama and that of the Glacier Peak. This ash is very thin, less than 1 inch, and has only been seen in Portage Bay as of the writing of this report.

A layer of fine gravelly sand is present mid-depth in west Union Bay and on the submerged ridge between Union Bay and Lake Washington (unit Qal/Ql on Figures 10 and 12; photograph page B-20, Appendix B). This deposit is oxidized and has other signs of subaerial exposure. This sand unit is 5 to 6 feet in thickness.

Landslide debris, unit Qls, is present in Lake Washington on the slopes (Figure 9) and in the bottom (photograph pages B-20 and 21, Appendix B). The upper 12 feet of Boring H-349-10 is considered a landslide deposit based on deformed bedding and the presence of many silt clasts, an ash clast, and radiocarbon dates that are reversed.

Fill	Materials placed at water's edge to reclaim land or dumped into water for disposal.
Qls	Landslide debris, subaerial, mixture of soil types commonly with internal deformation.
Qal/Ql	Alluvial and lacustrine deposits consisting of very loose silty sand and other sandy material, with some gravel. May contain organic matter.
Ql	Lacustrine deposits accumulated over the last few hundred to ten thousand years. May contain organic matter and diatoms..
Qlg	Lacustrine deposits consisting predominantly of very soft diatomaceous ooze (gytjja) with some organic silt layers. May contain thin layers of peat, and layers of Ql and Qlo.
Qlo	Lacustrine deposits ranging from very soft organic silt to peaty silt. May contain layers of peat, Qlg, and Ql.
Qp	Predominantly very soft peat with layers of organic silt and peaty silt. Peat types range from sedimentary to fibrous.
Qls	Landslide debris, subaqueous, mixture of material types commonly with internal deformation.
Ql/Qvrl	Transition zone from Qvrl at the base to Ql at the top. Represents a transition from deeper water environment to very shallow water environment followed by weathering and bioturbation. Consists of very soft, mottled, silty clay to clayey silt. In Lake WA also see marine and estuarine deposits with shells at top of deposit.
Qvrl	Vashon recessional lacustrine deposits dated to 16,000 years Cal B.P. Consists of very soft silty clay to clayey silt.
Qvrl-mx	Vashon recessional lacustrine deposits consisting of clay/silt with medium to dense sand layers and some gravel. May be, in part, in-situ weathered material. May be, in part, older Qvrl. Gradational with Qvr, Qvi, Qvrl, and Qvro.
Qvro	Vashon recessional outwash dated to 16,850 years Cal B.P. Consists of intermixed clean to silty: sand, sandy gravel, and gravelly sand.
Qvi	Vashon ice-contact deposits, dated to 16,850 years Cal B.P. Consists of intermixed clean to silty, sandy gravel and gravelly sand with till-like deposits of dense gravelly silty sand.
Qvat	Vashon ablation till or weathered Vashon till. Consists of compact gravelly silty sand to gravelly sandy silt. May have lenses of clean sand or gravel.
Glacially Overridden Material	Vashon and pre-Vashon deposits that have been overridden and compacted by the Vashon glacier. The uppermost surface of this material marks the scour depth and/or deposition resulting from the Vashon glaciation. Includes units Qvt-Vashon till and Qvtm-Vashon subglacial meltout till. Qvt-Consists of compact gravelly silt SAND to gravelly sandy SILT. Qvtm-Consists of compact intercalated gravelly sandy SILT and gravelly SAND.
Mazama Ash	Light gray to white, fine-grained ash, 1/4 to 1 inch thick, discontinuous. Correlates with the Mazama "O" tephra at 6850 years BP and 7.6ka Cal yrs BP. White line indicates ash is not present.
Glacier Peak Ash	Light gray to light brown, thin, discontinuous ash in Lake WA and Union Bay, correlates with the eruptive episode of 11,225+-120 years BP and 13.2-14.9 ka Cal yrs BP. White line indicates ash is not present.
Lower ash	Thin, light gray, discontinuous ash in Portage Bay, of unknown correlation.
Marine Shells	Obligate marine to estuarine shells, predominantly clams.
Shells	Unidentified shells, or shell fragments and barnacle plates that appear to be out of place.
4.4-4.6 Age	Radiocarbon age in thousands of years BP (calibrated 2 sigma range).
-40···· Possible Shoreline Elevation	Possible shorelines discussed in the text.
Glacially Scoured Surface	Irregularly shaped surface forming contact between glacially overridden material and basin-fill sediments.
465 Boring Location and Designation	Refer to Shannon & Wilson's geotechnical report for full details for these borings.
Water	

Figure 7. **Key to Cross Sections**



Notes for Radiocarbon ages:
Presented in 2 σ calibration range
BP=before present (1950 AD)
ka=thousand years
b-possible contamination and mixing from bioturbation
c-likely contamination with younger material
*-best fit selected from multiple calibrated age ranges, see Table 2 for complete data

General Notes:
1) Refer to Cross section key, Figure 7, for description of geologic units.
2) This cross section presents a geologic interpretation of materials encountered in the borings for the purposes of reconstructing geologic history and analyzing possible shorelines only. Refer to the geotechnical reports by Shannon & Wilson, Inc. for final characterization of borehole materials and project engineering cross sections.
3) 20x vertical exaggeration is used here to accentuate the geologic features and to fit this geographic extent on one piece of paper.
4) Cross section taken along the north side of SR-520, borings are projected perpendicular to the line of the cross section or projected along topographic features to the line of section.
5) Thin lenses and layers are not shown due to the small scale of the cross section.
6) Depth to glacially overridden material in Lake Washington is from a geophysical survey (Lister and others, 1967).

Figure 8. **West to East Cross Section through Portage Bay, Union Bay, and Lake Washington**

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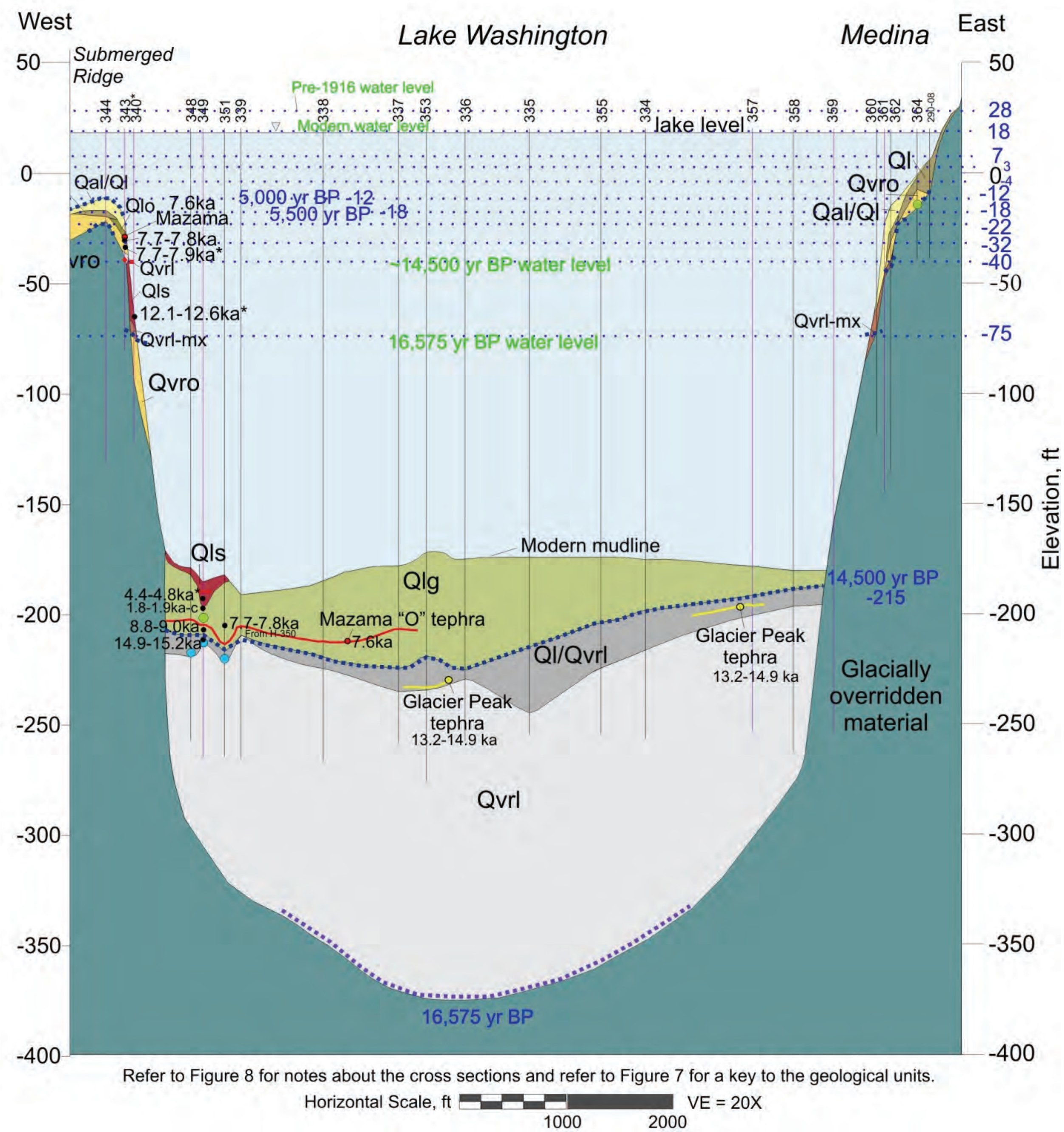


Figure 9. **West to East Cross Section through Lake Washington Showing ^{14}C Dates and Possible Shorelines**

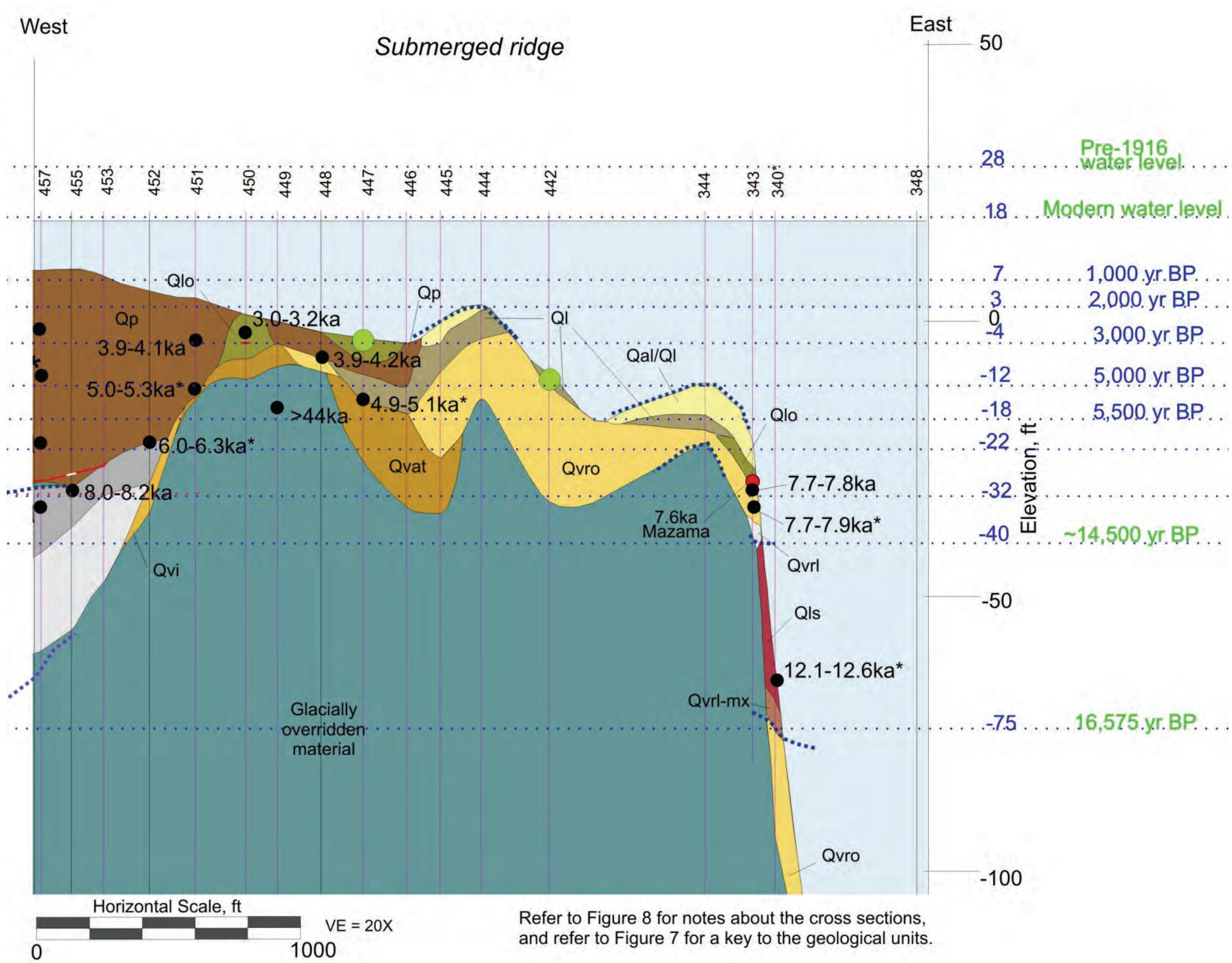


Figure 10. **West to East Cross Section through Submerged Ridge Showing ^{14}C Dates and Possible Shorelines**

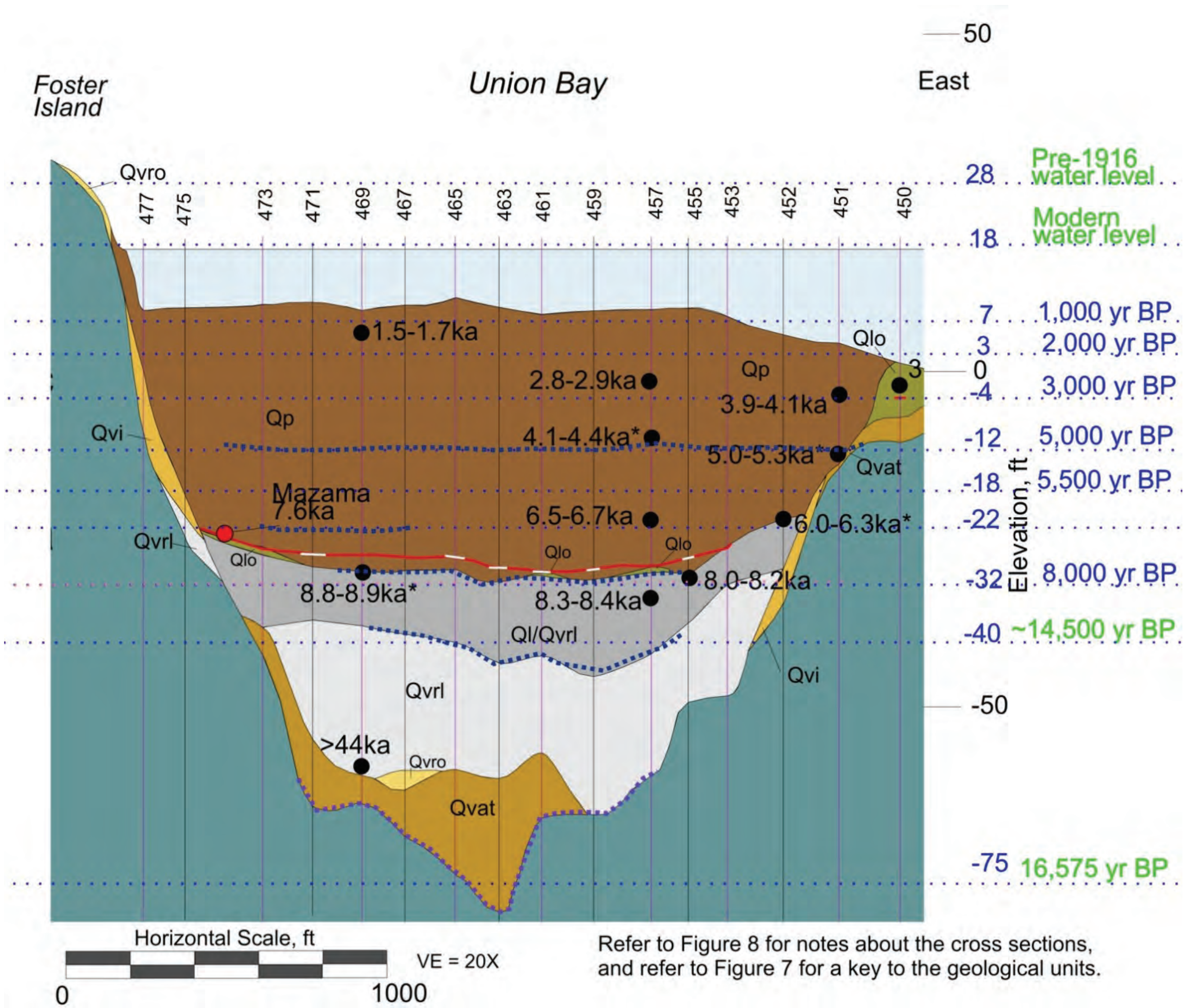
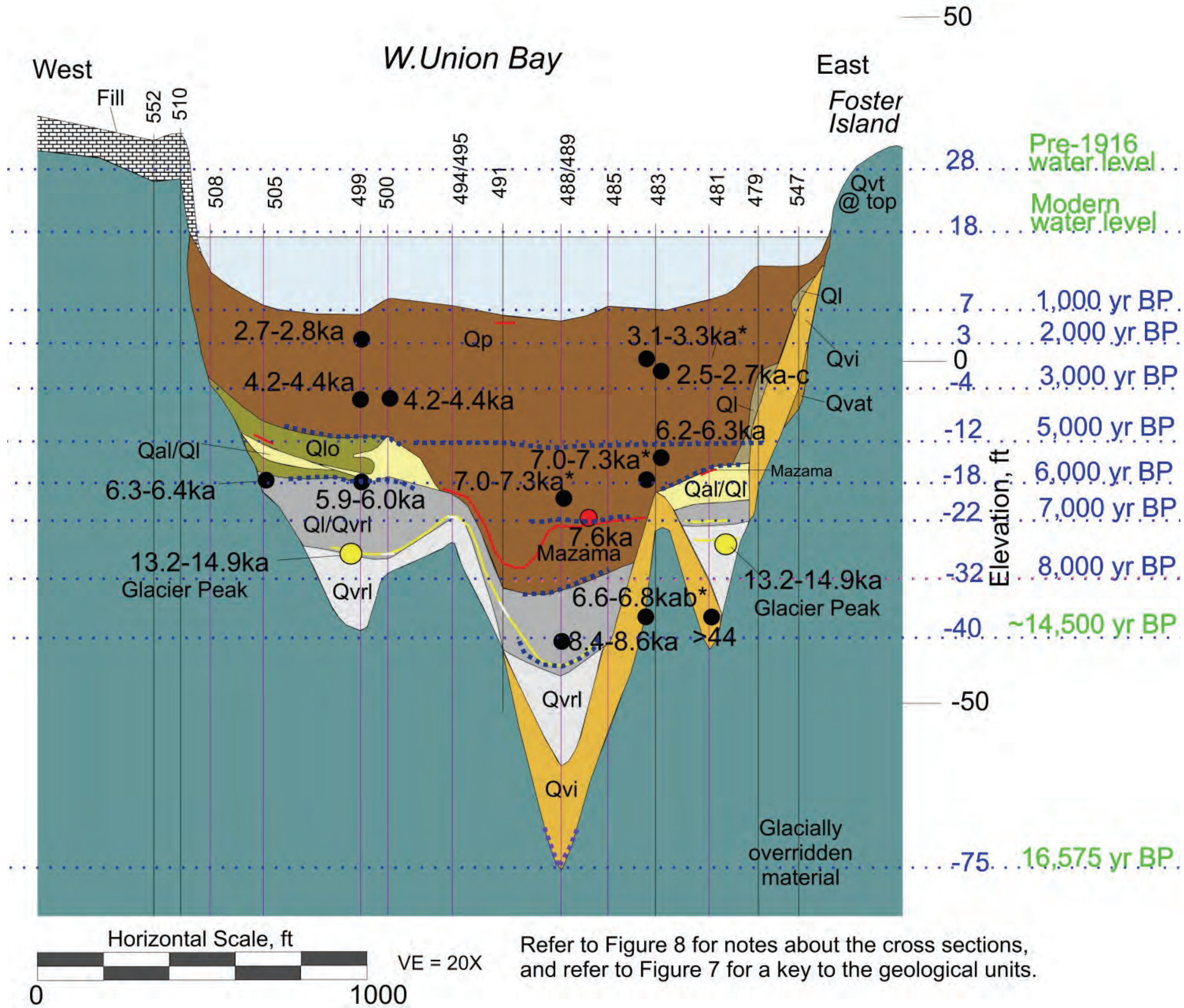


Figure 11. **West to East Cross Section through Union Bay Showing ^{14}C Dates and Possible Shorelines**



Refer to Figure 8 for notes about the cross sections, and refer to Figure 7 for a key to the geological units.

Figure 12. **West to East Cross Section through west Union Bay Showing ^{14}C Dates and Possible Shorelines**

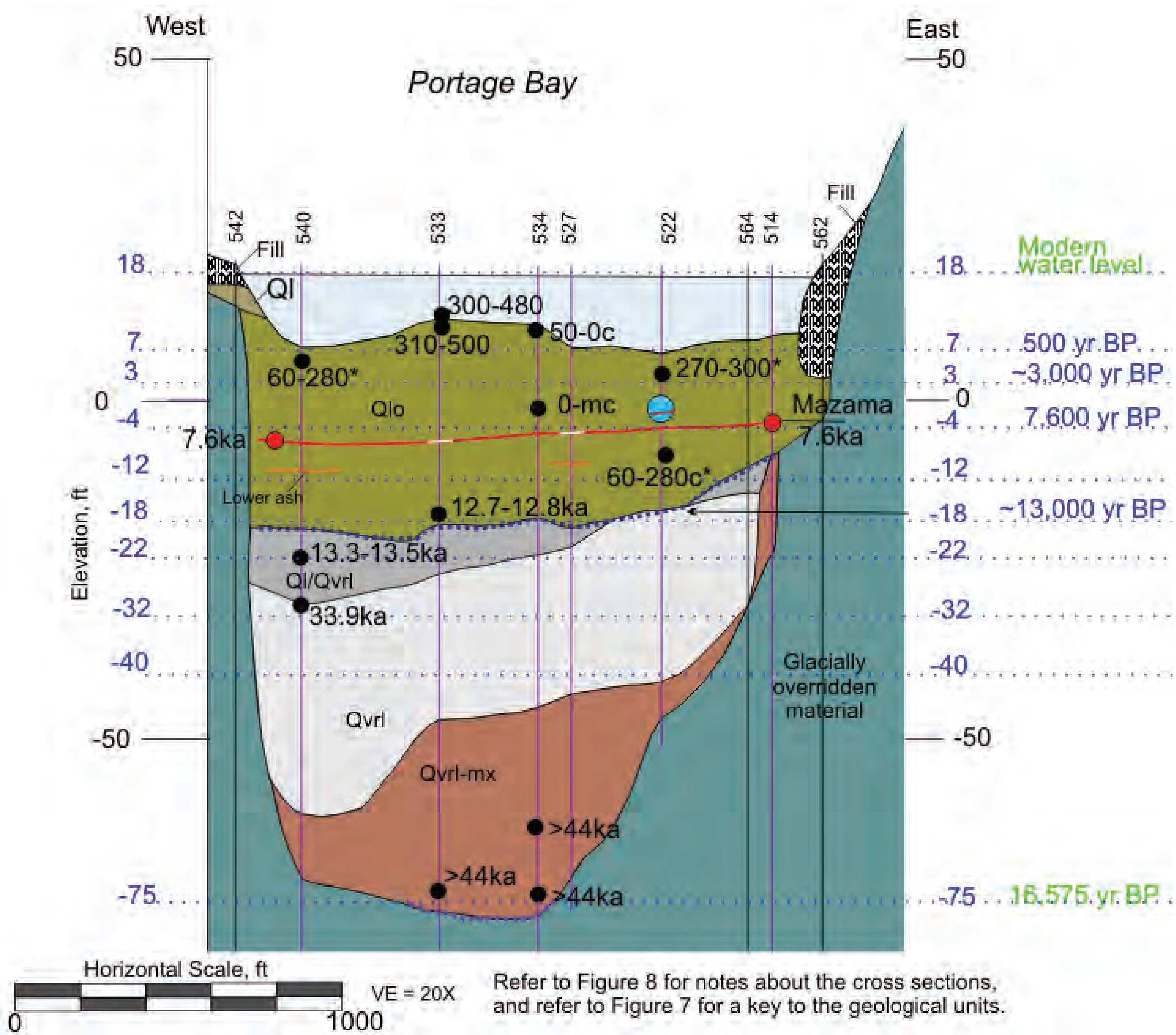


Figure 13. **West to East Cross Section through Portage Bay Showing ^{14}C Dates and Possible Shorelines**

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Table 2. Summary of Radiocarbon Test Results

Lab no.: BETA-	Boring	Sample	Depth (ft)	Elevation (ft)	Geo. Unit[a]	Northing Easting[b]	Method[c]	(Material): Pretreatment	Measured age[d]	$^{13}C/^{12}C$ o/oo[e]	Conventional age[f]	Calibrated Age, BC, 2 σ[g]	Calibrated Age, BP, 2 σ[h]
Lake Washington													
291572	H-340-10	S-1B	4.3	-70.3	Qls	237,096.756969 1,285,677.96725	AMS	(wood): acid/alkali/acid/ solvent extraction	10430 +/- 50 BP	-26.6	10400 +/- 50 BP	10640 - 10510 10450 - 10130	12590 - 12460 12400 - 12080
291573	H-343-10	S-4A	8.8	-30.8	Qlo	237,538.127443 1,285,411.76533999	AMS	(wood): acid/alkali/acid	6900 +/- 40 BP	-26.4	6880 +/- 40 BP	5840 - 5710	7790 - 7660
291574	H-343-10	S-5A	11.8	-33.8	Qvro	237,538.127443 1,285,411.76533999	AMS	(wood): acid/alkali/acid	6970 +/- 40 BP	-26.1	6950 +/- 40 BP	5970 - 5950 5910 - 5730	7920 - 7900 7860 - 7680
291576	H-349-10	S-5C	8.65	-192.65	Qls	237,689.660443 1,286,185.41995	AMS	(reed): acid/alkali/acid	4120 +/- 40 BP	-27.5	4080 +/- 40 BP	2860 - 2800 2750 - 2710 2710 - 2550 2540 - 2490	4810 - 4760 4700 - 4660 4660 - 4500 4490 - 4440
291577	H-349-10	S-7A	12.9	-196.9	Qlg	237,689.660443 1,286,185.41995	AMS	(reed): acid/alkali/acid	2000 +/- 30 BP	-29	1930 +/- 30 BP	10 - 130	1940 - 1820
291578	H-349-10	S-11F	21.85	-205.85	Qlg	237,689.660443 1,286,185.41995	AMS	(wood): acid/alkali/acid	8100 +/- 40 BP	-29.9	8020 +/- 40 BP	7070 - 6810	9020 - 8760
291575	H-349-10	S-14B	26.9	-210.9	Ql/ Qvrl	237,689.660443 1,286,185.41995	AMS	(shell): acid etch	13110 +/- 60 BP	-0.6	13510 +/- 60 BP	13210 - 12920	15160 - 14870
291580	H-350-10	S-5A	21	-207	Qlg	237,645.782463999 1,286,370.5012	AMS	(wood): acid/alkali/acid	6910 +/- 40 BP	-24.7	6910 +/- 40 BP	5880 - 5720	7830 - 7670
Union Bay - East of Foster Island													
293494	H-447-11	L-6A	10.45	-13.45	Qlo	238,290.088641999 1,284,227.68956999	AMS	(wood): acid/alkali/acid	4370 +/- 40 BP	-23.2	4400 +/- 40 BP	3270 - 3240 3110 - 2910	5220 - 5190 5060 - 4860
295050	H-448-10	S-3A	4-5	-6.0 to -7.0	Qp	238,325.861456999 1,284,113.29394	AMS	(peat): acid/alkali/acid	3680 +/- 40 BP	-24.2	3690 +/- 40 BP	2200 - 1960	4150 - 3910
293495	H-449-10	F-10A	16.1	-16.1	Qvtm	238,368.51 1,283,968.72	AMS	(wood): acid/alkali/acid	NA	-26	> 43500 BP	NA	NA
293496	H-450-10	L-2D	3.6	-2.6	Qlo	238,403.48 1,283,817.74	AMS	(wood): acid/alkali/acid	2980 +/- 40 BP	-27.3	2940 +/- 40 BP	1280 - 1010	3230 - 2960
293497	H-451-10	L-4E	7.85	-3.85	Qp	238,444.521866 1,283,667.21442	AMS	(reed): acid/alkali/acid	3670 +/- 40 BP	-26.8	3640 +/- 40 BP	2130 - 1900	4080 - 3850
293498	H-451-10	L-8C	15.4	-11.4	Qp	238,444.521866 1,283,667.21442	AMS	(moss): acid/alkali/acid	4590 +/- 50 BP	-27.8	4540 +/- 50 BP	3490 - 3470 3370 - 3090	5440 - 5420 5320 - 5040
295051	H-452-11	S-11A	27.0 - 27.5	-21.0 to -21.5	Qp	238,467.376549999 1,283,543.22826	AMS	(peat): acid/alkali/acid	5390 +/- 40 BP	-26.1	5370 +/- 40 BP	4330 - 4140 4140 - 4060	6280 - 6100 6090 - 6010

Table 2. Summary of Radiocarbon Test Results

Lab no.: BETA-	Boring	Sample	Depth (ft)	Elevation (ft)	Geo. Unit[a]	Northing Easting[b]	Method[c]	(Material): Pretreatment	Measured age[d]	$^{13}C/^{12}C$ o/oo[e]	Conventional age[f]	Calibrated Age, BC, 2 σ[g]	Calibrated Age, BP, 2 σ[h]
295052	H-455-11	S-13	39.0 - 41.5	-21 to - 23.5	Qvrl	238,513.331482 1,283,216.14174	AMS	(organic fibers): acid/alkali/acid	7260 +/- 40 BP	-26	7240 +/- 40 BP	6220 - 6020	8170 - 7970
293499	H-457-10	L-6B	10.5	-1.5	Qp	238,529 1,283,067	AMS	(moss): acid/alkali/acid	2760 +/- 40 BP	-28.1	2710 +/- 40 BP	920 - 800	2870 - 2750
293500	H-457-10	L-10D	19.6	-10.6	Qp	238,529 1,283,067	AMS	(moss): acid/alkali/acid	3910 +/- 40 BP	-30.1	3830 +/- 40 BP	2460 - 2190 2180 - 2140	4410 - 4140 4120 - 4100
293501	H-457-10	L-16D	31.75	-22.75	Qp	238,529 1,283,067	AMS	(peat): acid/alkali/acid	5830 +/- 40 BP	-25.9	5820 +/- 40 BP	4780 - 4560	6730 - 6500
293502	H-457-10	L-22AC	43	-34	Qvrl	238,529 1,283,067	AMS	(organic fibers): acid/alkali/acid	7620 +/- 50 BP	-27.8	7570 +/- 50 BP	6480 - 6380	8430 - 8330
293504	H-469-11	L-2E	3.75	5.25	Qp	238,629.729973999 1,282,150.44286	AMS	(peat): acid/alkali/acid	1750 +/- 40 BP	-26.4	1730 +/- 40 BP	AD 230 - 401	1720 - 1540
291935	H-469-11	L-20D	39.35	-30.35	Qvrl	238,629.729973999 1,282,150.44286	AMS	(wood): acid/alkali/acid	8110 +/- 50 BP	-26.6	8080 +/- 50 BP	7170 - 7020 6930 - 6920 6880 - 6840	9120 - 8970 8880 - 8870 8830 - 8800
293503	H-469-11	F-35B	69	-60	Qvrl	238,629.729973999 1,282,150.44286	AMS	(organic sediment): acid washes	NA	-27.8	> 43500 BP	NA	NA
Union Bay - West of Foster Island													
292557	H-481-10	L-4D	7.8	1.2	Qp	238,830.737365999 1,280,759.78654	AMS	(peat): acid/alkali/acid	3030 +/- 40 BP	-27.7	2990 +/- 40 BP	1380 - 1330 1330 - 1120	3330 - 3280 3280 - 3060
292558	H-481-10	L-6A	10.2	-1.2	Qp	238,830.737365999 1,280,759.78654	AMS	(reed): acid/alkali/acid	2540 +/- 40 BP	-26	2520 +/- 40 BP	790 - 520	2740 - 2470
292559	H-481-10	L-12C	23.6	-14.6	Qp	238,830.737365999 1,280,759.78654	AMS	(wood): acid/alkali/acid	5460 +/- 40 BP	-27.4	5420 +/- 40 BP	4340 - 4230	6290 - 6180
292730	H-481-10	S-13B	26	-17	Qal/Ql	238,830.737365999 1,280,759.78654	AMS	(wood): acid/alkali/acid	6220 +/- 40 BP	-23.1	6250 +/- 40 BP	5310 - 5200 5170 - 5070	7260 - 7150 7120 - 7020
292556	H-481-10	F-22B	46.6	-37.6	Qvi	238,830.737365999 1,280,759.78654	AMS	(wood): acid/alkali/acid	NA	-29.5	> 43500 BP	NA	NA
292560	H-488-10	L-14B	26.4	-20.4	Qp	238,867.547723 1,280,312.85889	AMS	(peat): acid/alkali/acid	6310 +/- 50 BP	-27.4	6270 +/- 50 BP	5330 - 5200 5170 - 5070	7280 - 7150 7120 - 7020
292561	H-488-10	L-22A	42.05	-36.05	Ql/ Qvrl	238,867.547723 1,280,312.85889	AMS	(wood): acid/alkali/acid	5920 +/- 40 BP	-28.7	5860 +/- 40 BP	4800 - 4670 4640 - 4620	6750 - 6620 6590 - 6570
292562	H-488-10	L-24ACF	47	-41	Ql/ Qvrl	238,867.547723 1,280,312.85889	AMS	(plant material): acid/alkali/acid	7780 +/- 40 BP	-27.6	7740 +/- 40 BP	6640 - 6470	8600 - 8420
292565	H-499-10	L-2E	3.7	3.3	Qp	238,877.541671 1,279,688.38042	AMS	(wood): acid/alkali/acid	2620 +/- 30 BP	-27	2590 +/- 30 BP	810 - 760	2760 - 2720

Table 2. Summary of Radiocarbon Test Results

Lab no.: BETA-	Boring	Sample	Depth (ft)	Elevation (ft)	Geo. Unit[a]	Northing Easting[b]	Method[c]	(Material): Pretreatment	Measured age[d]	$^{13}C/^{12}C$ o/oo[e]	Conventional age[f]	Calibrated Age, BC, 2 σ[g]	Calibrated Age, BP, 2 σ[h]
292563	H-499-10	F-7B	12.3	-5.3	Qp	238,877.541671 1,279,688.38042	AMS	(wood): acid/alkali/acid	3940 +/- 40 BP	-26.8	3910 +/- 40 BP	2480 - 2290	4430 - 4240
292564	H-499-10	F-13A	25.0 to 25.4	-18 to - 18.4	Qlo	238,877.541671 1,279,688.38042	AMS	(peat): acid/alkali/acid	5220 +/- 40 BP	-26.4	5200 +/- 40 BP	4050 - 3960	6000 - 5900
292566	H-500-10	L-8C	14.35	-4.35	Qp	238,788.6 1,279,691.7	AMS	(wood): acid/alkali/acid	3950 +/- 40 BP	-29.9	3870 +/- 40 BP	2470 - 2200	4420 - 4150
292567	H-505-10	L-14A	26	-18	Ql/ Qvrl	238,852.343943 1,279,382.79351	AMS	(wood): acid/alkali/acid	5540 +/- 40 BP	-26.3	5520 +/- 40 BP	4450 - 4330	6400 - 6280
Portage Bay													
289948	H-522-10	L-3B	4.8	2.2	Qlo	238,183.795543 1,276,417.40921	AMS	(wood): acid/alkali/acid	220 +/- 30 BP	-25.6	210 +/- 30 BP	AD 1650 - 1680 AD 1740 - 1810 AD 1930 - 1950	300 - 270 210 - 140 20 - 0
289949	H-522-10	L-8B	16.4	-9.4	Qlo	238,183.795543 1,276,417.40921	AMS	(wood): acid/alkali/acid	180 +/- 30 BP	-26.7	150 +/- 30 BP	AD 1660 - 1890 AD 1910 - 1950	280 - 60 40 - 0
289950	H-533-10	L-1B	1.6	10.4	Qlo	238,040 1,275,750	AMS	(wood): acid/alkali/acid	300 +/- 30 BP	-23.6	320 +/- 30 BP	AD 1470 - 1650	480 - 300
289951	H-533-10	L-1C	2.1	9.9	Qlo	238,040 1,275,750	AMS	(wood): acid/alkali/acid	340 +/- 30 BP	-23.8	360 +/- 30 BP	AD 1450 - 1640	500 - 310
289952	H-533-10	F-12A	27 to 30	-15 to -18	Qlo	238,040 1,275,750	AMS	(peat): acid/alkali/acid	10720 +/- 50 BP	-27.8	10670 +/- 50 BP	10870 - 10710	12820 - 12660
289953	H-533-10	F-34A	84.2	-72.2	Qvrl-mx	238,040 1,275,750	AMS	(wood): acid/alkali/acid	NA	-26.8	> 43500 BP	NA	NA
289954	H-534-10	L-1C	1.3	9.7	Qlo	238,059 1,276,049	AMS	(plant material): acid/alkali/acid	100.7 +/- 0.5 pMC	-25.2	100.7 +/- 0.5 pMC	AD 1950 to present	NA
289955	H-534-10	L-5C	11.6	-0.6	Qlo	238,059 1,276,049	AMS	(wood): acid/alkali/acid	104.7 +/- 0.7 pMC	-27.6	105.2 +/- 0.7 pMC	AD 1955 to present	NA
289956	H-534-10	L-31B	74	-63	Qvrl-mx	238,059 1,276,049	AMS	(wood): acid/alkali/acid	NA	-26	> 43500 BP	NA	NA
289957	H-534-10	L-37A	85	-74	Qvrl-mx	238,059 1,276,049	AMS	(wood): acid/alkali/acid	NA	-29.3	> 43500 BP	NA	NA
289958	H-540-10	L-2A	2.4	5.6	Qlo	238,137.382355 1,275,330.05762	AMS	(wood): acid/alkali/acid	190 +/- 30 BP	-27.3	150 +/- 30 BP	AD 1660 - 1890 AD 1910 - 1950	280 - 60 40 - 0
289959	H-540-10	L-13B	31.1	-23.1	Ql/ Qvrl	238,137.382355 1,275,330.05762	AMS	(peat): acid/alkali/acid	11580 +/- 60 BP	-27.5	11540 +/- 60 BP	11520 - 11320	13470 - 13270
289960	H-540-10	L-16B & S-16	38	-30	Qvrl	238,137.382355 1,275,330.05762	AMS	(wood): acid/alkali/acid	33920 +/- 230 BP	-27.6	33880 +/- 230 BP	Too old for calibration.	Too old for calibration.

Table 2. Summary of Radiocarbon Test Results

Lab no.: BETA-	Boring	Sample	Depth (ft)	Elevation (ft)	Geo. Unit[a]	Northing Easting[b]	Method[c]	(Material): Pretreatment	Measured age[d]	$^{13}C/^{12}C$ o/oo[e]	Conventional age[f]	Calibrated Age, BC, 2 σ[g]	Calibrated Age, BP, 2 σ[h]

Note: All ^{14}C analyses conducted by Beta Analytic in Miami, FL.

[a] Refer to Figure 7 for description of geologic units.

[b] State Plane coordinates provided by Shannon & Wilson, Inc.

[c] AMS = Accelerator Mass Spectrometry, used due to small sample sizes and for precision.

[d] Measure age.

[e] Ratio of ^{13}C to ^{12}C in parts per mil, or parts per thousand.

[f] Conventional age incorporates the $^{13}C/^{12}C$ ratio.

[g] Calibrated age, BC, 2 sigma. Cal BC and Cal AD correspond exactly to normal historical years BC and AD, while Cal B.P. refers to the number of years before 1950.

[h] Calibrated age, B.P., 2 sigma; 95% probability.

pMC=percent modern carbon. These samples date to the mid-1900's and have excess carbon from the testing of nuclear bombs.

Calibration Notes:

Results calibration is necessary to account for changes in the global radiocarbon (Carbon-14) concentration over time.
Database used was INTCAL04.
INTCAL04 Radiocarbon Age Calibration – IntCal04: Calibration Issue of Radiocarbon (Volume 46, No. 3, 2004).
Mathematics
All Beta Analytic reports are included in Appendix D.

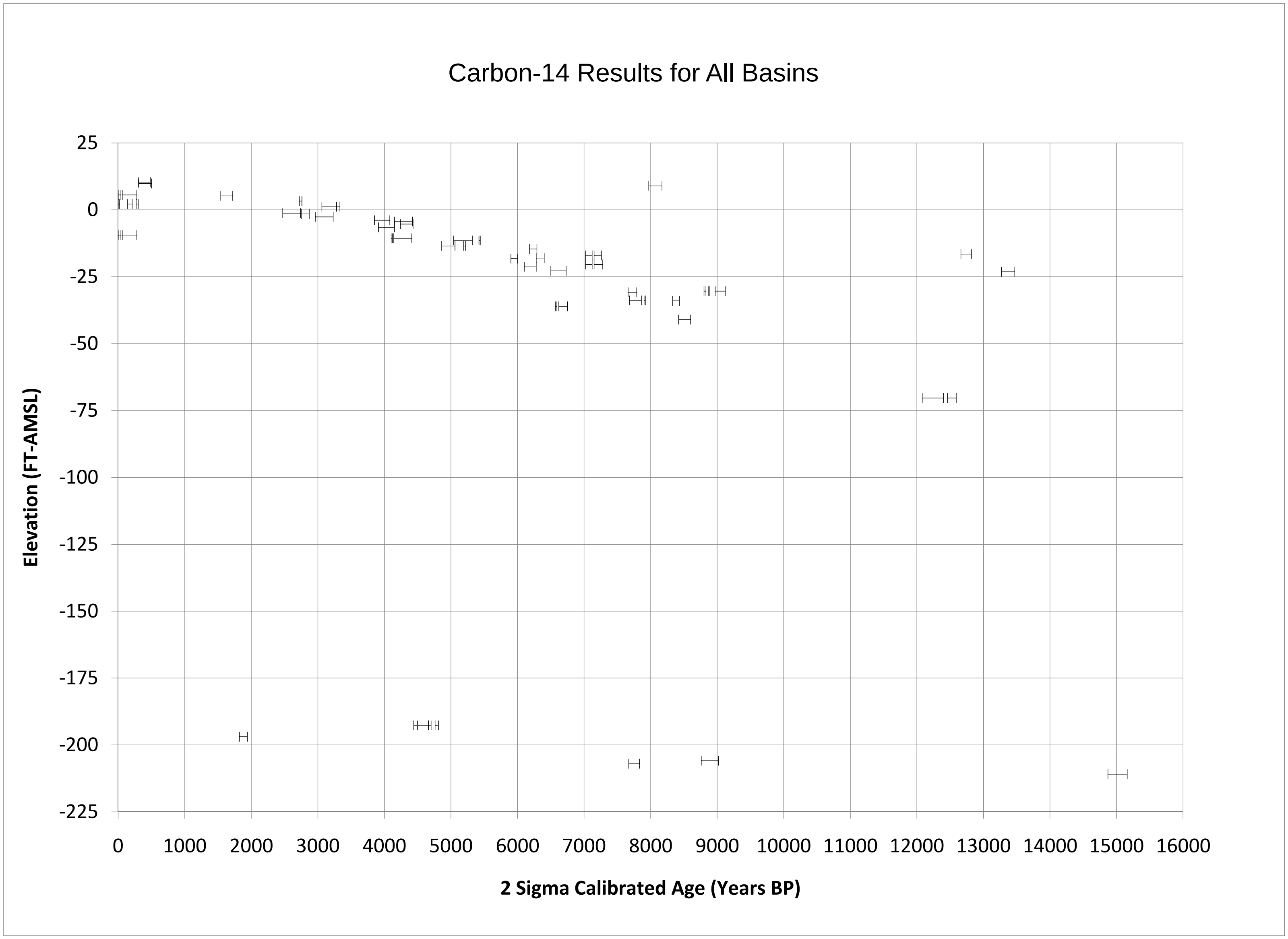


Figure 14. **Graph of Carbon-14 Results for all Basins**

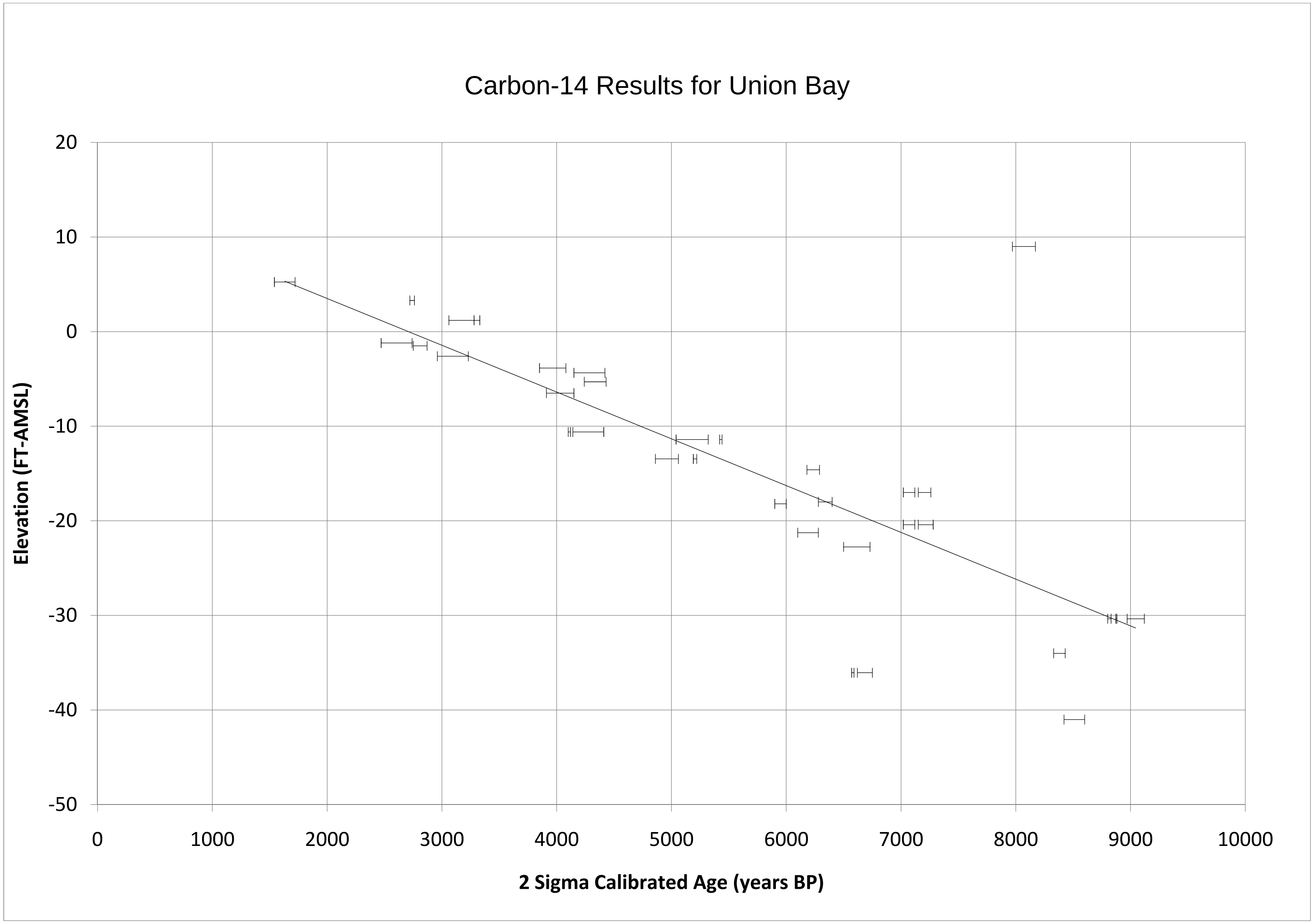


Figure 15. **Graph of Carbon-14 Results for Union Bay**

Table 3. Summary of Tephra Analyses

Boring	Sample No.	Depth (ft)	Lab	Refractive Index (RI)	Confirmed Event	Inferred Event	Notes
Lake Washington							
H-337-10	S-6A	28-30	MicroLabNW & TGC	1.5128-1.5125 1.5040>n>1.5000	Mazama O		Three seams
H-338-10	S-6A	27.0	MicroLabNW	1.5128-1.5125	Mazama O		Based on RI
H-339-10	S-4A	15.0				Mazama	Based on visual, age, position
H-343-10	S-3A	7.9				Mazama	Based on visual, age, position
H-348-10	S-5A	23.5				Mazama	Based on visual, age, position
H-349-10	S-3A	4.5	MicroLabNW	1.5110+-0.0005	Mazama O		Based on RI, but in Qls deposit, small clast of ash
H-349-10a	S-11A	20.1	MicroLabNW & WSU	1.5128-1.5125	Mazama O		Based on chemical composition
H-351-10	S-7	31-32				Mazama	Ash partings
H-353-10	S-13	61.0				Glacier Peak	Few 1/4" pockets of ash
H-357-10	S-10	18.0				Glacier Peak	Possible ash seam
Union Bay - East of Foster Island							
H-450-10	F-3ST	5.0-6.0				Mazama?	Small pocket, redeposited, reworked
H-453-10	L-17D	32.8-33.0	MicroLabNW	1.5110+-0.0005	Mazama O		Replicate yielded same RI
H-453-10	F-18C	34.6	MicroLabNW	1.5110+-0.0005	Mazama O		Based on RI, position, and age
H-457-10	L-21A	38.0-38.05	MicroLabNW	1.5110+-0.0005	Mazama O		Based on RI, position, and age
H-465-10	S-37	85-85.8				older	Pre-Vashon
H-469-11	F-19ST-A	36.0				Mazama	Based on RI, position, and age
H-473-10	F-19C	37.0	MicroLabNW	1.5110+-0.0005		Mazama	Based on RI, position, and age
Union Bay - West of Foster Island							
H-481-10	F-16C	32.8				Glacier Peak	Based on age and position

Table 3. Summary of Tephra Analyses

Boring	Sample No.	Depth (ft)	Lab	Refractive Index (RI)	Confirmed Event	Inferred Event	Notes
H-481-10	F-17B	36.5				Glacier Peak	Based on age and position
H-485-10	F-16B	32.0				Mazama	Based on age and position
H-485-10	L-16E	31.8-32.0	TGC	1.5040>n>1.5000		Mazama	Based on age and position
H-485-10	L-18A	34.3				Mazama	Based on age and position
H-488-10	F-16B	30.1				Mazama	Based on age and position
H-488-10	L-16A	30.05-30.15	MicroLabNW & TGC	1.5110 +-0.0005 & 1.5000>n>14960	Mazama O		Based on RI, position, and age
H-489-10	L-1C	1.1-1.5					Ash fragment
H-489-10	L-26B	50.4	MicroLabNW	1.4942 +-0.0005		Glacier Peak	Based on visual, age, & R.I.
H-491-10	S-12	36.0				Mazama	Based on age and position
H-494-10	F-14A	27.3				Mazama	Based on age and position
H-499-10	L-18C	35.1-35.3				Glacier Peak	Few specks
H-505-10	L-10E	19.7				Mazama?	Small pocket, reworked, redeposited
Portage Bay							
H-514-11	L-6D	11.5-11.6				Mazama	Based on position and age
H-522-10	L-5B	9.3-9.5					Small fragments of ash
H-522-10	L-6A	11.3-11.5					Small fragments of ash
H-522-10	L-6B	12.0-12.2					Small fragments of ash
H-527-10	F-6A	16.5				lower	Based on position and age
H-534-10	L-7A	15.2-15.3	TGC	1.5040>n>1.5000		Mazama	Based on RI, position, and age
H-540-10	L-6B	13.9-14.0	MicroLabNW, TGC, WSU	1.5110 +-0.0005 & 1.5000>n>1.4960	Mazama O		Based on chemical composition
H-540-10	F-7B	16.4				lower	Few specks
H-540-10	L-8A	17.5-17.8				lower	Small amount
H-564-11	S-5 & S-6	11-14				Mazama	Based on position and age

Table 4. Tephra Composition and Source

Oxide	H-349-10a, S-11a[a]	H-540-10, L6B[a]
SiO_2	72.95 (0.28)	73.21 (0.32)
Al_2O_3	14.58 (0.24)	14.74 (0.24)
Fe_2O_3	2.42 (0.06)	2.03 (0.08)
TiO_2	0.42 (0.04)	0.44 (0.02)
Na_2O	4.62 (0.19)	4.50 (0.38)
K_2O	2.77 (0.07)	2.76 (0.08)
MgO	0.45 (0.03)	0.44 (0.02)
CaO	1.58 (0.11)	1.59 (0.08)
Cl	0.22 (0.05)	0.29 (0.16)
Total[b]	100	100
Number of shards analyzed	16	17
Probable Source	Mazama O	Mazama O
	6850 BP	6850 BP
Similarity Coefficient[c]	0.98+	0.98+

Note: Microprobe analysis and source identification performed by Dr Franklin Foit, Jr., at Washington State University's GeoAnalytical Microbeam Lab. Results are presented in Appendix E.
[a] Standard deviations of the analyses given in parentheses.
[b] Analyses normalized to 100 weight percent.
[c] Borchardt and others, 1972.

3.3 Results of Microfossil Analyses

Two types of diatom analyses were completed on the stratigraphic control borings, a volumetric determination and a statistically significant count of identified species. These results are shown on the summary logs in Appendix A and the raw data are included in Appendix C. For boring H-349-10 in Lake Washington, the diatom percentage for the upper 23 feet of sediment is generally over 50 percent, meaning the fine-grained matrix is over one-half diatoms. The percentage drops below 50 at three depths, 16.7, 17.3, and 21.3 feet below mudline. These depths correlate with a clay seam, a silt seam, and a sand seam, respectively. Only a handful of diatoms were seen in the top of the glacial lake deposit, unit Ql/Qvrl, at a depth of 25 feet below the mudline. The diatoms then abruptly disappear, presumably because of the cold temperature and turbid water associated with the recessional lake.

Diatom identifications for this boring indicate that planktonic species are consistently dominant in the counts, thus supporting a deep water lake, with one exception. A deep sample indicates marine conditions at depths of 26 to 27 feet below the mudline. The marine conditions persisted for a short time, since the sample above indicates freshwater and the sample below has no diatoms. This temporary marine environment in Lake Washington is consistent with findings by Leopold and others (1982b) and is based on marine microfossils and diatoms (Abella, 1986). Leopold dated the marine interval, which occurs at an elevation of -189 feet, at 13,430 +/- 200 radiocarbon years B.P. (QL 1516) and that age was newly calibrated as 15,370 to 16,470 years Cal B.P. (BETA-QL-1516).

In borings H-457-10 and H-488-10, a repeated pattern of shallowing water is indicated by the diatom species counts. In H-488-10, three shallowing events are present as indicated by the cyclic transitions from “deeper” water to “very shallow” conditions. This does not include the starting shallow conditions at the end of the glacial lake period, at the close of the Pleistocene. This cyclic pattern may also be present in other borings but sampling density may be too low for detection.

3.4 Results of Macrofossil Analyses

Macrofossils were encountered in most of the geologic materials within the basins. Macrofossils found in the sediment include beetle elytra, sponges, freshwater mollusks, leaves, logs, rhizomes, cones, and many types of seeds, pods, and stems.

3.4.1 Insects

Beetle elytra (wings) were found in H-457-10 at a depth of 19.3 feet below mudline (Figure A-3 and photograph page B-23, Appendix B). The beetle was identified as *Dytiscus cordieri,* predaceous diving beetle, by Mr. Martin Adams of Portland, Oregon. The wings on this beetle are 3 cm long, bright fluorescent green, and have many ridges or sulci, making it relatively distinctive. Small and microscopic unidentifiable insect parts and *Daphnia* parts were also seen in some of the organic-rich sediments.

3.4.2 Mollusca and Porifera

Shells were not found in the peat deposits, probably because swamps, bogs, and marshes are not hospitable environments for mollusca given that decaying vegetation produces acid that is known to dissolve calcium carbonate. Open water was generally present adjacent to the peat areas in each basin, so mollusca could survive nearby. This was seen in one specimen of a freshwater mussel found in H-461-10 at a depth of 1.6 feet in peat where only the skin, or periostracum, remained (photograph page B-24, Appendix B). The two valves were still attached and closed, but only a partial set of the periostracum remained. Muck filled the void between the valves. Other shells encountered, with some of the original calcite shell remaining, are listed on Table 5 (some shown in photograph pages B-25 and B-26, Appendix B). Of those shells that could be identified, half are of obligate marine environments and the other half of freshwater environments. Obligate marine shell species were identified in Lake Washington in the top of unit Ql/Qvrl, from H-348-10, at a depth of 23.5 feet below the mudline and in H-349-10 at 27 feet below mudline. This finding is consistent with the marine diatoms found at 26.3 feet below mudline in H-349-10. Freshwater diatoms are noted above the marine diatoms at 26 feet below mudline, significantly limiting the marine phase to a depth of 26 to 27 feet below mudline, and a freshwater clam was found at 16.6 feet below mudline in H-349-10, confirming the freshwater environment.

Table 5. Summary of Shell Identifications

Boring	Sample No.	Depth	Environment	Identification	Notes
Lake Washington					
H-348-10	S-7aA	23.5'	Marine	*Macoma brota*	Juvenile clam, common in Puget Sound and outer WA coast. Infaunal, generally in fine-grained mud, often with low oxygen levels, ranges down to ~50m water depth, but usually more shallow.
H-349-10	S-9B	16.6'	Fresh	*Corbicula fluminea*	Fresh to brackish water clam. With vivianite. See also H-442-10, L-1B below.
H-349-10	S-14B	27.0'	Marine	*Macoma?*	Probably *Macoma* but no hinge for positive identification.
H-351-10		36.0'-39.0'	NA	NA	Sample not available, but sediments quite odoriferous.
H-364-10		11.5'-13.4'	NA	NA	Very small, thin, white shell fragment.
H-442-10	L-1B	0.5'-0.9'	Fresh	*Corbicula fluminea*	Live clam. Fresh to brackish water clam. *Corbicula fluminea*, the introduced Asian clam, now common in WA. They can bury themselves in the mud.
H-442-10	F-2A	3.2'	Fresh	*Corbicula fluminea*	Live clam. Same note as H-442-10 L-1B
Union Bay - East of Foster Island					
H-447-11	L-1C	1.7'-2.0'	NA	gastropod	Broken, thin-walled, off-white, small, 0.5cm shell. Not identified.
H-461-10	L-1D	1.6'	Fresh	*Anodonta oregonensis*	Skin, periostracum, of fresh-water mussel; Found in peat, not a likely habitat.
Portage Bay					
H-522-10	F-4B	8.9'	Marine	barnacle plate	Marine intertidal and very easily pushed or carried into an embayment or upstream.

Notes:

Samples were identified by Dr. Elizabeth Nesbitt, Curator of Invertebrate Paleontology at the Burke Museum, University of Washington, and K. Troost of TGC.

Samples were collected in the field during drilling of borings, or in the laboratory from Shelby tube cores.

More shells are likely present in the subsurface but were not encountered in the samples evaluated.

A barnacle plate was encountered in H-522-10 at a depth of 8.9 feet below the mudline in Portage Bay; however, diatom analyses from this interval in nearby borings indicate a freshwater environment. According to Nesbitt (written communication, 2010), barnacle plates are easily transported upstream. However, the organic silt at this depth is estimated to be about 7,000 years Cal B.P., much older than the historical connection of Lake Union to Puget Sound, therefore the sample was not transported upstream via the canal. Such a small specimen could have been carried by a bird, mammal, or Native American, then dropped into Lake Union or Portage Bay.

The freshwater clams found in Lake Washington were identified as the Asian clam, *Corbicula fluminea* (Table 5, Appendix B, photograph pages B-25 and B-26) (Nesbitt, written communication, 2010). According to the U.S. Geological Survey list of nonindigenous aquatic species (http://nas.er.usgs.gov/queries), this clam was first identified in the United States in 1938 (Counts 1986) in the Columbia River near Knappton, Washington. Two of the three clams were found alive in relatively shallow sandy sediment samples on the submerged ridge in H-442-10.

The third *C. fluminea* was only a partial shell and was partially covered with vivianite, a secondary mineral signaling the decay of organic material in the presence of phosphate. This specimen was found at a depth of 16.6 feet below the mudline in H-349-10 in a deep part of Lake Washington just below a landslide deposit. Based on radiocarbon dates in nearby boreholes and sedimentation rates, the age of the sediment at this location should be about 7,000 years Cal B.P. If the clam is accurately identified and this species of clams was indeed introduced by immigrants in 1938 in Washington, then the deposits enclosing the clam and those above the clam must all be part of the landslide deposit, and the landslide must have occurred after 1938. If the clam is incorrectly identified, the deposit just above the clam is still younger than normal for the depth of sediment. Given that the radiocarbon date of 1820 to 1940 years Cal B.P. was from 2.9 feet below the identified landslide deposit, then it is possible that young material was injected below the depth of the landslide deposit during the landslide or that the landslide deposit is thicker than described. Another possibility is that mixing of sediment in this deep part of the lake could be related to earthquake shaking followed by an earthquake-induced landslide.

Two specimens are tentatively identified as from the Porifera phylum, and appear to be freshwater sponges. A small segment of a freshwater sponge was identified in the organic silt in Portage Bay in boring H-540-10 at a depth of 8.8 feet below the mudline. The other sponge fragment was found in Union Bay in H-453-10 at a depth of 27.7 feet below the mudline. Living freshwater sponges are white to green in color and soft; the first fragment was encased in diatomaceous ooze, orange-yellow in color, and brittle, and the second was surrounded by muck and was dark brown in color. Sponge spicules were also seen when examining the diatom and smear slides (Appendix E, photos in 2/4/2011 report from Microlab Northwest).

3.4.3 Seeds

Seeds and seed pods were observed throughout the depth of the peat in Lake Union and only intermittently in the organic silt in Portage Bay. Seeds were collected from three borings and analyzed to assist with determination of depositional environment. Some seeds, although only 1 to 2 mm in size, were bright orange or yellow and therefore quite visible to the naked eye against the dark coloring of the peaty sediment (photograph page B-21, Appendix B). These occurred as lone seeds or in pockets together with about 6 to 12 seeds (photograph page B-22, Appendix B). The remaining seeds were retrieved and identified with the assistance of a microscope as described in Section 2.4.1. The results of the seed collection and identification are shown on the summary logs for H-457 in Union Bay, H-488-10 in west Union Bay, and H-534-10 in Portage Bay, all in Appendix A. A fourth boring, H-349-10, was screened for seeds. Seeds were not found in H-349-10 (Appendix A) in Lake Washington because the lake sediment, which was very fine, indicated that the distance from shore was too far for most seeds.

Identified seeds were found to be from the following families and categories, in order from moist habitat to aquatic habitat, exclusive of the “grasses” and “other" categories; some additional individual seeds were identified to the genus and species level and are listed separately on the summary logs:

- *Rosaceae* – rose family
- *Cerastium* – chickweed
- *Thuja plicata* – western redcedar
- *Ericaceae* – heath family
- *Ericaceae (Gaultheria shallon)* – salal
- *Corylopsis veitchiana* - winter hazel
- *Apiaceae (Umbelliferae)* – water parsley/carrot family
- *Scirpus/Carex* – bulrush/sedges
- *Menyanthes trifoliata* – buckbean (photograph page B-22, Appendix B)
- *Typha* – cattail
- Grass (photograph page B-22, Appendix B)
- Other

Most seeds fall close to their parent plant in aquatic and bog environments, and nearby land species (trees and shrubs) are generally well represented (Wasylikowa, 1986). However, not all of the vegetation from any given time period will be represented in sediment samples because some seeds, for example, are designed for distance air transport. Therefore vegetation assemblages are used as proxies to help identify environments. Some of the seeds recovered from the borings above fall into characteristic assemblages.

The results of the seed identification provided several findings. Few seeds were found in H-534-10 in Portage Bay. Most of the post-glacial sediment in Portage Bay is fine-grained organic silt. The lack of peat and fine-grained nature of the sediment indicate that the bay in the vicinity of this boring was not shallow enough to support a marsh. Overall water quality was rather poor in Lake Union and presumably in Portage Bay due to a lack of fresh water and stagnating conditions in the summer (Chrzastowski, 1983). This poor water quality condition may have persisted prehistorically as well. Vegetation was likely nearby, however, and provided sufficient organic material such that the lake sediment can be classified as "organic" silt.

In Union Bay, the seeds in borings H-457-10 and H-488-10 indicate that shallow water species are present throughout the peat as indicated by the presence of *Menyanthes trifoliata* and *Scirpus/Carex*. This is consistent with the presence of post-glacial peat and peaty organic silt. In addition to shallow water, periods of scrub/shrub to forested wetlands are apparent when large numbers of a wide variety of certain plants, in characteristic assemblages, are indicated by the seeds. These episodes occur at depths of 18 and 28 feet below the mudline in H-488-10 and at 2.5 and 8 feet below the mudline in H-457-10.

In addition to shallow conditions throughout the Holocene, the end of glacial lake conditions and deposition is marked by a very shallow water period, indicated by an abundance of seeds and a variety of plant types, shown best in H-457-10 at a depth of 39 feet below the mudline (Appendix A, Figure A-3). Seeds were generally not found in the glacial lake sediment.

Mixing of sediment from lake level fluctuations, waves, biogenic sources, and dynamic geologic processes can cause contamination. Evidence of this type of contamination with the seeds, redepositing younger seeds in older sediment or redepositing older seeds in younger sediment, was not identified. Mixing of sediments did occur, however, particularly in Portage Bay, as evidenced by the radiocarbon results (Figure 14).

3.4.4 Plants

Many types of plants were encountered in the samples retrieved from Lake Washington and Union and Portage Bays. Some types were seen throughout the organic sediments, including fragments from trees, shrubs, herbs, aquatics, rushes, sedges, grasses, ferns, and mosses. Some of the unique specimens are described below. A federal General Land Office (now Bureau of Land Management) survey in 1858 on and adjacent to "Fosters Island" noted fir to 60 inches in diameter, cedar to 30 inches in diameter, alder, ash, cottonwood, willow, and laurel (http://www.blm.gov/or/landrecords/survey/). In addition to these trees, birch was also encountered in the lake sediments along the SR 520 alignment.

Leaves

Leaf impressions were encountered in the organic silt in Portage Bay and in the peat of Union Bay. Some original leaf material was also found within the peat in Union Bay; some of the leaf fragments have diatoms attached. Of the 21 notable leaf fragments, 74 percent (15) are at (or within 1 foot of) a potential shoreline feature. Only five of the leaf fragments have sufficient detail to make at least tentative identifications.

In boring H-461-10, at 37.9 feet below the mudline (-30 feet in elevation) in west Union Bay, a partial leaf fragment with poor detail was encountered. The identification for this specimen can only be narrowed to five possibilities: wild ginger (*Asarum caudatum*), piggy-back plant (*Tolmiea menziesii*), fringecup (*Tellima grandiflora*), miterwort (*Mitella sp.*), or wild cucumber (*Marah oreganus*). All of these plants prefer moist forests with the exception of wild cucumber, which prefers a more open, moist habitat. This specimen was collected from 2 feet above the contact between units Ql/Qvrl and Qp with a sediment age of about 7,600 years Cal B.P. The basins had transitioned from a glacial recessional environment to a lacustrine environment, and forests were developed on the upland surfaces.

In boring H-481-10, at 19.7 feet below mudline (-12 feet in elevation) in west Union Bay, most of a leaf impression was encountered (photograph page B-27, Appendix B). Based on the shape and orientation of the veins, the leaf is possibly from a dogwood, *Cornus sp.,* or crab apple, *Malus fusca*, shrub/tree. Both of these shrubs/trees like moist soil, swamp, scrub, edges of standing or flowing water, and streamside forest environments. The age of the sediment at this depth is estimated at 5,000 years Cal B.P.

In boring H-533-10, at 20.86 feet below the mudline (-9.2 feet in elevation) in Portage Bay, a leaf impression was encountered in the organic silt deposit. The impression is faint, but some characteristics permitted a tentative identification: hazelnut (*Corylus cornuta*) or cascara (*Rhamnus purshiana*). This leaf impression was encountered 3 feet below the Mazama ash interval; therefore, this sediment is about 8,000 years Cal B.P. These shrubs have different habitats; hazelnut prefers moist, well drained sites in open forests while the cascara prefers dry to moist sites with mixed woods and swampy bottomlands.

In boring H-533-10, at 17.8 feet below the mudline (-6.2 feet in elevation) in Portage Bay, a partial maple samara, winged seed, was recovered (photograph page B-27, Appendix B). Some of the original leaf material is present. Given the size of the seed, the species is either a big leaf maple, *Acer macrophyllum,* or vine maple, *Acer circinatum;* however, based on the shape of the seed, the species is most likely a big leaf maple. The vine and big leaf maples have slightly different habitats with some overlap in moist areas at edges of forests. Big leaf maple is often found in association with Douglas-fir (*Pseudotsuga menziesii*); both are common after fire damage. This samara probably came from near-shore vegetation, but it could have sailed into the bay from a greater distance. This specimen was found at the elevation of the Mazama ash and therefore is about 7,600 years Cal B.P. In a nearby boring, a Douglas-fir cone was found in contact with the Mazama ash.

In H-505-10 at 2.5 feet below mudline (5 feet in elevation) in west Union Bay, a partial leaf was recovered from the peat. The leaf is possibly from a dogwood, *Cornus sp.*, or crab apple, *Malus fusca*, shrub/tree. Both of these shrubs/trees like moist soil, swamp, scrub, edges of standing or flowing water, and streamside forest environments. The age of the sediment at this depth is estimated at 1,000 years Cal B.P., which places the leaf in a pre-logging time period.

Other Plant Remains

In addition to leaves, other plant remains were encountered including large pieces of wood, beaver-chewed wood (photograph page B-28 Appendix B), thorns, cones, seed pods, milfoil, pondweed (photograph page B-28, Appendix B), and rhizomes(living and decayed). Some of the more unusual specimens are described below.

A large piece of wood was recovered from a Shelby tube sample from the peat in west Union Bay from H-488-10 at 31.4 to 31.9 feet below the mudline (-25 to -25.5 feet in elevation) (photograph page B-29, Appendix B). The diameter of the wood matched that of the Shelby tube and the length is 6 inches; apparently the Shelby tube cut into a log lying nearly vertically in the peat. The sample is spongy, saturated, and very soft. Tree rings became more visible as the sample was allowed to air dry for a few hours. Light and dark rings, patterns in the dark wood ring, and decay characteristics led to a tentative identification of the wood as Douglas-fir. This sample was collected from less than one foot below the Mazama ash; therefore, the sediment containing the wood is just older than 7,600 years Cal B.P.

A Douglas-fir cone was encountered in a Shelby tube sample from boring H-349-10 at 20.2 feet below the mudline (-203.8 feet in elevation) in gyttja in a deep part of Lake Washington (photograph page B-30, Appendix B). The cone was situated at the base of the Mazama ash; therefore, it can’t be any younger than 7,600 years Cal B.P. This cone measures 6.3 cm in length and 2.5 cm in width and is partly decayed.

Parts of *Equisetum* (horsetail) plants, segmented stalks, sheaths, and disk-shaped nodes, were found in many samples in a range of depths in all three basins. The fragments were not of sufficient quality or complete enough to permit species identification. Depending on the species, their habitat can range from moist to wet forests to shallow water. Disks of what appear to be the nodes of *Equisetum* stalks were noted in west Union Bay in H-505-10 from 4 to 6 feet below the mudline and in H-500-10 at 1 foot below the mudline. *Equisetum* sheath fragments were noted in Union Bay in H-500-10 at 1 foot below the mudline, in west Union Bay in H-505-10 at 2.8 feet below the mudline, and in Lake Washington in H-349-10 at 21.9 feet below the mudline (photograph page B-30 and B-31, Appendix B). *Equisetum* segments were noted in west Union Bay in H-499-10 at a depth of 21.5 feet below the mudline.

Part of a *Scirpus acutus* (tule) rhizome was found in west Union Bay in H-488-10 at a depth of 0.5 foot below the mudline. This fragment measures 3.5 by 2.5 cm in size. Assuming the specimen died in place or close to its growth location, the presence of tule indicates, marsh, muddy shores, or shallow water conditions.

Sprouting *Nuphar* (pond-lily) tubers were noted in west Union Bay in H-501-11 at depths of 0.9 foot and 1.2 feet below the mudline (photograph page B-31, Appendix B). Older tubers were noted in west Union Bay in H-499-10 at a depth of 5.8 feet below the mudline. *Nuphar* leaves were also encountered in the sediment, including in west Union Bay H-485-10 at a depth of 37.8 feet below the mudline. *Nuphar* live in ponds, shallow lakes, and sluggish streams. Many of the borings were drilled next to thick patches of pond-lily in Union Bay.

Needles and Thorns

Some needles and thorns were encountered in Portage Bay that can be tentatively identified. In H-527-10 at a depth of 2.35 feet below the mudline, a needle was noted in the organic silt in Portage Bay. This specimen is tentatively identified as *Tsuga heterophylla* (Western hemlock) or *Pseudotsuga menziesii* (Douglas-fir), both native and present prior to logging in the late 1800s and early 1900s. A thorn-like specimen was found in H-533-10 at a depth of 1.9 feet below the mudline in the organic silt in Portage Bay. The thorn is tentatively identified as one of a *Crataegus douglasii* (black hawthorn) shrub/tree, which prefers moist forest edges, shorelines, and stream sides. Other needles may be correlated to the Pacific yew or Western hemlock. In H-540-10 at a depth of 8.7 feet, two thorns were encountered that are tentatively identified as belonging to the genus *Rosa.* All species are known to have inhabited this area prior to settlement and logging.

3.5 Results of Tephra Analyses

Three different ash layers were encountered in the samples evaluated. Representative samples of volcanic ash were evaluated, index of refraction determined, and chemical composition measured to identify source (Tables 3 and 4). The laboratory reports and raw data from outside labs are included in Appendix E. These analyses allowed the separation of 3 different tephra layers, Mazama O, an unidentified ash, and a Glacier Peak tephra. Two samples, one in Lake Washington at H-349-10 at a depth of 20.1 feet below the mudline (photograph page B-32, Appendix B) and one in Portage Bay in H-540-10 at a depth of 14 feet below the mudline, underwent chemical composition analyses (Table 4) and are positively correlated with the Mazama O ash, dated at 7580 to 7990 years Cal B.P. (BETA-TX-487) and 7610 to 8030 years Cal B.P. (BETA-GaK-1124) on charcoal at Muir Creek, Oregon (Kittleman, 1973). The samples from H-349-10 and H-540-10 also have the characteristic refractive index of 1.500 to 1.515 (Randle and others, 1971). Other samples with similar refractive index and age are correlated with the Mazama ash as shown on Table 3 and on the cross sections, Figures 8 through 13. The Mazama ash is most continuous in the west part of Lake Washington along the alignment and in the center area of west Union Bay along the alignment. Other photographs of the Mazama ash in a Shelby tube core are included in Appendix B (photograph pages B-32 and B-33). Under the microscope, the Mazama ash is fine-grained with small bubbles and has angular glass fragments with some thin, needle-like shards.

In several borings, two distinct ashes are present, one that correlates with the Mazama ash and another within unit Ql/Qvrl (photograph pages B-32 and B-33, Appendix B). Characteristics of this lowest ash, such as refractive index, texture, and age, are consistent with tephra from the Glacier Peak event dating to 13250 to 14920 years Cal B.P. (BETA-WSU-155) based on a shell age in a lacustrine deposit 5 miles north of Soap Lake in Eastern Washington (Fryxell and Loope, 1965). Glacier Peak ash has a characteristic refractive index of 1.495 to 1.50 (Powers and Wilcox, 1964). Steen and Fryxell (1965) reported index of refraction as high as 1.504 for the Glacier Peak ash. Under the microscope, the Glacier Peak ash is coarser grained than the Mazama ash, with angular fragments, a frothy, stretched to swirled appearance, and thin needle-like shards are either absent or abundant.

The third ash occurs within the organic silt in Portage Bay below the elevation of the Mazama ash but well above the age/elevation horizon expected for the Glacier Peak ash (photograph page B-32, Appendix B). Little is known about this ash at this time as it was discovered late in the analyses.

In a few samples ash was found as a clast rather than as part of a layered deposit. Presence in clast form indicates that the ash could be reworked and redeposited. For example a clast of ash, identified as Mazama, was noted at a shallow depth in Lake Washington in H-349-10 in a landslide deposit 15 feet above the in-situ layered Mazama ash location.

3.6 Sedimentation Rates

Sufficient age data were collected to calculate sedimentation rates in the different basins (Table 6). Some rates varied significantly between the basins and between different geological boundaries. Rates were determined for 3 major geological boundaries:

1) for the glacial recessional deposition and transition—units Qvrl and Ql/Qvrl;

2) for the earliest of the organic material until deposition of the Mazama Ash—units Qp, Qlo, Qlg; and

3) for the last half of the organic unit deposition in Qp, Qlo, Qlg from time of deposition of the Mazama ash until today.

The fastest depositional rate was found in the glacial recessional lacustrine unit Qvrl, including Ql/Qvrl, in Lake Washington at 25 mm per year or 1.02 years per inch. The slowest accumulation rate was measured in west Union Bay for the peat between unit Ql/Qvrl and the Mazama Ash at 0.37 mm per year or 68 years per inch. The most consistent sedimentation rate occurs in the uppermost layer in Lake Washington, Union Bay, and west Union Bay.

Sedimentation rate appears to have remained steady in Portage Bay after deposition of units Qvrl and Ql/Qvrl at a rate of about 61 mm per year or 41 to 42 years per inch.

Table 6. Summary of Depositional Rates

Geologic Boundary	Portage Bay	W. Union Bay	Union Bay	Lake Washington
Mudline to Mazama ash; in gyttja, peat, or organic silt	41 yr/inch 0.62 mm/yr	19 yr/inch 1.33 mm/yr	16 yr/inch 1.59 mm/yr	19 yr/inch 1.33mm/yr
Mazama ash to top of unit Qvrl; in gyttja, peat, or organic silt	42 yr/inch 0.60 mm/yr	68 yr/inch 0.37 mm/yr	4.2 yr/inch 6.10 mm/yr	51 yr/inch 0.50 mm/yr
Top of unit Ql/Qvrl to base of unit Qvrl; in silty clay to clayey silt	2.98 yr/inch 8.53 mm/yr	12.5 yr/inch 2.03 mm/yr	19.44 yr/inch 1.31 mm/yr	1.02 yr/inch 25.0 mm/yr

Notes:

Top of Qvrl dates to about 13.5 ka radiocarbon years, 14,900 yrs Cal B.P. in Lake Washington.

Top of Qvrl ends much later in Union Bay and west Union Bay.

Mazama ash dates to about 6.9 ka radiocarbon years, 7,600 yrs Cal B.P.

Unit Qvrl is the glacial recessional lake deposit.

4.0 Discussion and Interpretations

4.1 Depositional Environments and Geomorphology

A wide range of depositional environments is represented in the sediments in Lake Washington, Union Bay, and Portage Bay, from glacial to marine estuary to warm-climate forested wetland. The analyses conducted on the borehole samples were designed to determine the depositional environment and water depth as partial evidence for shorelines. No single type of analysis is adequate to make such determinations due to the amount of discontinuity between the basins, so an integrated approach was taken.

Depositional environment was interpreted and recorded on the stratigraphic control borings, and summary logs for these borings are shown in Appendix A along with a key for understanding the abbreviations and symbols. The interpreted environment listed on the boring applies to the location of that boring, keeping in mind that different environments could be present a short distance away. The following is a summary of the depositional environments for the lake and bays starting with the end of glaciation.

4.1.1 Glacial Recessional Environment

Exclusive of the glacially overridden substrate, the oldest deposit in the study area belongs to the Vashon glacial recessional stage starting about 16,850 years Cal B.P. With glacial recession, ice blocks likely occupied Union Bay, west Union Bay, and Portage Bay, much like in the kettles aligned in the American Lake, Steilacoom Lake, and Gravelly Lake area south of Tacoma, Washington (Troost, 2007). These ice blocks occupied low depressions in the landscape and contributed ice-contact debris to the bottoms of Portage Bay, west Union Bay, and Union Bay. These deposits are also seen on the submerged ridge and further north in Union Bay (from GeoMapNW database, http://geomapnw.ess.washington.edu). The basins of Portage Bay, the south end of Union Bay, and west Union Bay were subglacially scoured to about the same depth at about 95 to 100 feet from the water surface (elevation -75 to -80 feet), and the northwest central part of Union Bay was scoured even deeper at about 145 feet from the water surface (elevation -130 feet). Scour depth at the southern end of Union Bay varies and is known to exceed elevation -95 feet (Shannon & Wilson, 2011b). Recessional outwash deposits may have been reworked with residual subglacial deposits within the basins. Climate was cool during this time.

The modern ship canal valley occupies a channel that was also carved subglacially and it consists of a series of smaller, deep basins separated by small ridges with low-lying saddles. Portage Bay and Union Bay are two of these basins. The valley served as a glacial marginal meltwater channel during recession and kettle lakes occupied these deep basins.

The shape of the glacially scoured surface is readily apparent on the cross section shown on Figure 8 as the upper surface of the "glacially overridden material" or GOM. At modern lake level, a submerged ridge separates Union Bay from Lake Washington. Another submerged ridge is present extending north of Foster Island. The deepest part of each basin may not be shown on the cross section since this cross section follows the current route of SR 520. For example, Union Bay extends down to -130 feet in elevation northwest of Foster Island close to where Ravenna Creek enters the bay. Even though Union Bay is deeply scoured, the outlet to Lake Washington along the edge of the submerged ridge is not as deep, with an elevation of -20 feet at the deepest point where a "ravine" cuts into the ridge presumably for a paleo Ravenna Creek (Figure 4).

During glacial recessional lake occupation, around 16,630-15,500 years Cal B.P., the basins were inundated with a cold freshwater lake (Figure 6). Water depth extended to the uplands since the land was still isostatically depressed. Glacial Lake Russell shorelines are now seen at an elevation of about 330 feet. The lack of pollen and diatoms and the melting ice suggest the cool temperature of the water. Debris from the melting ice and from hillsides settled into the lake bottom, accumulating relatively rapidly. The lake mud varies from massive to laminated; laminations in the glacial lake deposits may indicate seasonal changes (Edmondson, 1975).

During lake occupation, turbidity currents, dewatering of the soft sediments, and delta formation occurred as sediment entered Deltaic structure is noted toward the deepest part of the lake, near H-349-10. Soft sediment deformation and turbidite deposits could be the result of loading from landsliding, sedimentation, and/or earthquake shaking.

Glacial Lake Bretz was deep enough to connect Lake Washington, Puget Sound, Portage Bay, and Union Bay and cover much of the upland area to an elevation of about 100 feet in the Seattle area (Figure 6). When it drained, some water was left in the bays but only very little in Lake Washington since it was then connected to Puget Sound via the Duwamish/Green River valley trough. The turbid water took longer to settle out in the bays than in Lake Washington based on the younger dates for the top of unit Qvrl and Ql/Qvrl in the bays.

As water receded from the upland by the draining of Glacial Lake Bretz, the region became vegetated. According to Leopold and others (1982a) the vegetation history in the Lake Washington area consists of five pollen zones. No pollen was found in the bulk of the glacial lake deposits, consistent with the lack of diatoms. However in the upper few feet, a cool-climate pollen assemblage was noted: some pine (*Pinus*) with lesser amounts of spruce (*Picea*), mountain hemlock, (*Tsuga mertensiana*), and grass (*Poaceae*).

4.1.2 Marine Incursion

Marine water entered Puget Sound and inundated the interconnected troughs, including Lake Washington, because land was still isostatically depressed and sea level was rising due to the warming global climate following glaciation. Marine diatoms and bivalves were encountered in one sample interval near the top of unit Qvrl, indicating the presence of a marine environment as noted by Leopold and others (1982b). Diatoms recovered from that interval suggest that the water was relatively shallow but that planktonic species were being carried in to the lake area. Some of the diatoms and the bivalve recovered are also of an estuarine habitat, indicating that as the marine phase ended, and perhaps as it started, estuarine conditions existed in the Lake Washington trough where the freshwater from the Sammamish River met the marine water. The marine phase ended about 14,800 years Cal B.P. when the rate of isostatic rebound exceeded the rate of sea level rise such that marine water was drained from Lake Washington back to the upper Duwamish valley near Tukwila. Rebound recovered faster in the south than in the north and was complete in the Seattle area by 11,600 years Cal B.P., if not sooner.

The settling of suspended sediment in the recessional lakes took longer in Union Bay than in Lake Washington or Portage Bay. As the recessional water level dropped, each basin contained a separate water body. Ravenna Creek flowed into Union Bay then on into Lake Washington. Lake Washington then flowed out the Black River to the Duwamish River.

4.1.3 Weathering and Bioturbation

After the glacial lake deposit, unit Qvrl, accumulated, it was altered in place by weathering, unloading, and biological means. The altered layer at the top of unit Qvrl is called unit Ql/Qvrl. Throughout this zone, iron-oxide and manganese-oxide staining and nodules were noted. Fine blocky texture is almost exclusively limited to this zone. Near the top of the zone, black and dark gray mottling is present along with worm burrows. These factors strongly suggest that in addition to unloading, the deposit underwent subaerial weathering and water level changes and provided a habitat for worms, which prefer very shallow water to dry environment.

4.1.4 Deep Freshwater Lake

A deep freshwater lake followed the short weathering period and water level rose in the lake relatively rapidly (see Section 4.2 and Figure 16). Pollen (Leopold and others, 1982b) and diatom (Abella, 1986) evidence indicates that the lake began filling during cool climate conditions and continued during warm climate conditions. Several stillstands are interpreted based on knickpoints on the steep slopes of Lake Washington. All the collected evidence suggests that while the lake level fluctuated somewhat, the water remained deep once it began filling (see boring H-349-10, Figure A-2, Appendix A).

Gyttja and organic silt accumulated in Lake Washington during the freshwater environment that persists today. Deposition of this unit was continuous except for minor interruptions during storm, landslide, and earthquake events when turbidity currents carried sandy and/or silty material out into the lake, leaving a thin layer in the gyttja. One such sand deposit has been tentatively correlated with the lowering of the lake when the ship canal was opened in October 1916, in boring H-349-10 at a depth of 1.3 feet below the mudline.

Four of the remaining five pollen zones belong to the time when Lake Washington was a fresh-water lake. The second pollen zone began during early deposition of unit Qlg, and is characterized by pine with spruce, alder (*Alnus*), and bracken fern (*Pteridium*) spores (Leopold and others, 1982a). Leopold and others interpret this assemblage as evidence for a local pine forest with some spruce and understory shrubs and herbs lasting until about 13,000 years Cal B.P. The third pollen zone is a transition period, then the fourth pollen zone lasts until about 7,600 years Cal B.P. with deposition of the Mazama Ash during which alder, Douglas-fir (*Pseudotsuga*), grass, and bracken fern spores dominate. The fourth pollen zone is warmer and drier than at present, with evidence of fires. Leopold and others interpret this as an open forest of Douglas-fir and alder or a forest mosaic. The fifth pollen zone begins immediately after the deposition of the Mazama ash and ends at present. This interval is characterized by a cooler, moister climate, a marked increase in western redcedar (*Thuja plicata*), and a decrease in Douglas-fir and alder.

4.1.5 Freshwater Lakes in Union and Portage Bays

Shallow freshwater environments occupied Union Bay, west Union Bay, and Portage Bay. Evidence shows that water level cycled between deeper (less than 20 feet) water, very shallow water, shallow water, and dry on sandy alluvial surfaces. Boring H-488-10 in west Union Bay shows the best cyclic pattern of deeper to very shallow water based on the diatom work (Figure A-4, Appendix A). Similar patterns of transitions from sphagnum marsh to shallow aquatic environment are observed in the Mercer Slough peat (Leopold, oral communication, March 9, 2011).Very shallow water depths are noted at elevations -32, -22, -12, and 3 feet. These elevations also align with submerged benches north of but continuous with Foster Island and objects like beaver-chewed wood at -22 feet, a forest with rooted trees on a bench at -22 ft (Chrzastowski, 1983), a large range of plant types including those requiring drier conditions at -12 feet, and an increase in shoreline plant types at 3 feet. The amount of wood seen in the peat in Union Bay also suggests near-shore environments. The conditions are ideal in Union Bay for the accumulation of peat and peaty organic silt, units Qp and Qlo. The basin is isolated from the waves of Lake Washington and has sources of freshwater, and a shallow water depth is maintained.

West Union Bay is somewhat different than the rest of Union Bay (see Figure 11 vs. Figure 12, and Figure 3 vs. Figure 4) displaying considerable topographic relief. Mid-depth benches are depicted on the sides of the cross section of west Union Bay, making the basin look as if a graben occupies the middle. Some of the borings are projected onto this cross section and the section is vertically exaggerated making the deep vee look more extreme than its actual geometry.

The benches in west Union Bay are overlain by unit Qal/Ql, most likely deposited by a stream entering the basin from the south side, i.e., Washington Park Creek (inset on Figure 1). The coarse particles in the sand, debris in the sand, lack of ash in the sand, and other evidence at this elevation all lead to this same conclusion. For stream deposits to accumulate at this elevation interval only suggests that the water depth in this part of the bay was very shallow; indeed, pollen and seeds indicate a forested wetland environment at elevation -12 to -15, 5,000 to 6,000 years Cal B.P.

Portage Bay is somewhat different from Union Bay, having no peat (Figure 13). Organic silt accumulated in the freshwater lake, which had shallow to deeper water. Few seeds were found in the organic sediment in boring H-534-10 in Portage Bay (Figure A-6, Appendix A). In the vicinity of SR 520, the environment must have been open water with marsh conditions at the very south end of the bay. Even the diatom concentration is low compared to the other water bodies, consistent with the modern degraded water quality reported by Chrzastowski in 1983.

Prior to the construction of a log chute in the 1800s and the ship canal in 1916, the bays were not connected by surface water. A saddle between the bays parallel and north of present-day SR 520, at its maximum about 50 feet in elevation, was exploited for a log chute in the late 1800s; then the ship canal was constructed further north in 1916. When the ship canal was completed, the lake level in Lake Washington and Union Bay was lowered by 9 feet, exposing the northern part of Foster Island and extensive muddy shorelines.

4.2 History of Water Level Rise in Lake Washington, Union Bay, and Portage Bay

The following summary of water level rise comes from a combination of sources; some of the early dates are from published literature, some are by correlation with volcanic ash, and the remainder is from radiocarbon dating done for this study. Table 2 provides a detailed list of the 49 ages obtained on organic material from lake sediments. This report has already mentioned water levels associated with various depositional environments, but here the focus is strictly on time and elevation by basin.

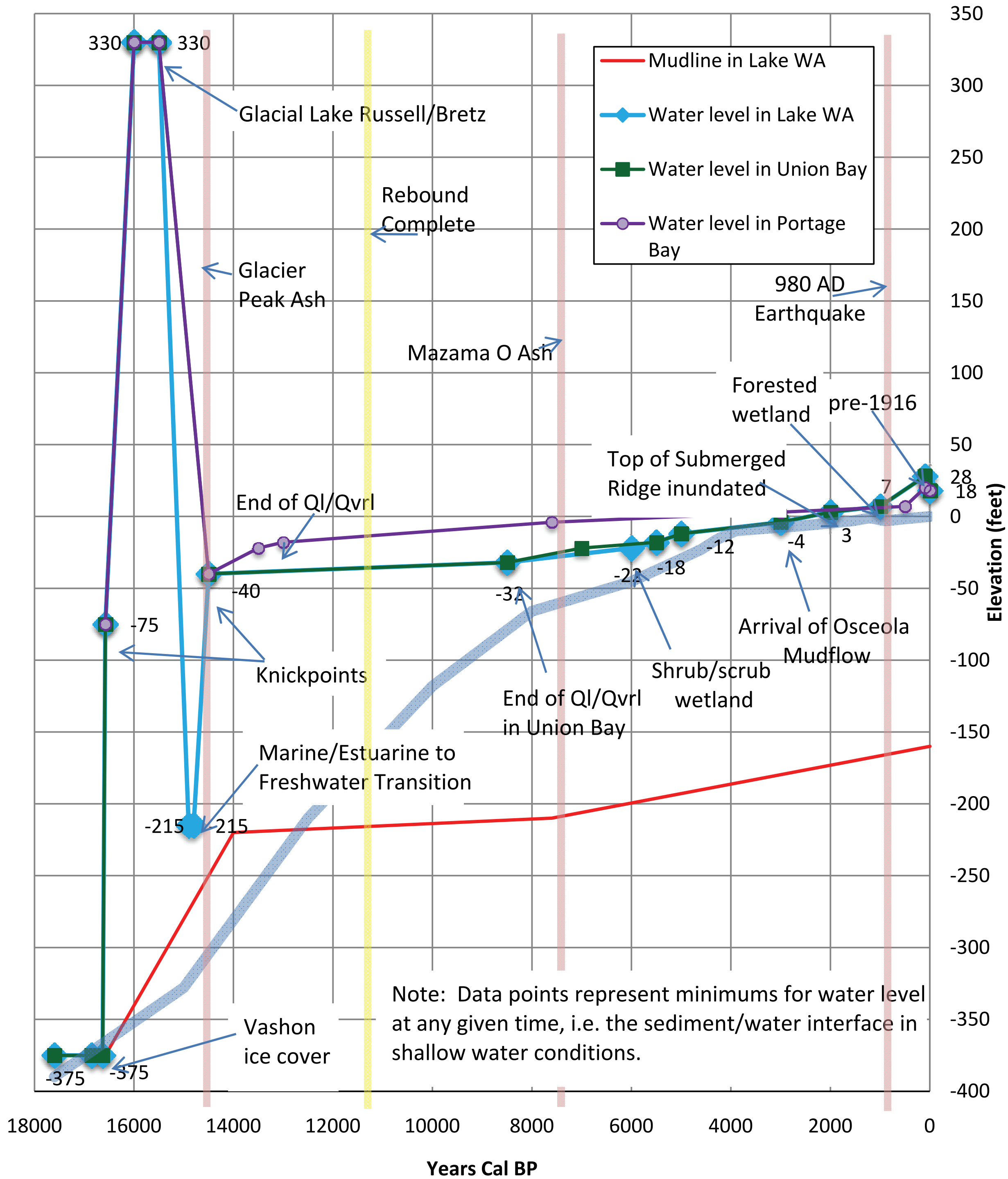


Figure 16. **Submergence Curves for Lake Washington, Union Bay, and Portage Bay**

Figure 16 provides submergence curves for Lake Washington, Union Bay, and Portage Bay. The dates shown on the curves provide water level minimums, since many of these dates are on sediment that would have been at the water/sediment interface at the time of deposition, not at the top of the water. The onset of recessional lakes is shown on the left side of the graph, and the level of Lake Washington today is shown on the right. The initiation of Lake Washington as a freshwater lake started at around 14,800 years Cal B.P. The lake reached a level of -40 feet in elevation at 14,500 years Cal B.P. where a prominent submerged bench is noted around the lake. At an elevation of -22 feet, another prominent submerged bench persists around the sides of the Lake, this one reportedly with submerged remains of forests in growth position (Chrzastowski, 1983). This elevation matches a platform in the submerged ridge north of Foster Island in Union Bay. Lake level rise continued gradually until after 1,000 years Cal B.P., when it quickens, possibly due to land subsidence related to the Seattle fault or changes at the Cedar River fan, allowing the lake to deepen. Finally, the curve shows lake level drop related to the opening of the ship canal in 1916.

Postglacial water level rise in Lake Washington was controlled by the outlet elevation at Renton via the Black River. Initially, the south end of the lake was open to the Kent valley, but as the Cedar River fan developed, a natural dam grew and blocked the south end of Lake Washington. The fan was also drained by the Black River. The fan grew in response to sediment flux, flood deposition, and, in part, base level control imparted by sea level rise. The Cedar River fan aggraded rapidly during the Holocene with an accumulation of 66 feet since 7,900 years Cal B.P. (Mullineaux, 1970). In addition, the Osceola Mudflow added thick sediment (5,700 years Cal B.P., Dragovich and others, 1994) to the Kent/Green River valley to contribute to the blockage, which may not have reached the fan until around 3,000 years ago (Figure 16) based on a slight increase in the rate of water level rise. Contrary to opinions of earlier researchers (Thorson, 1998; Chrzastowski, 1983; and Leopold, 1982a,b), Lake Washington water level rise was not linked to sea level rise until perhaps around 4000 years Cal B.P. (Figure 16).

Local climate may have impacted the submergence curve directly or indirectly. During a moister local climate, rainfall increases, thus providing more water for watersheds and basins. The Lake Washington submergence curve has a low gradient between 14,000 and about 8,000 years Cal B.P., coincident with the fourth pollen zone of Leopold and others (1982a) from 13,000 to 7,600 years Cal B.P. (Figure 16). Perhaps this low gradient is reflective of the drier and warmer climate indicated by the pollen, or perhaps more data would result in a refined curve in this interval of lower data density. When the local climate is moister, after deposition of the Mazama ash (pink line on Figure 16), the submergence curve for Lake Washington and the bays steepens, indicating a deepening of water in the basins.

Although the curves show water level in Lake Washington and Union Bay tracking together, the physical opening between the two is at elevation -22 feet, so when water level in Lake Washington is deep enough to reach -22 feet in elevation, the two water bodies are once again joined. Freshwater lake deposition in Union Bay doesn't begin until around 8,500 years Cal B.P. at elevation -32 feet. The submergence curve for Union Bay is the same as that for Lake Washington between elevations -22 and 18 feet, 6,000 years Cal B.P. to present.

Portage Bay appears to have operated on a different time scale than the combined Union Bay and Lake Washington. Freshwater lake conditions began about 13,000 years Cal B.P. The Portage Bay submergence curve is smoother than for Lake Washington and Union Bay. In Portage Bay, the 7,900 years Cal B.P. Mazama ash is at elevation -4 feet; in Union Bay it is at -30 feet, and in west Union Bay the elevation ranges from -18 to -30 feet. Less sediment accumulated after the Mazama ashfall in Portage Bay than in Union Bay or Lake Washington.

Prior to construction of the ship canal, Lake Washington and Union Bay were 8.9 feet higher than today. Prior to 1902, lake level probably fluctuated as much as 7 feet. Some flood control measures were implemented by 1902, decreasing the fluctuation to 3 to 4 feet (Chrzastowski, 1983).

4.3 Evidence for Former Shorelines

4.3.1 Possible Paleoshorelines

Possible shorelines and paleoshorelines were identified on the basis of morphology, weathering, lithology, age, and depositional environment as determined from microscopy and peat identification. This process yielded 10 possible paleoshorelines, described in Table 7 and shown on Figure 17.

Table 7. Possible Paleoshorelines

Basin	Approx. Elev. (ft)	Approx. Age (yrs Cal B.P.)	Comment	Character	Primary Evidence for Shoreline
Lake Washington	-215	14,900	Estuarine environment. Probable shoreline areas on adjacent higher ground.	Short-lived, more accessible at north and south ends of the lake where slopes aren't as high.	Estuary will have adjacent shorelines.
Lake Washington	-75	16,575	Consistent scour depth for Portage Bay and west Union Bay; correlates with Qvrl-mx deposits on Lake Washington slopes and knickpoint.	Weak, poorly developed.	Correlation between knickpoint and scour depth.
Lake Washington and Union Bay	-40	14,500	Knickpoints on Lake Washington slopes, also observed by sonar methods; bottom of zone of blocky texture in Union Bay; bench in	Strong, longer-lived to allow drying of lake clays and	Knickpoints correlating with blocky texture.

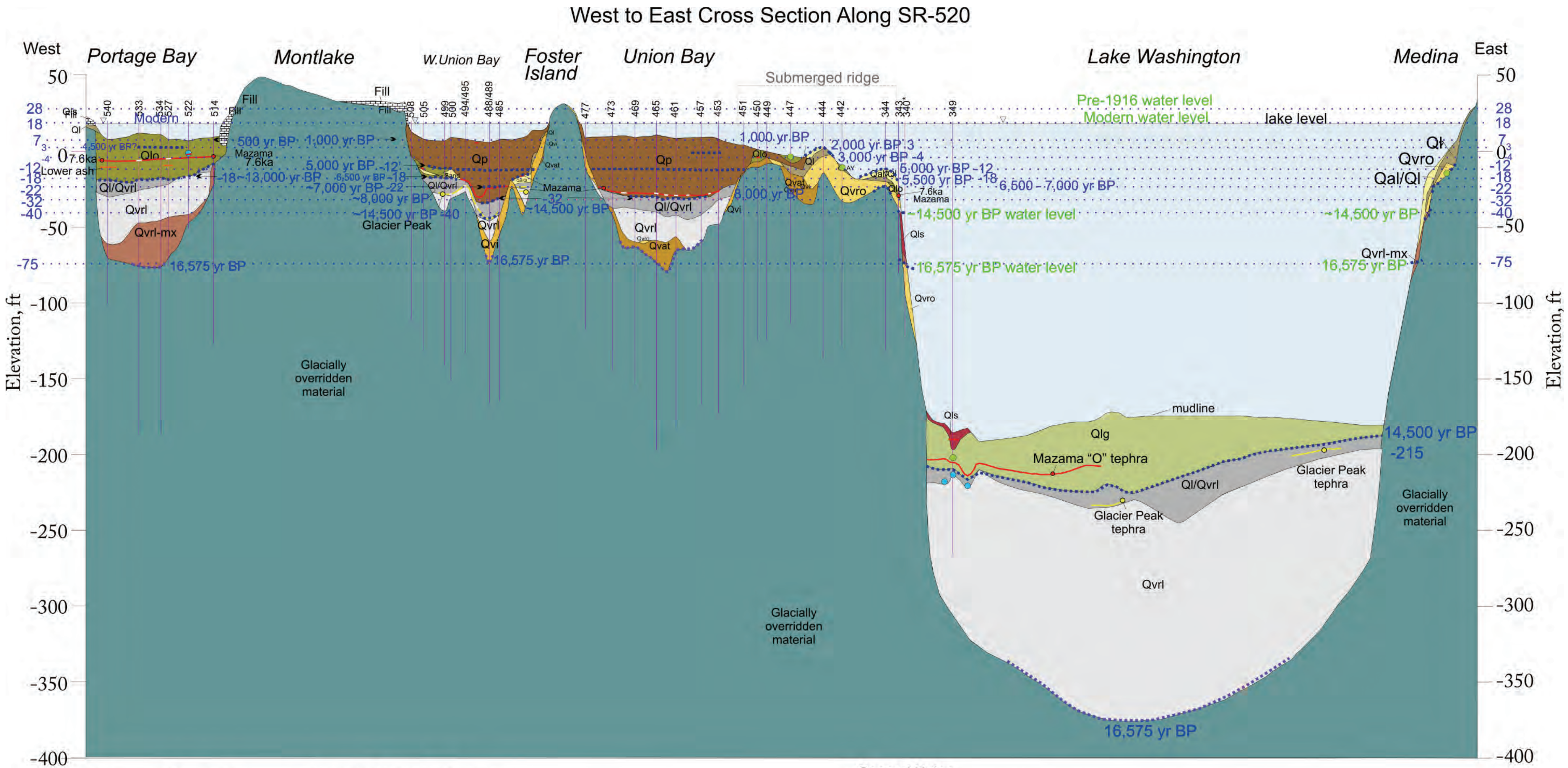
Table 7. Possible Paleoshorelines

Basin	Approx. Elev. (ft)	Approx. Age (yrs Cal B.P.)	Comment	Character	Primary Evidence for Shoreline
			Union Bay.	weathering.	
Union Bay	-32	8,500	Top of zone of blocky texture and oxidation, top of unit Ql/Qvrl, in part; platform in Union Bay.	Strong, longer-lived to allow for weathering and texture development.	Correlation between top of unit Ql/Qvrl, blocky texture, and platform.
Lake Washington and Union Bay	-22	7,000 to 7,600	Pronounced knickpoint on Lake Washington slopes. Outlet elevation between Lake Washington and Union Bay. Aligns with depositional elevation and age of Mazama O ash in west Union Bay. Shrub/scrub wetland conditions in part of west Union Bay. Forests in growth position in the lake. Douglas-fir and maple noted. Platform extending from Foster Island.	Strong, long-lived.	Pronounced knickpoint, platform, and shrub/scrub wetland.
Portage Bay	-18	13,000	Aligns near top of unit Ql/Qvrl.	Moderate to Strong.	Unit Ql/Qvrl is indicative of subaerial exposure.
West Union Bay	-18	6,500	Aligns with top of part of Qal/Ql .	Weak.	Represents the surface of possible alluvial deposits.
Union Bay	-18	5,500	Aligns with unit Ql on outer part of submerged ridge.	Weak.	Lithologic change to overlying alluvial/fluvial deposits.
West Union Bay and Lake Washington	-12	5000	Aligns with unit Ql/Qal in west Union Bay, top of outer part of submerged ridge between Lake Union and Lake Washington, and of both sides of Lake Washington. Pollen and diatoms suggest forested wetland in west Union Bay. Weathered upper surface of GOM. Platform north of Foster Island in Union Bay.	Strong.	Evidence for forested wetland, platform, and weathering.
Union Bay	-4	3,000	Bottom of upper submerged ridge.	Moderate.	Top of peat on west side of ridge.
Union Bay	3	2,000	Top of submerged ridge inundated.	Strong.	Dates, length of time of exposure,

Table 7. Possible Paleoshorelines

Basin	Approx. Elev. (ft)	Approx. Age (yrs Cal B.P.)	Comment	Character	Primary Evidence for Shoreline
					degree of weathering in surficial materials.
The Bays and Lake Washington	7	1,000	Consistent top of organic sediment (units Qlo and Qp) including top of unit Ql on the east side of the lake. Time of Seattle fault and possible drop of 3 feet.	Moderate. Forested wetland indicators.	Consistency in top of units Qp and Qlo.
The Bays and Lake Washington	18	present	Modern shoreline.	Weakly developed, only since 1916.	Visible on ground surface.
The Bays and Lake Washington	25 and 17	980 AD	Submerged shoreline resulting from movement on the Seattle fault. Rims all of the basins.	Important but likely degraded feature.	Occurrence of subsidence.
Union Bay and Lake Washington	28	pre-1916	Top of units Ql and Qp around the shores of Lake Washington and Union Bay. Forms a distinct bench in many areas about 9 feet above modern shoreline.	Strong. Artificially induced.	Visible on ground surface.

The submerged ridge shown on Figures 8 and 10 would have been exposed above water as a peninsula extending north from the Madison Park area during the time period of about 15,500 years Cal B.P. until 2,000 years Cal B.P., with most of it inundated by about 3,000 years Cal B.P. Therefore, this landform appears to be encircled by several paleoshorelines, but they are most apparent on the east side, for example where the bathymetric contours show a relatively flat surface at -12 feet in elevation (Figures 4 and 5).



Horizontal Scale, ft

1000 2000

VE = 20X

Notes for Radiocarbon ages:
Presented in 2 σ calibration range
BP=before present (1950 AD)
ka=thousand years
b-possible contamination and mixing from bioturbation
c-likely contamination with younger material
*-best fit selected from multiple calibrated age ranges, see Table 2 for complete data

General Notes:
1) Refer to Cross section key, Figure 7, for description of geologic units.
2) This cross section presents a geologic interpretation of materials encountered in the borings for the purposes of reconstructing geologic history and analyzing possible shorelines only. Refer to the geotechnical reports by Shannon & Wilson, Inc. for final characterization of borehole materials and project engineering cross sections.
3) 20x vertical exaggeration is used here to accentuate the geologic features and to fit this geographic extent on one piece of paper.
4) Cross section taken along the north side of SR-520, borings are projected perpendicular to the line of the cross section or projected along topographic features to the line of section.
5) Thin lenses and layers are not shown due to the small scale of the cross section.
6) Depth to glacially overridden material in Lake Washington is from a geophysical survey (Lister and others, 1967).

Figure 17. **Cross Section Showing Possible Shoreline Elevations**

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4.3.2 Best Developed Paleoshorelines

Paleoshorelines are present within the proposed SR 520 corridor but are of limited extent, limited by elevation and limited geographically. Some paleoshorelines are more developed than others. Of these, eight paleoshorelines appear to have been either long-lived or particularly well-developed:

- Elevation -40 feet at about 14,500 years Cal B.P. in Lake Washington and Union Bay
- Elevation -32 feet at about 8,500 years Cal B.P. in Union Bay
- Elevation -22 feet at about 7,000 to 7,600 years Cal B.P. in Lake Washington and Union Bay
- Elevation -18 feet at about 13,000 years Cal B.P. in Portage Bay
- Elevation -12 feet at about 5,000 years Cal B.P. in Lake Washington and Union Bay
- Elevation -22 to 3 feet until 2,000 years Cal B.P. on the submerged ridge
- Elevation 25 +/- 4 feet and 17 +/- 4 feet at 980 AD around all of the basins
- Elevation 28 +/- 2 feet at September 1916 around Lake Washington and Union Bay

Elevation -40 aligns with knickpoints on the submerged steep slopes of Lake Washington. These knickpoints occur on relatively steep slopes and appear to be geographically limited to relatively short vertical distances. Although these knickpoints are shown as occurring during the freshwater filling of the lake on Figure 16, they could also have occurred during the draining of the lake with isostatic rebound, so the age of the shoreline features would be about 15,200 years Cal B.P. This second scenario would fit better with the coincidence of the knickpoints and the bottom of the zone of blocky texture seen in units Ql/Qvrl and Qvrl. This elevation, -40 feet, matches a platform in the submerged northern extent of Foster Island. Geographically, the shoreline in Lake Washington appears to be a knickpoint limited to a small area on both sides of the lake. In Union Bay, this shoreline elevation is below the level of the unit Ql/Qvrl deposits except where GOM protrudes above the lake mud at the submerged ridge on the east side of Union Bay and at the northern extension of Foster Island. At these two ridges, at elevation -40 feet, shoreline indicators such as a bench or platform are present at Foster Island and likely present around the ridge. The shoreline in the bay is therefore geographically limited as well.

Elevation -32 aligns with the top of the blocky texture and weathered zone in units Ql/Qvrl and Qvrl in Union Bay at 8,500 years Cal B.P. This lake stand must have been relatively long-lived for these textures to develop. This surface, the top of unit Ql/Qvrl, would be the first hospitable surface in Union Bay. Diatoms, pollen, and seeds indicate very shallow water conditions. A shoreline platform developed at about this elevation on the submerged ridge extending north from Foster Island. Geographically, this -32-foot shoreline is extensive in Union Bay and west Union Bay, matching with the planar surface at the top of the fine-grained lake mud, unit Ql/Qvrl. In addition to shallow water, dry land was available based on subaerial weathering of unit Ql/Qvrl and the platform on the northern extension of Foster Island. This shoreline is not perfectly horizontal at -32 feet in elevation; rather it follows the topographic relief on the top of unit Ql/Qvrl (Figures 11 and 12).

Elevation -22 aligns with part of the depositional elevation of the Mazama ash in west Union Bay and with knickpoints on the slopes of Lake Washington at 7,000 to 7,600 years Cal B.P. One of the knickpoints is the outlet from Ravenna Creek into Lake Washington at the mouth of Union Bay. The presence of the Mazama ash does not indicate a shoreline; however, associated with that feature in west Union Bay are strong indicators of shrub/scrub wetland conditions with a forested edge nearby hosting Douglas-fir and maple trees. Also in Union Bay, a platform at approximately -22 feet in elevation extends north from Foster Island and likely represents a stillstand. These data are strong indicators of a shoreline in Union Bay and west Union Bay following closely the level of the Mazama ash, a non-horizontal planar surface. In Lake Washington, a slope break is present on both sides of the lake with only a few feet of silty deposits on the slope.

Elevation -18 aligns with the top of unit Ql/Qvrl in Portage Bay at 13,000 years Cal B.P. This may be the first hospitable surface in Portage Bay even though it was likely relatively short-lived since the blocky texture and weathering in unit Ql/Qvrl is not well developed there and a date of 12,800 years Cal B.P. was obtained above the contact. This planar shoreline surface has an apparent slope down to the west so that the elevation changes from -10 to -19 feet and corresponds with the top of the glacial lake clay/silt deposit.

Elevation -12 aligns with the alluvial benches in west Union Bay, the top of the outer part of the submerged ridge on the Lake Washington side, a submerged platform extending to the east northeast from Foster Island, and a knickpoint on the inside of the submerged ridge in Union Bay. The alluvial benches in west Union Bay are likely related to deposition from Washington Park Creek and may extend in a deltaic shape from the creek’s mouth, except where disturbed by filling and dredging for the Arboretum. The surface of the bench varies from -15 feet to -12 feet in elevation, just along the line of Figure 12, possibly reflecting the passage of time over the course of more than a thousand years. Seeds, diatoms, and pollen indicate the presence of a forested wetland at about 5,000 years Cal B.P. This is consistent with Thorson’s (1998) findings of a stable delta platform and bar at the north end of Lake Washington. This shoreline is an undulatory surface culminating at about -12 feet in elevation, including the surfaces of the alluvial bench, outer ridge, and platform north of Foster Island.

Elevation -22 to -3 feet aligns with the submerged ridged between Union Bay and Lake Washington. This ridge was exposed for a long period of time, > 5,000 years, long enough to develop a weathered surface. It was inundated gradually as water level rose in Lake Washington and Union Bay from -22 feet to over 3 feet in elevation, the top of the ridge not being covered until only about 2,000 years ago based on adjacent radiocarbon dating. Most of the surface of the ridge is sandy or gravelly, as if enhanced by long-shore drift or simply in situ weathering of glacial coarse-grained material. This shoreline surface is convex as it covers the ridge.

Elevation 25 +/- 4 feet around Lake Washington, Union Bay, and Foster Island, and elevation 17 +/4 feet around Portage Bay relate to possible land level change during the 980 AD Seattle Fault earthquake. If Thorson (1998) is right and submergence on the order of 3 feet did occur north of the Seattle fault, then a feature representing the pre-earthquake shoreline may be present within the study area. This shoreline should be more pronounced than the post-earthquake, pre-1916 shoreline, a younger feature; however inundation of the shoreline, flooding, excavation and filling, and lake level fluctuations may have caused substantial degradation. The pre-earthquake shoreline was not encountered in this study; however, borings at the edge of land were not completed by the time of this study. This shoreline should be a linear bench about 3 feet high encircling the basins

Elevation 28 +/- 2 feet around Lake Washington, Union Bay, and Foster Island represents the pre-1916 shoreline, prior to the lowering of the lake when the ship canal was opened. The shoreline is noticeable as a distinct bench about 9 feet high around the lake. Historical information indicates that this shoreline was used to access the lake for recreation, harvesting, and transportation purposes. This shoreline is obvious as a linear bench around the lake and bay or peaty embayments.

4.4 Sedimentation Rates

The sedimentation rates obtained on the deposits in Lake Washington, Union Bay. and Portage Bay, Table 6, are not internally consistent. Only Portage Bay has rates similar to other Washington peat deposits (Rigg, 1958). For each of the basins, peat accumulation exceeds that of most other bogs in the state; bogs with peat thickness exceeding 50 feet include Mercer Slough (Badger, 2008) and the State Capitol bog (Walsh, 2010). The average thickness of organic sediments in the Puget Lowland is 24 feet, compared to 18.8 feet for areas outside of the lowland but within the Pacific Northwest (Rigg, 1958). The average thickness for peat in the lowland is 24 feet, and for bogs outside of the lowland it is 23 feet (Rigg, 1958).

By comparison to other Washington glacial lakes, silt depositional rates in Lake Washington and the bays are within normal range. For example, the recent sedimentation rate for Lake Whatcom is 2 mm/year, for Baker Lake is 9.9 mm/year, and for Lake Samish is 4.7 mm/year (Paulson, 2004). For peat, which generally grows upward each year, the depositional rate is lower than would be expected if the basal, more decomposed part of the deposit, is included. In several Midwest U.S. bogs, peat accumulation rates average 0.16 mm/year over the last 200 years, a much slower rate than in Union Bay (Wieder and others, 1994), even though it is based on a shorter time scale.

As peat decomposes and as the load on peat increases by further growth, peat at the base of the deposit compacts. This compaction leads to total thickness values for the deposit that are too thin by an amount that is impacted by many variables such as vegetation type, acidity, biogenic factors, and water level changes. Therefore the peat thickness values measured for Union Bay and west Union Bay may be too small and the corresponding sedimentation rates slower than would be expected. The trend of increasing compaction with depth is apparent with the increase in dry density values in Boring H-488-10, from west Union Bay, Appendix A.

5.0 Conclusions

5.1 Portage Bay

Portage Bay was temporarily connected to Union Bay and Lake Washington during occupation by glacial recessional lakes, beginning about 16,630 years Cal B.P. and ending around 15,500 years Cal B.P. Water remained in this basin and fine-grained sediment accumulated until around 13,000 years Cal B.P., much later than for Lake Washington but earlier than Union Bay. The water dried or nearly dried, then very shallow water persisted in the SR 520 area of the basin for a short period of time, followed by shallow water conditions until today. The basins remained disconnected until the log chute was dug in 1860, and then the Lake Washington Ship Canal was opened in 1916.

The top of unit Ql/Qvrl has the most potential as a paleoshoreline based on the degree of weathering in the sediment, diatoms, and type of vegetation. This contact has some relief, varying from elevation -19 feet to elevation -8 feet within the area explored, and dates to 13,000 years Cal B.P.

Other paleoshorelines could be present in the Portage Bay basin, like one related to the 980 AD Seattle fault earthquake, although evidence for this and others was not seen within the resolution of the data. Radiocarbon dates obtained from above the Mazama ash indicate that the upper sediment in the basin may be disturbed or the samples were contaminated with reworked sediment. According to Chrzastowski (1983), Portage Bay all but dried up in the summer, so it is possible that shorelines exist but were not seen within the resolution of the sampling.

5.2 Union Bay

Union Bay was temporarily connected to Portage Bay and Lake Washington during occupation by glacial recessional lakes, beginning about 16,630 years Cal B.P. and ending around 15,500 years Cal B.P. Water remained in this basin and fine-grained sediment accumulated until around 8,000 years Cal B.P., much later than for Lake Washington and Portage Bay. The water then dried, and dry to very shallow water persisted in the SR 520 area of the basin for a short period of time. This initial drying phase was followed by water level cycling between very shallow, shallow, and deeper until today. Portage Bay and Union Bay remained disconnected until the log chute was dug in 1860, and a better connection was made when the ship canal was opened in 1916. Union Bay and Lake Washington were reconnected when the water level in Lake Washington reached -22 feet elevation.

The Union Bay basin has several paleoshorelines because of the repeated episodes of shallowing water and connection to Lake Washington and its stillstands. Starting with the oldest, the surface of unit Ql/Qvrl appears to be a paleoshoreline based on the degree of weathering in the sediment, diatoms, and type of vegetation. This surface is gently concave in Union Bay, generally at elevation -32 feet and dating to 8,000 years Cal B.P.; however, in west Union Bay, the concavity is much more pronounced, ranging from -18 to -34 feet in elevation just along one line of cross section. The next oldest paleoshoreline occurs at elevation -22 feet, corresponding to a knickpoint on the east slope of Lake Washington, and shrub/scrub wetland conditions in west Union Bay, and the re-entry into Union Bay from Lake Washington. Next, a paleoshoreline is likely at elevation -12 to -15 feet in west Union Bay, aligning with the top of unit Qal/Ql with a forested wetland and the top of the outer part of the submerged ridge. At elevation 7 feet, very shallow water indicators point to another likely shoreline. A shoreline related to the Seattle fault event in 980 AD may be present. The pre-1916 shoreline is also obvious about 9 feet above the modern shoreline as a bench encircling Union Bay.

5.3 Submerged Ridge

A submerged ridge extends 750 feet into Union Bay, forming the outer limit of and separating Union Bay from Lake Washington. The sediment at the surface of the ridge is weathered, indicating that it was exposed subaerially for over 5,000 years, more than long enough to develop a weathering profile. The ridge was gradually inundated as the water level rose in both Lake Washington and Union Bay. Around 5,500 years Cal B.P. water level was near the base of the ridge at -18 feet, and as the water level rose, it inundated the top of the ridge around 2,000 years Cal B.P. at elevation 3 feet.

5.4 Lake Washington

Lake Washington was temporarily connected to Union Bay and Portage Bay during occupation by glacial recessional lakes, beginning about 16,630 years Cal B.P. and ending around 15,500 years Cal B.P., when the glacial lakes drained. Some water remained in this basin and fine-grained sediment was accumulating when a short-lived marine incursion occurred with an associated estuary about 14,800 years Cal B.P. The land rebounded, marine water drained from the lake basin, all water nearly drained, then freshwater filled the basin and has persisted as deep water until today. Lake Washington reconnected to Union Bay once the depth of the water reached and exceeded an elevation of -22 feet. When the ship canal was opened in 1916, the level of Lake Washington was lowered by about 9 feet.

The opportunities for paleoshorelines in Lake Washington are limited along the SR 520 alignment. A possible shoreline exists at the top of unit Ql/Qvrl. A knickpoint at elevation -75 feet on the sides of Lake Washington likely also correlates with the scour depth of Union Bay and Portage Bay. A more prominent knickpoint occurs at elevation -40 feet on the sides of the lake, corresponding with the bottom of a blocky zone in the lake clays and detectible on side-scan sonar. Another pronounced knickpoint occurs at elevation -22 feet on the sides of the lake, particularly at the connection between Union Bay and Lake Washington. Granular deposits are present at this elevation on the east side of the lake, but the drilling was complete before this study began, so no samples were analyzed in that area. The last submerged prominent knickpoint occurs at elevation 7 feet and may correspond to the lake sediment surface prior to subsidence from the Seattle fault earthquake at 980 AD, about 1,100 years ago. A shoreline related to the Seattle fault event in 980 AD may be present. The pre-1916 shoreline is also obvious about 10 feet above the modern shoreline as a bench encircling the lake.

5.5 Additional Conclusions

- The top of unit Ql/Qvrl in each basin correlates to a time of weathering and possibly even dry conditions. In Lake Washington this occurs at elevation -215 feet and at 14,800 years Cal B.P., in Union Bay at an elevation of -32 feet at 8,500 years Cal B.P., in west Union Bay at an elevation ranging from -22 to -40 feet at 7,600 to 14,500 years Cal B.P., and in Portage Bay at an elevation of -18 feet at 13,000 years Cal B.P. These are the first possible shorelines and first possible hospitable surfaces following the Vashon glaciation.
- The submerged ridge partly separating Union Bay from Lake Washington is weathered at its surface and was subaerially exposed from 15,500 until 2,000 years Cal B.P. This peninsula projects into the lake with a peaty lake bottom to the west and sandy bottom to the east and would have looked like a smaller version of Foster Island.
- Good age control, botanical information, radiocarbon dates, and ash bed correlation led to well constrained submergence curves for Lake Washington and Union Bay. Portage Bay is less well constrained.
- Sedimentation rates for silt and peat in Lake Washington and the bays are typical of lakes and bogs in Western Washington. However, values from other basins are not based on the 13,000-year history available for measurement in this study.
- Lake level rise fluctuated, but generally rose steadily until about 1,000 years ago. The submergence curve then rises rapidly, perhaps reflecting a land subsidence event associated with the Seattle fault.
- Seed and diatom data indicate a moving shoreline and/or minor fluctuations in water depth in Union Bay.
- Lake Washington sediment shows evidence for subaqueous slides, storm deposits, turbidite deposits possibly from earthquakes, evidence of the 980 AD event, and disturbance from the water level lowering in 1916.

- Although the data evaluated provide ample information to draw conclusions about shorelines and submergence, data gaps exist that may affect these interpretations and conclusions.

6.0 Limitations and Biases

Many factors impact the interpretations and conclusions of this report.

The most significant bias is that of data gaps:

- Fewer borings were sampled than proposed, and in many of the continuously sampled borings some depth intervals were not examined since some of the Shelby tube samples were not extruded before this report was written. Some of these tubes are in known intervals where ash layers are expected.
- In some of the borings advanced in peat, recovery was poor, creating significant data gaps.
- Fewer borings and samples were available from Portage Bay than in other basins.
- In light of these data gaps, the conclusions presented herein should be considered provisional until additional information from Shannon & Wilson is reviewed.

Another significant bias and limitation is that of representativeness:

- In marshes, seeds are assumed to be representative of the vegetation where they fall; however, geologic processes can disturb the sediment and thus the seeds. Interpretations based on seed data alone should be considered tentative.
- Some conclusions are based on the appearance and recognition of biological materials (i.e., seeds, diatoms, shells) in samples. The apparent absence of these indicators can significantly influence conclusions. Many natural factors beyond the control of this study affect the deposition, preservation, and representative nature of such materials. The conclusions presented herein assume that representative biological and geological materials were sampled.
- Some of the data presented on the Summary Boring Logs is based on preliminary information from Shannon & Wilson. Final geotechnical boring logs will be presented by Shannon & Wilson.
- Corrections for peat compaction were not incorporated into thickness measurements.
- Mixing of sediment from lake level fluctuations, waves, biogenic sources, and dynamic geologic processes can cause contamination. Evidence of this type of contamination with the seeds, such as redepositing younger seeds in older sediment or redepositing older seeds in younger sediment, was not identified. Mixing of sediments did, however, occur, particularly in Portage Bay as evidenced by the radiocarbon results. Mixing in any of the basins may have contributed to the absence of certain layers and impacted the recognition of paleoshorelines.

- Boring locations and hence sampling locations for this study were limited to those already selected for the geotechnical engineering study. Conclusions assume these locations provide representative sampling.
- Construction related to the development of the Washington Park Arboretum and SR 520, particularly, changed the natural stratification around Foster Island, south Union Bay, and west Union Bay.

Standard limitations of liability apply:

- The interpretations presented on the cross sections are based on sound geological principles and a limited snapshot of data; actual conditions are known to vary and are expected to vary.
- The conclusions presented herein are those of TGC and are intended solely for use by Parametrix and WSDOT for the SR 520 Bridge Replacement and HOV Program in the defined study area. This report is intended to address water level rise and potential paleoshorelines and should not be used or relied upon for other purposes.

7.0 References

Abella, S.E.B. 1982. Studies on diatoms in the sediments of two lakes in the state of Washington. Master's thesis. University of Washington, Seattle, Washington.

Abella, S.E.B. 1986. Diatom Analysis of the Postglacial Sediments of Lake Washington. American Quaternary Association, Biennial Meeting, Program and Abstracts, p. 110.

Abella, S.E.B. 1988. The effect of the Mt. Mazama ashfall on the planktonic diatom community of Lake Washington. *Limnology and Oceanography*, Vol. 33, No. 6, pp. 1376-1385.

Atwater, B.F., and Moore, A.L. 1992. A tsunami about 1000 years ago in Puget Sound, Washington. *Science*, Vol. 258, pp. 1614-1617.

Badger, T. 2008. Peat flow in Mercer Slough, Lake Washington. *In* Baum, R.L, Godt, J.W., and Highland, L.M., eds., *Landslides and Engineering Geology of the Seattle, Washington, Area*. Geological Society of America Reviews in Engineering Geology, Vol. XX, pp. 153-166.

Beale, H. 1990. Relative Rise in Sea-Level during the Past 5000 Years at Six Salt Marshes in Northern Puget Sound, Washington. Washington Department of Ecology, Olympia, WA.

Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y. 2002. Location, structure, and seismicity of the Seattle fault zone, Washington: Evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data. *Geological Society of America Bulletin*, Vol. 114, pp. 169-177.

Blukis Onat, A.R., and Kiers, R.A. 2007. Ethnohistoric and Geoarchaeological Study of the SR 520 Corridor and Archaeological Field Investigations in the SR 520 Bridge Replacement and HOV Project Including the Pacific Interchange and Second Montlake Bridge Option. King County, Washington. BOAS, Inc. June 2007.

Blukis Onat, A.R., Kiers, R.A., and LeTourneau, P.D. [BOAS]. 2005. Preliminary Ethnographic and Geoarchaeological Study of the SR 520 Bridge Replacement and HOV Project. Report on file, Washington Department of Transportation, Seattle, WA.

Booth, D.B. 1987. Timing and processes of deglaciation along the southern margin of the Cordilleran ice sheet. *In* Ruddimann, W.F., and Wright, H.E., Jr., eds., *North America and Adjacent Oceans during the Last Deglaciation*. Boulder, Colorado, Geological Society of America, Geology of North America, Vol. K-3, pp. 71-90.

Booth, D.B. 1994. Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation. *Geology*, Vol. 22, pp. 695-698.

Booth, D.B., Troost, K.G., Clague, J.J., and Waitt, R.B. 2004. The Cordilleran Ice Sheet. Chapter 2 *in* Gillespie, A., Porter, S.C., and Atwater, B., eds., *The Quaternary Period in the United States*. International Union for Quaternary Research, Elsevier Press, pp. 17-43.

Borchardt, G.A., Aruscava, P.J., and Millard, H.T. 1972. Correlation of the Bishop ash, a Pleistocene marker bed, using instrumental neutron activation analysis. *Journal of Sedimentary Research*, Vol. 42, No. 2, pp. 301-306. DOI: 10.1306/74D72527-2B21-11D7-8648000102C1865D.

Chrzastowski, M.J. 1983. Historical changes to Lake Washington and route of the Lake Washington Ship Canal, King County, Washington. U.S. Geological Survey Water-Resources Investigations Report 81-1182, 9 p., 1 sheet, scale 1:24,000.

Clague, J.J., and James, T.S. 2002. History and isostatic effects of the last ice sheet in southern British Columbia. *Quaternary Science Reviews*, Vol. 21, pp. 71-87.

Counts, C.L., III. 1986. The zoogeography and history of the invasion of the United States by *Corbicula fluminea* (Bivalvia: Corbiculidae). *American Malacological Bulletin*, Special Edition No. 2:7-39.

Dethier, D.P., Pessl, F., Jr., Keuler, R.F., Balzarini, M.A., and Pevear, D.R. 1995. Late Wisconsinan glaciomarine deposition and isostatic rebound, northern Puget Lowland, Washington. *Geological Society of America: Bulletin*, Vol. 107, No. 11, pp. 1288-1303.

Dragovich, J.D., Pringle, P.T., and Walsh, T.J. 1994. Extent and geometry of the mid-Holocene Osceola Mudflow in the Puget lowland - Implications for Holocene sedimentation and paleogeography. *Washington Geology*, Vol. 22, No. 3, pp. 3-26.

Edmondson, W.T. 1975. Microstratification of Lake Washington sediments. *Journal of Limnology*, Vol. 19, pp. 770-775.

Friele, P.A., and Hutchinson, I. 1993. Holocene sea-level change on the central west coast of Vancouver Island, British Columbia. *Canadian Journal of Earth Sciences*, Vol. 30, No. 4, pp. 832-840.

Fryxell, R., and Loope, W.L. 1965. Mazama and Glacier Peak volcanic ash layers: Relative ages. *Science*, Vol. 147, No. 3663, pp. 1288-90.

Galster, R.W., and Laprade, W.T. 1991. Geology of Seattle, Washington, United States of America. *Bulletin of the Association of Engineering Geologists*, Vol. 28, pp. 239-302.

Golder Associates. 2003. SR 520 Lake Washington Floating Bridge Marine Geophysical Investigation for Washington State Department of Transportation.

Gould, H.R., and Budinger, T.F. 1961. Control of Sedimentation and Bottom Configuration by Convection Currents, Lake Washington, Washington. Department of Oceanography, University of Washington, Seattle, Washington.

Gould, H.R., Budinger, T.F., and Ragan, D.M. 1956. Bathymetry and postglacial sediments of Lake Washington [abs.]. *Geological Society of America Bulletin*, Vol. 67, No. 12, part 2, pp. 1767-1768.

Haugerud, R. A., 2009, Deglaciation of the southern Salish lowland [abstract]. In Northwest Scientific Association, The Pacific Northwest in a changing environment—Northwest Scientific Association 81st annual meeting; Program with abstracts: Northwest Scientific Association, p. 27-28.

Henderson, R.E., and Doiron, R. 1982. Some identification hints for field classification of peat. *In* H.W. Rees (comp.), *Proceedings of the Organic Soils Mapping and Interpretations Workshop.* Land Resource Research Institute, Contribution 82-44, Agriculture Canada, pp. 105-110.

Hodges, C. 2010. SR-520, I-5 to Medina: Bridge Replacement and HOV Project Supplemental Draft EIS, Draft Geomorphic Investigations at Foster Island. Technical Memorandum. Report on file at WSDOT, Seattle, Washington.

ICF Jones & Stokes. 2010. SR 520, I-5 to Medina: Bridge Replacement and HOV Project, Draft Foster Island Archaeological Inventory Report: Phase 1. Report on file at WSDOT, Seattle, Washington.

Jacoby, G.C., Williams, P.L., and Buckley, B.M. 1990. Timing and distribution of landslides in Lake Washington, Seattle: Geohazards of possible seismic origin [abs.]. *Eos* (American Geophysical Union Transactions), Vol. 71, No. 43, p. 1560.

Johnson, S.Y., Dadisman, C.V., Childs, J.R., and Stanley, W.D. 1999. Active tectonics of the Seattle fault and central Puget Sound, Washington—implications for earthquake hazards. *Geological Society of America Bulletin*, Vol. 111, No. 7, pp. 1042-1053.

Jones, M. A. 1996. Thickness of unconsolidated deposits in the Puget Sound Lowland, Washington and British Columbia. U. S. Geological Survey Water-Resources Investigations Report 94-4133, scale 1:455,000.

Karlin, R.E., and Abella, S.E.B. 1992. Paleoearthquakes in the Puget Sound region recorded in sediments from Lake Washington, U.S.A. *Science,* Vol. 258, p. 5088.

Karlin, R.E., and Abella, S.E.B. 1996. A history of Pacific Northwest earthquakes recorded in Holocene sediments from Lake Washington. *Journal of Geophysical Research*, Vol. 101, No. B3, pp. 6137-6150.

Karlin, R.E., Holmes, M., Abella, S.E.B., and Sylwester, R. 2004. Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington. *Geological Society of America Bulletin*, Vol. 116 (1/2).

Kittleman, L.R. 1973. Mineralogy, correlation, and grain-size distributions of Mazama tephra and other postglacial pyroclastic layers, Pacific Northwest. *Geological Society of America Bulletin*, Vol. 84, pp. 2957-2980.

Leopold, E.B. , March 9, 2011. Oral communication.

Leopold, E.B., and Newman, D.E. 1986. Significance of Lake Washington to postglacial rise in sea level. *American Quaternary Association*, Biennial Meeting, Program and Abstracts, p. 146.

Leopold, E.B., Nickman, R., Hedges, J.I., and Ertel, J. 1982a. Pollen and lignin records of late Quaternary vegetation, Lake Washington. *Science*, Vol. 218, No. 4579, pp. 1305-1307.

Leopold, E.B., Nickman, R., and Stuiver, M. 1982b. An early marine phase of Lake Washington, Seattle, Washington. *American Quaternary Association Abstracts 7*, p. 121.

Liberty, L.M., and Pratt, T.L., 2008. Structure of the eastern Seattle fault zone, Washington State: new insights from seismic reflection data. *Bulletin of the Seismological Society of America*, Vol. 98, No. 4, pp. 1681-1695.

Lister, C.R.B., Whetten, J.T., and McKee, B. 1967. Sonar reflection profiling on the Columbia River and in Lake Washington. *Northwest Science*, Vol. 41, No. 4, pp. 152-154.

McKee, K.L., and Faulkner P.L. 2000. Mangrove peat analysis and reconstruction of vegetation history at the Pelican Cays, Belize. *Atoll Research Bulletin*, No. 468, pp. 45-58.

McManus, D.A. 1963. Postglacial Sediments in Union Bay, Lake Washington, Seattle, Washington. Department of Oceanography, University of Washington, Seattle, Washington.

Miller, J., and Blukis Onat, A.R. 2004. Winds, Waterways, and Weirs: Ethnographic Study of the Central Link Light Rail Corridor. BOAS, Seattle, Washington.

Mullineaux, D.R., 1967. Gross Composition of Pleistocene Clays in Seattle, Washington. U.S. Geological Survey Professional Paper 575B, pp. B69-B76.

Mullineaux, D.R. 1970. Geology of the Auburn, Renton, and Black Diamond Quadrangles, King County, Washington. U.S. Geological Survey Professional Paper 672.

Nesbitt, E.A. 2010. Written communication to K. Troost on November 30, 2010.

Paulson, A.J. 2004. Sources of Mercury in Sediments, Water, and Fish, of the Lakes of Whatcom County, Washington. U.S. Geological Survey Scientific Investigations Report 2004-5084.

Porter, S.C., and Swanson, T.W. 1998. Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation. *Quaternary Research*, Vol. 50, pp. 205-213.

Powers, H.A., and Wilcox, R.E. 1964. Volcanic ash from Mount Mazama (Crater Lake) and from Glacier Peak. *Science*, Vol. 144, No. 3624, pp. 1334-1336.

Pratt, T.L., and Troost, K.G. 2008. Is Downtown Seattle on the Hanging Wall of the Seattle Fault? *EOS* Trans., American Geophysical Union 89 (53), 2008 Fall Meeting Supplement, San Francisco.

Randle, K., Goles, G.G., and Kittleman, L.R. 1971. Geochemical and petrological characterization of ash samples from Cascade range volcanoes. *Quaternary Research*, Vol. 1, pp. 261-282.

Rigg, G.B. 1958. Peat Resources of Washington. Bulletin 44. Washington State Department of Natural Resources, Olympia, Washington. http://www.dnr.wa.gov/ResearchScience/Pages/PubReports.aspx.

Rigg, G.B., and Gessel, S.P. 1956. Peat Deposits of the State of Washington. *Soil Science Society of America*, Vol. 20, No. 4, pp. 566-570.

Rigg, G.B., and Gould, H.R. 1957. Age of Glacier Peak eruption and chronology of postglacial peat deposits in Washington and surrounding areas. *American Journal of Science*, Vol. 255, pp. 341-363.

Scheffer, V.B., and Robinson, R.J. 1939. A limnological study of Lake Washington. *Ecological Monographs*, Vol. 9, No. 1, pp. 95-143.

Shannon & Wilson, Inc. 2006. Existing Geotechnical Data Report. Prepared for Washington State Department of Transportation. Vol. 1-8.

Shannon & Wilson, Inc. 2011a. Geotechnical Report Addendum Floating Bridge Anchors. Prepared for Washington State Department of Transportation.

Shannon & Wilson, Inc. 2011b. Written communication, July 13, 2011.

Sherrod, B.L. 2002. Late Quaternary surface rupture along the Seattle fault zone near Bellevue, Washington. *EOS* (Transactions, American Geophysical Union), Vol. 83 (47), abstract S21C-12.

Sherrod, B.L. 2005. Prehistoric earthquakes in the Puget Lowland, Washington. *EOS* (Transactions, American Geophysical Union), Fall Meeting abstract S54A-05.

Sherrod, B.L., Haeussler, P.J., Wells, R., Troost, K., and Haugerud, R. 2001. Surface rupture in the Seattle fault zone near Bellevue, Washington. *Seismological Research Letters*, Vol. 72, No. 2, p. 253.

Steen, V.C., and Fryxell, R. 1965. Mazama and Glacier Peak pumice glass: Uniformity of refractive index after weathering. *Science*, Vol. 150, No. 3698, pp. 878-880.

Stephenson, W.J., Frankel, A.D., Williams, R.A., Odum, J.K., and Pratt, T.L. 2007. Seismic imaging of the Seattle fault zone at West Seattle and Mercer Island, Washington: Implications for earthquake hazards. *Seismological Research Letters,* Vol. 78, p. 280.

Talma, A.S., and Vogel, J.C. 1993. A simplified approach to calibrating C14 dates. *Radiocarbon*, Vol. 35, No. 2, pp. 317-322.

Thorson, R.M. 1989. Glacio-isostatic response of the Puget Sound area, Washington. *Geological Society of America Bulletin*, Vol. 101, pp. 1163-1174.

Thorson, R.M. 1998. Neotectonics and shoreline change, Sammamish Delta, Lake Washington. Final Report Project 1434-HG-97-GR-03057. University of Connecticut, Storrs, Connecticut.

Troost, K.G. 2007. Jökulhlaups from Glacial Lake Puyallup, Pierce County, Washington. Paper No. 6-11, Geological Society of America, Abstracts with Programs, Cordilleran Section Meeting, Bellingham, Washington, May 2007.

Troost, K.G., and Booth, D.B., 2008. Geology of Seattle and the Seattle area. *In* Baum, R.L, Godt, J.W., and Highland, L.M., eds., *Landslides and Engineering Geology of the Seattle, Washington, Area*, Geological Society of America Reviews in Engineering Geology, Vol. XX, pp. 1-35, 2 plates.

Troost, K.G., Booth, D.B., Wisher, A.P., and Shimel, S.A. 2005. The Geologic Map of Seattle, a Progress Report. U.S. Geological Survey, Open-file report 2005-1252, scale 1:24,000.

Troost, K.G., and Stein, J. 1995. GeoArchaeology of West Point. *In* Larson, L.L., and Lewarch, D.E., eds., *The Archaeology of West Point, Seattle, Washington: 4,000 Years of Hunter-Fisher-Gatherer Land Use in Southern Puget Sound*, Volumes 1-2. Larson Anthropological/ Archaeological Services.

Von Post, L. 1992. Sveriges Geologiska Undersoknings Torvinventering Och Nagre av Dess Hittills Vunna Resultat, Sr. Mosskulturfor. *Tidskr*, 1, pp. 1–27.

Walsh, T.J., 2010. Oral Communication. March 15, 2010.

Wasylikowa, K. 1986. Analysis of fossil fruits and seeds. *In* Berglund, B.E., ed., *Handbook of Holocene Palaeoecology and Palaeohydrology.* The Blackburn Press, New Jersey, pp. 571-590.

Wieder, R.K., Novak, M., Schell, W.R., and Rhodes, T. 1994. Rates of peat accumulation over the past 200 years in five *Sphagnum*-dominated peatlands in the United States. *Journal of Paleolimnology*, Vol. 12, pp. 35-47.

Williams, P.L., Jacoby, G.C., and Buckley, B. 1992. Coincident ages of large landslides in Seattle's Lake Washington. *Geological Society of America*, Abstract Program, Vol. 24, No. 5, p. 90.

Zehfuss, P.H. 2005. Distal Records of Sandy Holocene Lahars from Mount Rainier, Washington [Ph.D. thesis]. University of Washington, Seattle, Washington.

8.0 Glossary

accelerated mass spectrometry (AMS) - a high-precision means of carbon-14 dating that involves accelerating the ions to extraordinarily high kinetic energies before mass analysis; can be used on very small samples.

aliquot - a portion of a larger whole, especially a sample taken for some kind of analysis or other treatment.

assemblage – group of items that serves as an indicator of the presence of a larger group, for example the presence of the Western Redcedar-Alder-with some Douglas Fir pollen assemblage indicates that some bracken fern, western hemlock, and pine are present as well and that the climate is likely warm and moist.

Atterberg Limits – this is one of the basic index property tests and is the primary form of classification for cohesive soil and fine-grained soil like clay, clayey silt, and organic soils. This test helps to determine soil strength and settlement characteristics and determines the state of the soil along a continuum from non-plastic to viscous fluid.

bioturbation – the displacement and mixing of sediment particles by fauna or flora.

calibrated – adjusted, corrected, or determined by comparison with a standard.

diatom – as a microfossil in sediment, diatoms are the siliceous cell structure of algae; as a living organism, diatoms are a common type of phytoplankton.

diatom assemblage – a small group of diatoms that when found together indicate a particular environmental setting such as shallow marine or deep water.

diatomaceous ooze – sediment consisting predominantly of diatoms.

dry density - a measurement of the dry unit weight of the solids in a sample; unit weight equals the ratio of the dry weight of the solids to the total volume.

drumlin - an elongated hill or ridge formed by glacial ice and/or subglacial water acting on underlying till or substrate. The long axis parallels the direction of ice flow.

elytra - modified, hardened forewings of certain insects.

embayment - a recess or indentation in a coastline forming a bay; larger than a cove, smaller than a gulf.

fossil - the preserved remains or traces of animals, plants, and other organisms from the past; for this report, fossils can be as young as the peat in Union Bay.

fibrous peat – peat whose predominant constituent is fibrous material, such as roots, stems, leaves, and reeds.

geomorphic position – position on the landscape such as the side or top of a drumlin, the bottom of a valley, the flat surface of a river terrace, or a shoreline bench.

granular - consisting of or appearing to consist of granules; containing sand, gravel, or some other material providing grit.

granular peat – essentially amorphous peat; most of the water is in an adsorbed state rather than as free water due to high colloidal content; also non-woody and non-fibrous, may have very small particles of plant debris.

graben – a block of land bordered by faults producing a valley with a distinct scarp on each side.

gyttja – sediment consisting of diatoms and fine organic matter.

humic acid - a complex mixture of many different acids produced by the biodegradation of dead organic matter; also a principal component of humic substances.

humification - the process of biochemical decomposition; transformation of organic matter into humus.

humus – the stable, long-lasting product of decayed and humified organic matter; no further natural breakdown will occur.

index of refraction – the measure of the speed of light in a substance; the ratio of the speed of light in a vacuum to the speed of light in a substance under consideration; effectively, a measure of the extent to which a substance slows down light waves passing through it. Different materials have different refractive indices.

index property testing – a series of geotechnical tests that help to classify soil and determine basic properties such as moisture content, unit weight, grain size, and Atterberg Limits. The results of the testing help to determine soil behavior, strength, and compressibility.

isostatic loading and rebound – the process of land mass and crustal depression due to the weight of a glacier and the subsequent uplift of the land and crust as the glacier retreats. In the Seattle area, isostatic loading depressed the land about 230 feet.

kettle – a steep, bowl-shaped depression left after a block of glacial ice melts in place. Locally, kettles are filled with sediment and peat and some with water. Green Lake is a local example.

knickpoints – a location where there is a sharp change in slope resulting from differential rates of erosion above or below the knickpoint.

lithics – consisting of, or relating to, rock; any size fragments of rock.

lithologic setting – an environment that is conducive to the accumulation of a particular soil type, such as a muddy lake bottom, gravelly river bank, or sandy beach.

macrofossil – preserved organic remains large enough to be visible without a microscope.

microfossil – preserved organic remains so small that a microscope or other type of magnification is needed to see it.

mollusca – aka mollusc or mollusks, a large phylum (group similar to a division) of invertebrate animals comprising about 23% of all the named marine organisms; contains snails and clams.

muck – highly to completely decomposed remains of plant material and other organisms.

paleosol - a buried, preserved soil horizon.

paleolimnology - the study of past environments of inland waters.

paleoshorelines – former shorelines that are permanently abandoned.

peat – a concentration of decaying or partly decayed plant matter.

porifera – phylum of invertebrate animals containing sponges.

radiocarbon dating - a dating method that uses the naturally occurring radioisotope carbon-14 to estimate the age of carbon-bearing materials.

reservoir effect – distortions in the radiocarbon age due to samples having been exposed to or that grew in water bodies with different carbon-14 than in the atmosphere.

rhizome - a characteristically horizontal stem of a plant that is usually found underground, often sending out roots and shoots from its nodes to start new plants; ginger root is a good example.

samara – winged seed from a maple tree; usually comes in pairs.

sedimentary peat – similar to granular peat except that this peat type forms in deeper water and the matrix is fine-grained such that individual plant remains are not distinguishable.

sponge spicules – microscopic spikes that are part of the endoskeletal structure of many sponges; made of either calcium carbonate or silica. In fresh water sponges, the spicules are typically made of silica.

stratigraphic position – describes a place/layer within an ordered stack of geologic strata.

stillstand – time when a moving entity stops temporarily, for example when a lake fills to a certain depth then stops for a significant length of time or when an advancing glacier stops advancing and holds its position for a length of time. Usually accompanied by some indicator, physical or biological.

tephra – volcanic ash; usually occurs in layers.

tubers - various types of modified plant structures, usually oblong or rounded, that are enlarged to store nutrients for plant survival; a potato is an example of a tuber.

turbidite deposits – deposits from a subaqueous (underwater) density flow that form a sequence of fining upward layers with specific structures, starting with coarse grained-units like gravelly sand and ending with laminated clay.

vivianite – a secondary iron phosphate mineral; usually found as white prismatic to flattened crystals that look almost fuzzy without magnification; oxidizes to a blue or deep bluish green color when exposed; replaces organic matter.

worm burrows – tunnels left by worms or worm-like animals as they burrow into sediment while feeding or moving; the burrows are filled with host material plus secretions and often cause mixing of sediment.

Geomorphology and Shoreline History

of Lake Washington, Union Bay and Portage Bay

Appendix A

Geologic Summary Logs

Appendix A

Geologic Summary Logs

Table of Contents

Notes:
1-Lithologic descriptions and USCS (Unified Soil Classification System) based on TGC field observations and preliminary boring log information from Shannon & Wilson, Inc.(S&W, 2011b). See S&W geotechnical reports for the official engineering log of this boring. Refer to cross section key for description of geologic units, here listed as symbols (i.e. Qlg).
2-Visual estimate of percent diatoms present by volume. Determined using sediment slide mounts under 80 times magnification.
3-Degree of humification based on manual squeeze test per ASTM D5715-00. Sample tested immediately upon retrieval.
4-Peat classification based on visual estimate of fine and coarse plant matter and identification of plant type.
5-Organic Content and Dry Density values measured by S&W.
6-Calibrated radiocarbon age, thousands of years BP, range of 2 sigma values. Refer to Table 2 radiocarbon results for more information. "C" indicates probable contamination. * indicates multiple ranges of values.
7-Raw count of seed types present in organic samples.
8-Interpretation of water depth from diatom counts and identifications from individual samples.
9-Interpretation of depositional environment from all of the available indicators.
10-amsl=above mean sea level
11-Depth of water was determined by tagging the lake bottom with a weighted cloth tape measure. Lake bottom (mudline) was often difficult to "sense" with this method due to soft nature of bottom sediment. Therefore mudline elevation, which is based on water depth, is approximate.

Definitions:
Alnus rubra = Red alder
Arbutus = madrone
Carex = sedges
Cerastium = chickweed
Corylopsis = winter hazel
Ericaceae = heath family
E. Gaultheria shallon = salal
Menyanthes = buckbean
Pseudotsuga = Douglas fir
Rosaceae = rose family
Scirpus = bulrush
Thuja = Arborvitae
Thuja plicata = Western Redcedar
Typha = cattail
Umbelliferae/Apiaceae = water parsley family
"grassy" = any blades or narrow leaves

TABLE 1 Determination of Degree of Humification or Decomposition

Degree of Humification	Nature of Material Extruded on Squeezing	Nature of Plant Structure in Residue
H1	Clear, colorless water; no organic solids squeezed out	Unaltered, fibrous, undecomposed
H2	Yellowish water; no organic solids squeezed out	Almost unaltered, fibrous
H3	Brown, turbid water; no organic solids squeezed out	Easily identifiable
H4	Dark brown, turbid water; no organic solids squeezed out	Visibly altered but identifiable
H5	Turbid water and some organic solids squeezed out	Recognizable but vague, difficult to identify
H6	Turbid water; ⅓ of sample squeezed out	Indistinct, pasty
H7	Very turbid water; ½ of sample squeezed out	Faintly recognizable; few remains identifiable, mostly amorphous
H8	Thick and pasty; ⅔ of sample squeezed out	Very indistinct
H9	No free water; nearly all of sample squeezed out	No identifiable remains
H10	No free water; all of sample squeezed out	Completely amorphous

TABLE 1 Soil Classification Chart

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification: Group Symbol	Soil Classification: Group Name[B]
COARSE-GRAINED SOILS More than 50 % retained on No. 200 sieve	Gravels (More than 50 % of coarse fraction retained on No. 4 sieve)	Clean Gravels (Less than 5 % fines[C])	Cu ≥ 4 and 1 ≤ Cc ≤ 3[D]	GW	Well-graded gravel[E]
			Cu < 4 and/or [Cc < 1 or Cc > 3][D]	GP	Poorly graded gravel[E]
		Gravels with Fines (More than 12 % fines[C])	Fines classify as ML or MH	GM	Silty gravel[E,F,G]
			Fines classify as CL or CH	GC	Clayey gravel[E,F,G]
	Sands (50 % or more of coarse fraction passes No. 4 sieve)	Clean Sands (Less than 5 % fines[H])	Cu ≥ 6 and 1 ≤ Cc ≤ 3[D]	SW	Well-graded sand[I]
			Cu < 6 and/or [Cc < 1 or Cc > 3][D]	SP	Poorly graded sand[I]
		Sands with Fines (More than 12 % fines[H])	Fines classify as ML or MH	SM	Silty sand[F,G,I]
			Fines classify as CL or CH	SC	Clayey sand[F,G,I]
FINE-GRAINED SOILS 50 % or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	inorganic	PI > 7 and plots on or above "A" line[J]	CL	Lean clay[K,L,M]
			PI < 4 or plots below "A" line[J]	ML	Silt[K,L,M]
		organic	$\frac{\text{Liquid limit – oven dried}}{\text{Liquid limit – not dried}} < 0.75$	OL	Organic clay[K,L,M,N] / Organic silt[K,L,M,O]
	Silts and Clays Liquid limit 50 or more	inorganic	PI plots on or above "A" line	CH	Fat clay[K,L,M]
			PI plots below "A" line	MH	Elastic silt[K,L,M]
		organic	$\frac{\text{Liquid limit – oven dried}}{\text{Liquid limit – not dried}} < 0.75$	OH	Organic clay[K,L,M,P] / Organic silt[K,L,M,Q]
HIGHLY ORGANIC SOILS	Primarily organic matter, dark in color, and organic odor			PT	Peat

Figure A-1. Key to Geologic Summary Logs

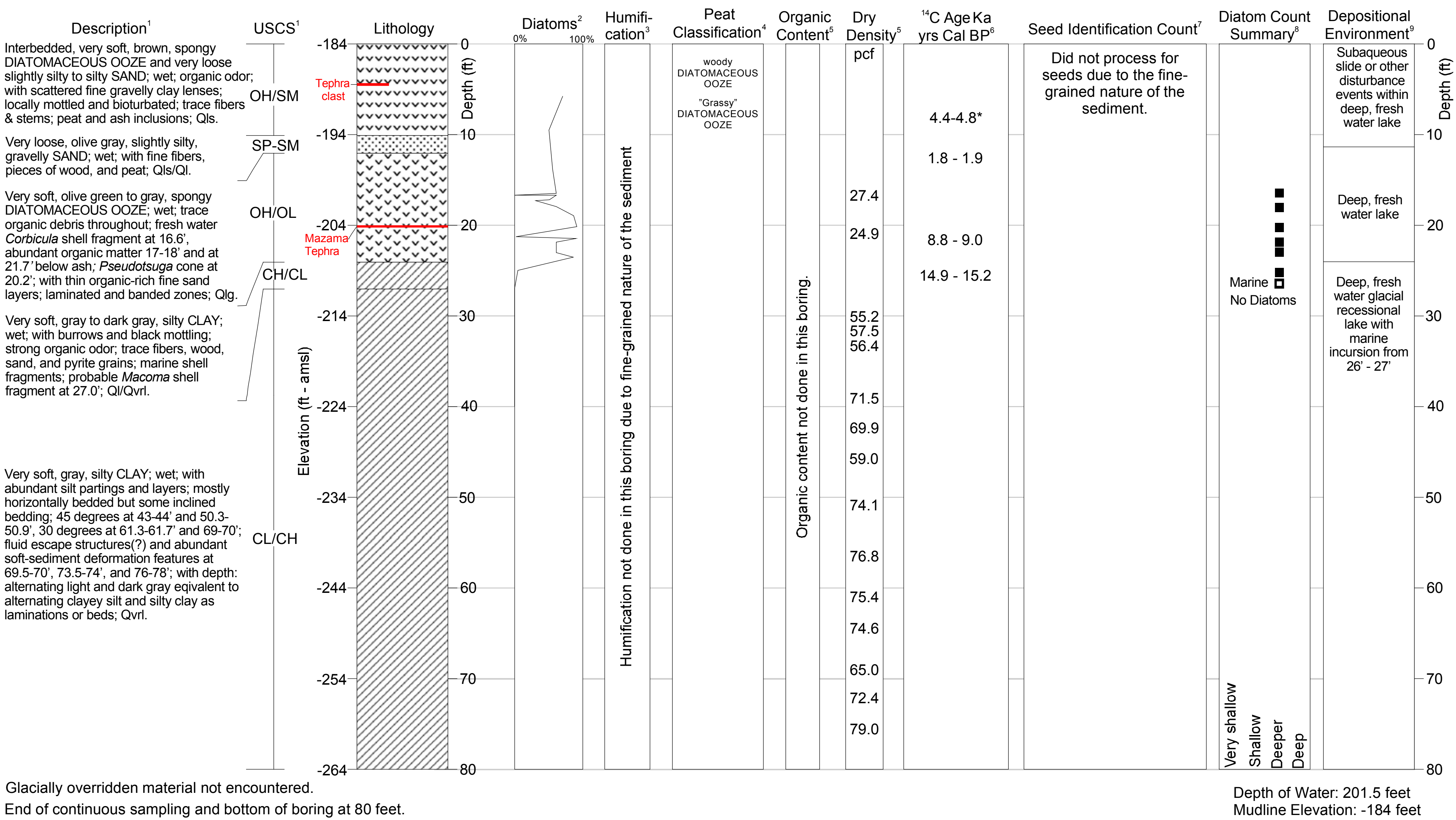


Figure A-2. Geologic Summary Log of Boring H-349-10

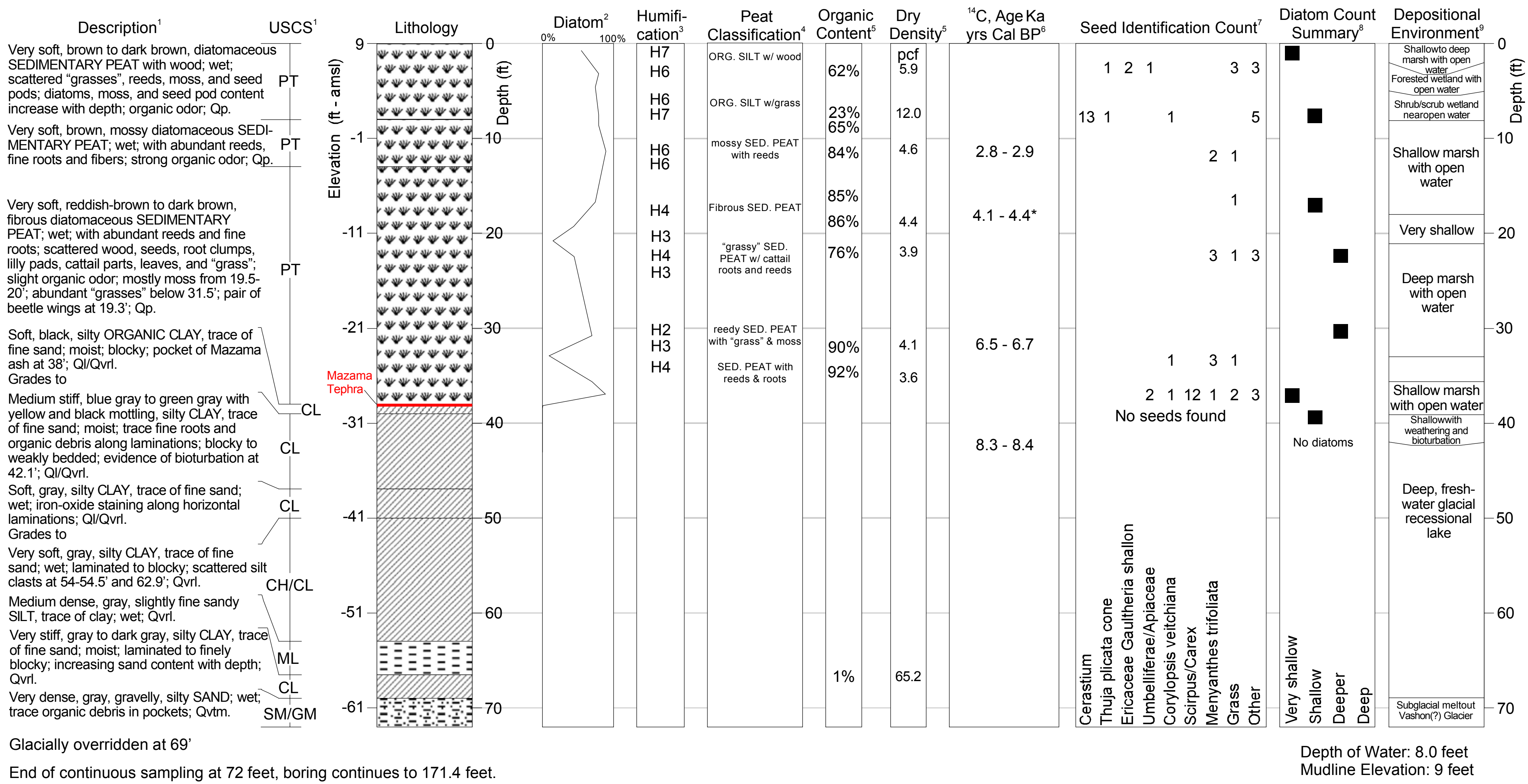


Figure A-3. Geologic Summary Log of Boring H-457-10

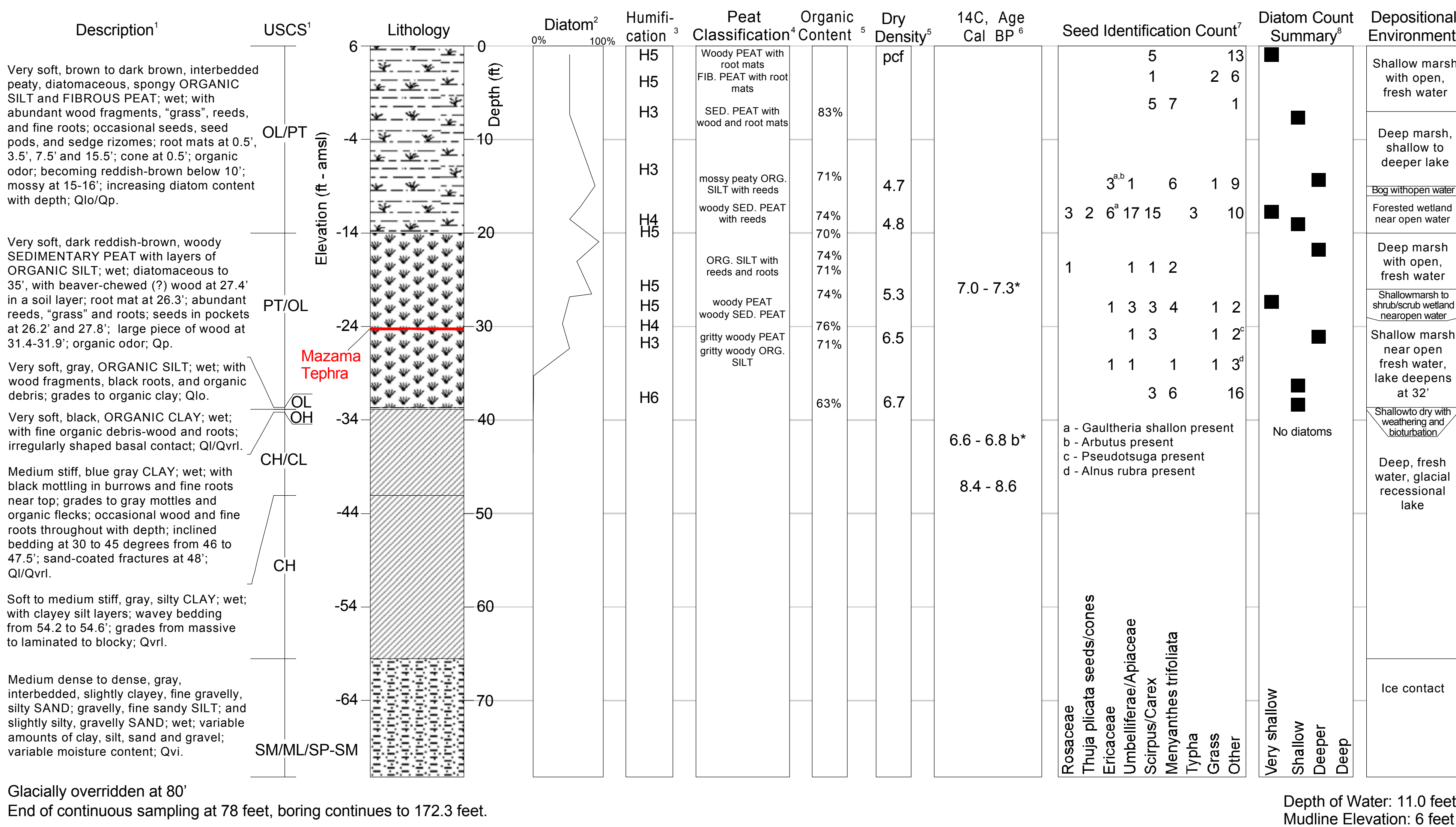
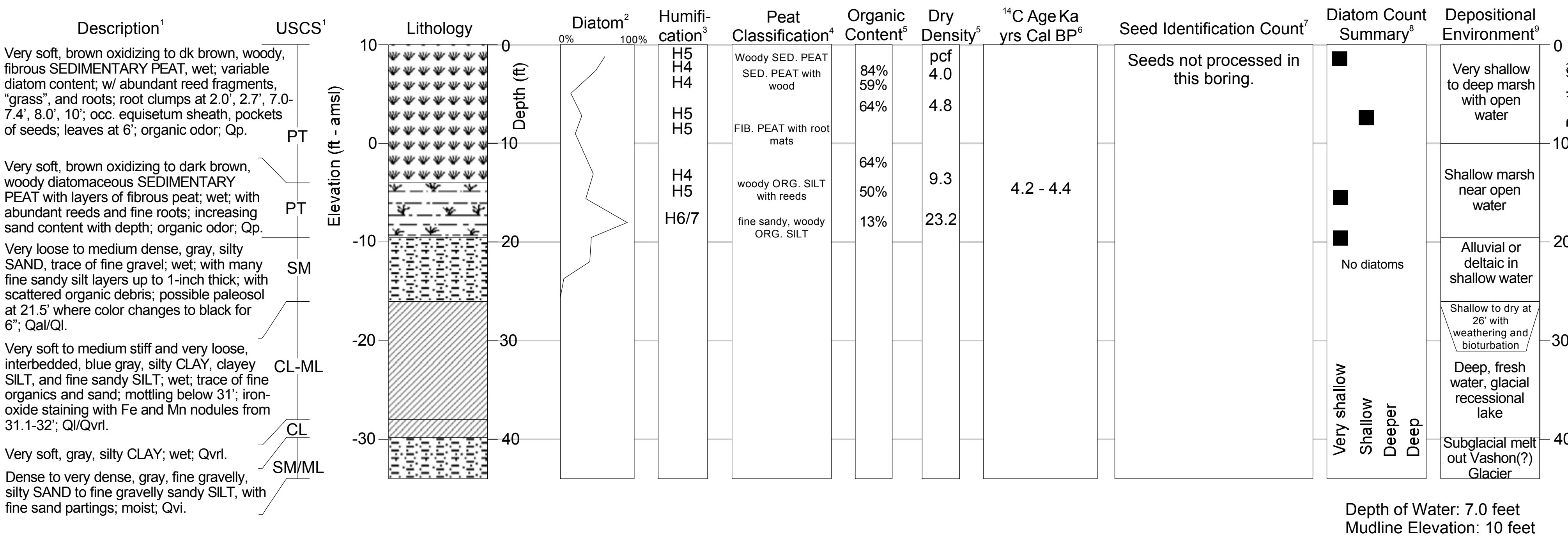


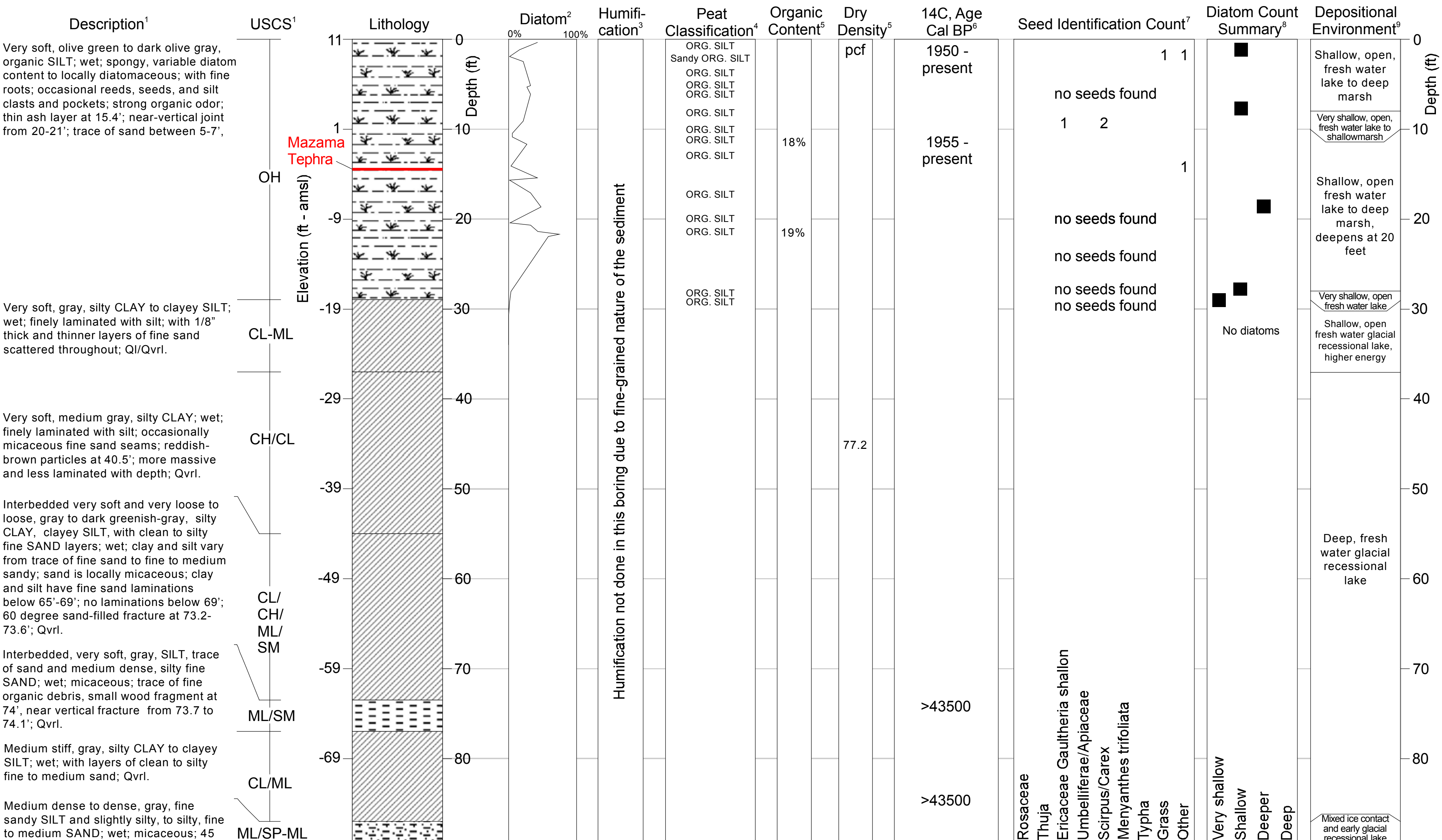
Figure A-4. Geologic Summary Log of Boring H-488-10



Glacially overridden at 63'

End of continuous sampling at 44 feet, boring continues to 160.2

Figure A-5. Geologic Summary Log of Boring H-500-10



Glacially overridden at 89.5'

End of continuous sampling at 97 feet, boring continues to 196.5 feet.

Depth of Water: 7.0 feet

Mudline Elevation: 11 feet

Figure A-6. Geologic Summary Log of Boring H-534-10