Investigation of a Pre-Vashon Interglacial Fine-Grained Organic-Rich Sedimentary Deposit, South Lake Union, Seattle, Washington

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Executive Summary

This study evaluates a fine-grained interglacial deposit found in the subsurface of the South Lake Union (SLU) area, Seattle, Washington. The nearly one-square-km SLU study area is defined as north of Denny Way, south of Aloha Street, east of Aurora Avenue, and west of Interstate 5. The evaluation required an in-depth study of over 600 existing geotechnical and environmental boring logs found for the study area. My evaluation consisted of mapping the distribution, determining the depositional environment, and characterizing the organic-rich pre-Vashon deposits. The fine-grained organic-rich deposits correlate to the Olympia formation, which occurred prior to the last glaciation of the Puget Sound Lowland known as the Vashon. To characterize the subsurface conditions in SLU, I assigned the materials described on the boring logs to one of 3 basic layers: pre-Vashon, Olympia Formation (Qob), and Vashon. In the SLU, the Qob consists of grey silt with interbeds of sand and gravel, and has an abundance of organic debris including woody debris such as well-preserved logs and branches, fresh-water diatoms, and fresh-water aquatic deposits such as peat. Several other Qob deposits have been mapped including deposits in the South Puget Sound Lowland (Borden and Troost, 2001), and deposits in the Seattle region (Booth et al., 2003), but no current data exist on the Qob deposits located within the SLU area. Evidence of Qob deposits exists on Capitol Hill, and has been characterized and mapped during a project performed by Aspect Consulting. To evaluate the distribution of the Qob, I prepared a model using the software RockWorks 16 and visited excavation sites. I found that Qob in the SLU region is confined to the western edge of the project area along the Dexter Avenue corridor from John Street on the south to Mercer Street on the north. The constraints of Qob to the western portion of the project area can be attributed to several factors including localized unconformities and historical topography. The past advance and retreat of glaciers through the region likely removed evidence of Qob deposits beyond the valley-like feature found on the western side of the project area. This valley like feature was likely part of a Paleocene drainage to Puget Sound as evidenced by the strike and shallow dip of the valley configuration. The shallow nature of the valley, with a dip of 3.6 percent, was likely an area of wetlands feeding into the lake. Future work could include more observations of Qob, permitting a more detailed model to better understand this unit and the pre-Vashon topography.

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1.0 Introduction

The Seattle urban region has been going through a developmental construction boom in the past 10 years. As of December 2016, 68 buildings were under construction in the downtown region according to local construction and development trackers, downtownseattle.com. The investment in downtown Seattle construction projects was close to $4.4 billion, which is nearly 4 times as much development as in 2010 (Development and Construction Projects, 2016). The extensive development and investment into downtown Seattle and in particular South Lake Union (SLU), means that a more in depth mapping and stratigraphic characterization of the subsurface geology is necessary. A more detailed subsurface characterization would allow for a more comprehensive database for geotechnical analysis and subsequent foundation design.

The area has been glaciated many times with interglacial periods occurring between each glacial period. The Olympia Interglaciation occurred prior to the most recent glaciation, the Vashon Stade of the Fraser Glaciation. The Vashon glaciation, part of the Cordilleran ice sheet, advanced out of British Columbia approximately 25,000 years ago, reaching Seattle about 15,000 years ago, and ended its advance about 14,000 years ago (Booth et al., 2003). Non-glacial sediments accumulated in the Seattle region during the Olympia Interglaciation prior to Vashon advance, and the deposits are known as the Olympia Formation (Troost, 2017).

To better understand the local Seattle geologic stratigraphy, my study investigated the presence of the interglacial layer known as the Olympia Formation (Qob). The Olympia Formation can be found throughout the Puget Lowland where it survived scour by the Vashon Glacier. My study focuses on an approximate 1-square-kilometer project area in the SLU region and the specific Olympia Formation deposits found there (Figure 1).

The Olympia Formation in the SLU region consists primarily of silty sand with some fine-grained sand and intermittent clay interbeds, and well-preserved woody debris. These deposits are recorded on boring logs, and exposed in construction excavations in the western side of the study area. The Olympia Formation (Qob) is defined as the deposits that accumulated in the Puget Lowland during the time period of about 15,000 to 60,000 years ago (Troost, 2017; Mullineaux et al., 1965).

The subsurface extent and distribution of Qob deposits is important to better understand the local SLU subsurface geology and for future engineering development. The Olympia Formation consists of primarily silty sand with occasional gravel and interspersed organic debris. The formation was over ridden by Vashon Glaciers and the material compacted. The behavior of the formation in regards to hydrology is important because it is has relatively low hydraulic conductivity in contrast to other units such as Quaternary Vashon Outwash (Qvo) and Quaternary Pre-Vashon Outwash (Qpvo).

1.1 Study Area

The area of study is approximately 1 square kilometer in size and is bordered by Aloha Street on the North, Denny Way on the South, Dexter Avenue on the West, and Eastlake Avenue on the East (Figure 1). This area was chosen due to the presence of organic-rich sediment noted in several excavations and the availability of a large number of geotechnical reports and boring logs.

1.2 Scope of Work

The goal of this study is to compile existing subsurface data sufficient to characterize, map and model the Olympia Formation in the SLU region of Seattle, Washington. Data from 23 boring logs within the SLU region (Figure 1) were used to create a 3D representation of the local stratigraphy down to an average depth of 64 feet. A literature review was completed using various methods of investigation, including reviewing over 600 boring logs to determine the final 23 logs used for this study. Rockworks 16 was used to create 3D models and to help with the interpretation of the data.

2.0 Background

2.1 Regional Geological Setting

The Puget Lowland region has been shaped by at least 7 glacial periods in the past 2.4 m.y. (Troost and Booth, 2008). The most recent three glacial and interglacial intervals to shape the Puget Lowland are the Possession Glaciation, the Olympia interglacial, and the Vashon Stade of the Fraser Glaciation.

The Possession glaciation occurred approximately 80,000 yr B.P. and extended at least south of Tacoma (Troost, 2017). After the Possession glaciation many changes were occurring in the Puget Lowland. The sea level was rising due to the warmer climate, with evidence of sea level variation being between 120 to 10 meters below current levels (Fairbanks, 1989). The Possession Glacier was retreating to the north and large volumes of sediment were being deposited by fluvial and glacial methods. Valley infilling was occurring due to increased sediment loads from eustatic rebound, and valley flooding due to sea level rise (Booth et al., 2003).

After the Possession glaciation and the Olympia interglaciation, the Vashon Glaciation advanced through the Puget Lowland and deposited large amounts of sediment and reworked the existing sediments. The glacial advance produced large scale scouring during advancement into the Puget Lowland and likely is responsible for large scale discontinuities found in the sediment stratigraphy. During the Vashon glacial period, large ice dams occurred and produced large pro-glacial lakes in the Puget Lowland region that helped to deposit large fans of outwash as well as depositing lacustrine formations and forming large recessional outwash channels (Booth et al., 2003).

The Olympia Formation was deposited between the Possession and Vashon glaciations. All of the layers in the Olympia Formation are of interglacial origin, meaning that they were deposited during a period of time when there were no glaciers impacting the local geology. The Olympia

Formation units found in the Tacoma region are of volcanic origin, composed mostly clasts of volcanic lithologies with some mixed lithology gravel near the top of the unit (Borden and Troost, 2001). Because the Olympia Formation represents an interglacial interval, deposition, like present in the Puget Lowland today, occurred. Therefore deposits reflect local sediment origins. The same Olympia Formation unit found further north in SLU has significantly fewer volcanic lithologies and instead consists of material with more localized origins consisting of primarily silt with sand and some varying degrees of gravel and organics.

The Olympia Formation deposits were placed between 60,000 and 15,000 yr B.P. during a period when the Puget Lowland was relatively glacier free (Troost, 1999 and Booth et al., 2003). The climate of the region was such that abundant organic material was deposited during a climatic period of relative warmth and organic matter accumulated in low-lying areas. Radiocarbon dates on Olympia-age organic matter yield ages from about 15,000 yr B.P. to beyond the limit of radiocarbon dating, greater than 40-45,000 yr B.P. (Troost, 1999). Samples of pollen, diatoms, and macrofossils analyzed from the Olympia Formation reveal several key climatic factors during this interglaciation. The pollen suggests that the dominant tree species were spruce and pine; the presence of certain diatom species points to the presence of clear, cool, fresh water lakes; and the macro fossils, such as mammoth teeth and tusks, suggest the presence of abundant grazing lands (Booth et al., 2003). Specific beetle fossils identified within the Olympia Formation at Magnolia Bluff (Discovery Park, Seattle, Washington) indicate that the beginning of the Olympia Formation had a climate had very similar to current summer temperatures, with estimated mean summer temperatures ~ 17° C. However the presence of other fossils, indicate a cooling of the average summer temperature and the lessening of available moisture which could indicate the presence of more prolonged periods of snow accumulation (Ashworth and Nelson, 2014).

Many north-south oriented glacially carved troughs characterize the region, including Lake Washington, the Duwamish Valley, and Lake Sammamish. The last glacier that reached the Seattle region was approximately 14,000 years ago (Booth et al., 2003). This glacial event is called the Vashon Stade of the Fraser Glaciation and it strongly influenced the surface geology of the region, with glacial scouring and deposition of material. During this glacial event the thickness of the ice was about 3,000 feet as evidenced by the topography surrounding the Puget Lowland (Troost and Booth, 2008). The glacier extended to south of Olympia, WA. During the Fraser Glaciation large volumes of sediment were deposited during both the advance and retreat of the ice sheet.

Types of deposits placed by the last glaciation can be put into two categories; glacially consolidated and unconsolidated. The glacially consolidated materials include advance lacustrine deposits, advance outwash, and subglacial till. Advance lacustrine deposits consist of primarily laminated clayey silt and silty clay. Advance outwash consists of primarily well-sorted sand with silt and gravel interbeds deposited in a lacustrine to fluvial environment. Till was deposited in contact with glacial ice. All three of these deposits were overridden by the glacier, causing dewatering and consolidation of the sediments by the weight of the glaciers or, over-consolidation. Unconsolidated materials were also placed and consist of ice-contact and recessional deposits, both lacustrine and outwash placed during the retreat of glacier.

2.2 Land Modification

During the turn of the 20th century major landscape engineering projects occurred in the Seattle region. The improvements included sluicing that moved sediment from the hills east of the waterfront to the current Seattle tidelands in the Duwamish River (Galster and Laprade, 1991) and heavily modified SLU in order to help facilitate the ease of access and urban expansion. From 1862 until 1928, efforts to remove and regrade the former Denny Hill took place and essentially eradicated a 62-city-block hill that was more than 100 feet tall (Figure 2; Galster and Laprade, 1991). The Denny Hill regrade completely changed the stratigraphy of the SLU region by allowing units that used to be buried under 100 feet of sediment to have surface contacts. Besides removing Denny Hill, the SLU area was completely regraded to a flatter topography to help with the continued development of the area. Fill was also used to help flatten the region. Boring log data from this review indicates that up to 32 feet of fill was placed in order to create more land near the south end of Lake Union.

2.3 Summary of Previous Work

Several studies investigating the origin and extent of the Olympia Formation throughout the Puget Lowland have been conducted. Borden and Troost (2001) performed a study that characterized the Late Pleistocene stratigraphy in the South-Central Puget Lowland. Included in this characterization is a detailed description of the Olympia Formation in the Tacoma region, correlative in time to the Olympia Formation at SLU. Olympia Formation in the Tacoma region has different provenance than that of the SLU, with sediment being primarily volcanic in origin. The radiocarbon dates from Borden and Troost (2001) range from 17,000 to greater than 46,000 yr. B.P. (Borden and Troost, 2001). More locally significant to SLU, Booth et al. (2003) briefly describe the Olympia Formation as being deposited during a relatively ice free time period similar to that described by Borden and Troost in 2001.

In separate investigations Mullineaux et al. (1965), and Armstrong et al. (1965), briefly describe the Olympia Formation, noting that it is a non-glacially deposited material. The material is also described as having abundant wood and organic debris with some aqueous fossils having been recovered and identified. The specific fossils identified by Mullineaux et al. 1965 are known to only live in shallow-water lakes and streams.

Armstrong et al. 1965 further characterize the Olympia Formation with several radiocarbon dates from samples taken at bluff exposures along the Puget Sound north of West Point in Seattle. The dates are consistent with more recent studies (Borden and Troost, 2001), with Armstrong et al. 1965 obtaining date ranges from 18,100 to 22,400 yr B.P. (±750 years). Armstrong et al. 1965, also describe the depositional setting at the time of deposition as being comprised of shallow lakes, swamps, and flood plains. Forest cover existed, as evidenced by pollen samples showing primarily spruce and pine (Armstrong et al., 1965).

3.0 Methods

The tasks used to investigate the Olympia Formation in SLU included; 1) a Boring log review, 2) RockWorks 3D modeling of all pertinent stratigraphy found in boring logs, and 3) observations in excavations.

3.1 Boring Log Review

Using online databases I performed extensive searches for viable boring log data containing evidence of the Olympia Formation in SLU. I used the Washington Department of Natural Resources Geologic Information Portal (formerly GeoMapNW), the City of Seattle Department of Construction and Inspections interactive map search, and GeoEngineers Inc. internal servers. I reviewed and assessed over 600 boring logs within a square kilometer around the SLU area of Seattle, WA. During this review I selected 23 boring logs out of the 600 reviewed that contained reliable data. Out of the 23 boring logs selected for further scrutiny and modeling I observed 7 bore holes with reliable data showing top and bottom contacts for the Olympia Formation.

I chose the final 23 boring logs to be used for this study based on several factors. The boring logs needed to be well distributed across the entire project area so the area was best represented. I also required boring logs with accurately described samples in order to correctly assign stratigraphy units based on the local USGS geological maps. Finally, I was looking for boring logs that contained either unit descriptions that were consistent with Qob deposits or contained descriptions of confining marker stratigraphy units such as Qvl and Qpvo.

I focused on finding data with descriptions of fine-grained material with organic debris called out in the boring logs to help refine my searches. However, not all field staff logging bore holes were concerned with determining whether the Olympia Formation was indeed observed. Several markers were needed to help me identify the Olympia Formation. The markers used were the upper and lower constraining units. Vashon-age Lawton Clay and pre-Vashon outwash were used as observable markers since they are easily identified. The Lawton Clay, a pro-glacial lacustrine deposit, is dark grey clay, interbedded with light grey silt, sometimes with horizontal bedding (Mullineaux et al., 1965). The pre-Vashon outwash has an oxidized color near the contact with the Olympia Formation, although this is not necessarily a defining characteristic. Pre-Vashon outwash consists of gray-brown, fine to medium grained sand with minor sandy gravel interbeds. I was only able to correctly interpret the presence of Qob deposits with the presence of woody debris or the top and bottom marker units of both Qvlc and Qpvo. It is possible that other Qob deposits existed within the project area and were not identified.

3.1.1 GeoEngineers Inc.

The internal servers at GeoEngineers allowed for an internal geotechnical reports search within the area of study. I was able to download and review all boring logs and local geological data deemed pertinent for given projects. The geotechnical reports include boring logs from holes drilled specifically for each project and past bore holes drilled around the project area.

3.1.2 WADNR Geologic Information Portal

The online portal for geologic information was used to help search for boring hole data within the study area (https://fortress.wa.gov/dnr/protectiongis/geology/?Theme=subsurf). The subsurface geology option is chosen from the main page and an interactive map is displayed. Basic GIS functions can be used to refine the search for only geotechnical bore holes in the desired region (Figure 3). Each of the boreholes contains data about the location, and some of the holes contain boring logs and info about the project. The borehole data was reviewed with regards to the Olympic Beds and the confining marker units. Boring logs were selected based on the quality of unit descriptions and the location of the data.

3.1.3 City of Seattle Department of Construction and Inspections Interactive Map Search

The City of Seattle website is an interactive map feature that allows for a block-by-block search in any desired region within the City of Seattle. This process requires a search first by moving the map into the desired region, then highlighting a part of a city block. A list of addresses will appear, current and previously filed documents are available for reviewing on an address-by-address basis. I primarily used this method of log reviewing to fill in any gaps of data within the project area, since this search method was extremely time consuming.

3.2 Modeling with RockWorks 16

RockWorks version 16 was used to perform all modeling on this project. RockWorks is a 3-D modeling software that uses data such as lithology, stratigraphy, hydrology, and quantitative data to analyze subsurface data. The data can be shown in numerous modeling options including 2-D and 3-D striplog diagrams, fence diagrams, layer cake models, and many other options including 3-D layer cake models. All of the aforementioned modeling options can be built using both stratigraphy and lithology data. Assigning location data requires the use of map applications in order to get coordinate information and ground surface elevation data if location data is not provided. I attended a two day seminar in Golden, Colorado near the Colorado School of Mines to learn basic RockWorks 16 functions.

3.2.1 Data

Before starting data input, a project folder is created and linked to RockWorks, in order to save and access all of the data being input into the program and created by the program. Project coordinates must be defined either manually, or using RockWorks to scan bore holes with data attached to the bore holes. The desired coordinate system must be defined before any data input, in this project the coordinates used are the Universal Transverse Mercator system with WGS-84 (NAD-83) Zone 10 datum.

I manually assigned location data for each of the 23 bore holes used for the project. This was done by using Google Earth and site maps of bore hole locations concurrently. A temporary location was added to Google Earth and the latitude and longitude was used to input coordinates into RockWorks while continually referencing the site plans for correct bore hole locations. Elevation data was cross referenced using both Google Earth and boring logs. After all of the boring log coordinate and elevation data was input, the “scan bore holes” option was used to automatically create a project fence around the location data present within the bore holes. All of the assigned locations and project fence are then available for export to Google Earth (Figure 4) and all of the stratigraphic data can be exported to display in 3-D striplogs within Google Earth (Figure 5).

Once all of the coordinate data was created, all of the stratigraphic units were assigned an order of deposition, with number 1 being the upper-most (Table 1). The stratigraphy for each bore hole is manually designated with depth data being used to identify the bottom and top of the units. All units must be input into each borehole in order for RockWorks models to interpolate pinch-outs of units (Table 2).

In order to quantify the average strike and dip of Qob in the study area, a three point problem was created using data points from the model. The boring logs used were SB-1, SW-1, and HC-2 (Figure 6). These three boring logs were used due to the placement of the bore holes and because of the requirements for a high, medium and low elevation data for a three point problem. I used the lower surface contact elevation of Qob as my control points for the calculation, and to indicate the topographical nature of the unit at the time of deposition. The top contact of the formation was not used due to the probability of erosion during the advancement of the Vashon glacier. The highest unit surface contact for Qob was found on boring log SB-1, and the medium and low points were SW-1 and HC-2 respectively. Using Google Earth to measure the distance between the boring logs and measure the azimuth, I created an excel spreadsheet to calculate the strike and dip for the surface of Qob (Table 3).

3.3 Modeling

I used modeling options available in the Borehole Manger of RockWorks to produce. 2-D and 3-strip-log sections, and stratigraphic sections. My goal during modeling was to have a visual representation of Qob in relation to the current and historic topography.

For 2-D strip-log sections, the Borehole manager tab must first be initiated. The StripLog tab can then be highlighted and 2- Dimensional Section option can be chosen. The Hole-to-Hole window will appear and menu options will appear. The menu options chosen were to plot all Striplogs, plot Correlations and no other menu options were chosen. The 2D StripLog Designer is chosen and only the log Title, Depths, Stratigraphy and Stratigraphy Text is chosen. If desired the text can be manipulated to better display the units on the model. The desired boreholes are selected as desired in the Section Selection Map and the Process tab is chosen to display the new model. This model will create a two-dimensional cross section of the boreholes chosen with no three-dimensional aspects even if the boreholes selected are not in a straight line.

The 3-D model process is nearly identical except the 3-D StripLog option is chosen from the StripLogs tab and the 3-Dimensional Multi Logs w/Linear Correlations option if chosen. Similar menu options are chosen to 2-D methods with, Include Stratigraphy Legend, Plot Outline Around Each Panel and Plot Logs options chosen. The Fence Selection Map is chosen and bore holes are identified and chosen as desired. The Process tab is chosen and a 3-D correlated model is created based on stratigraphy.

3.4 Site Reconnaissance

On February 14th, 2017, I was able to gain access to an excavation site at 8th and Thomas in SLU. The base of the site excavation was approximately 44 feet below street level as described by onsite surveyors. This location is consistent with the boring logs where I was able to identify Qob deposits and is within a 250-foot radius to bore holes HC-2, HC-4, HMW-1-13, and HMW-3-13. While onsite I observed Qob in situ and used a small shovel to clean the surface of the exposed unit to better identify the material. I observed two wood logs with a diameter of 6 to 10 inches embedded in the unit. Numerous smaller woody debris was also embedded in the unit. Several large wood logs (6-10 inches) were also laying on the ground of the excavation. The woody debris observed was in relatively good condition with no visible decomposition. None of the woody debris observed while onsite had bark remaining on the surface

Observations of other site excavations were made by Doctor Kathy Troost and were verbally communicated. Doctor Troost described in several meetings the locations where she has encountered Qob deposits. The most notable deposits discussed were located at 1260 Republican Street, 777 Thomas Avenue, and Mercer and 8th Avenue. The 1260 Republican Avenue location is notable due to the discovery of an 8.5-foot mammoth tusk approximately 30 feet below street level (A Mammoth Undertaking, 2017). The tusk was discovered during excavation for residential apartments by a backhoe operator and removed for further evaluation. Doctor Troost stated that the mammoth tusk was discovered within Qob. Doctor Troost also described much larger diameter wood 12 to 18-inches, at 777 Thomas where the base elevation was 66 feet. The color of the Olympia Formation as described was gley in color and represented an anoxic environment. The Mercer and 8th avenue site was described as having Qob deposits present with a top elevation of 15 feet and woody debris was observed.

4.0 Results

4.1 Lithology and Variability of Qob in SLU

The prominent identifier for the Olympia Formation is woody debris and a lower contact with pre-Vashon outwash with a noticeable oxidized color.

During my site visit I observed a grey, varved, silt with fine-grained sand, containing numerous detrital pieces of large woody debris with sizes ranging from 1 to 8 inches in diameter (Figure 7). The wood was very well preserved and appeared to be unmolested by decomposition except for the lack of bark. The material was located at a depth of approximately 40 to 44 feet below ground surface. The upper 40 feet was covered by lagging boards for shoring operations, and therefore overlying sediments were not exposed for description. The depth of the wood was consistent with depths determined during my desk review efforts to identify Qob deposits. Bore holes in close proximity to the open excavation, HC-4, HMW-1-13, and HMW-3-13, show depths to Qob as 40, 44, and 51.5 feet respectively.

The unit is grey in color and slightly moist, the primary sediment composition is sand with silt and occasional small gravel. The unit appeared varved and the woody debris contained within was located at different elevations and found throughout the thickness of the Olympia Formation.

4.2 Lateral and vertical extent of Qob

Qob deposits are not observed to the east of Dexter Ave North. After reviewing all of the boring logs insufficient data existed to assign Qob units to any of the bore holes east of Dexter Ave North. The lateral changes throughout the study region are shown by the discontinuation of stratigraphy units such as in bore hole HMW-3-13 as illustrated in Figure 10. The expected sequence in this location would be as follows starting from the surface, Fill, Quaternary Vashon recessional lacustrine (Qvl),Quaternary Vashon recessional deposits (Qvr), Quaternary Vashon till (Qvt), Quaternary Vashon advanced outwash (Qva), Quaternary Vashon Lawton clay (Qvlc), and then the Olympia Formation (Qob). Quaternary Vashon recessional lacustrine (Qvl) deposits overlie the Qob as well as Lawton Clay deposits (Qvlc). However, Quaternary Vashon recessional deposits (Qvr) pinch out at bore hole HWW-3-13 and no Quaternary Vashon advance or till deposits are present in these boreholes. The missing stratigraphic units Qvr, Qvt, Qva, and Qvlc are present in other bore hole locations throughout the project area and help to confirm that glacial scouring and subsequent stratigraphic discontinuities exist within the SLU region.

A 2-D cross section from borehole HC-2 to SW-1, modeled in RockWorks 16, shows evidence of the Qob deposits forming a valley (Figure 10). The average depth to the top contact is 32 feet and the average depth the bottom of this contact is 43 feet (Table 4). The vertical variability in Qob is likely a product of erosion from glacier sourced rivers or glacial scour. Qob in SLU has variability of unit thickness from 2.5 to 26 feet (Table 4), with an average thickness of 11 feet. The variability is probably a direct product of erosion and an existing unconformity. Other unconformities exist throughout the SLU area and are not limited to Qob deposits. Areas within the project region show a lack of Vashon sediment deposits such as in bore hole GEI-2 where the known stratigraphy section shows only Qva, Qvlc, and Qpvo in a bore hole with a depth of 66.5 feet below the surface.

As calculated by a three point problem, the dip azimuth of the top of the Qob in SLU is 31.3° and the dip is 3.6°. This dip direction, measured from the high point bore hole SB-1, leads directly to the present location of Lake Union. The top of the Qob contact has likely been reworked during the Vashon glaciation, however the top contact is relatively consistent with the lower unit contact. The modeled unit shows significant variability in the relative elevation of the top contact, but the model is consistent with slight average dip to the northeast (Figures 8 and 9).

5.0 Discussion

Based on my findings, it appears that the depositional environment for the Olympia Formation in the SLU area was a shallow north-flowing stream valley. The local topography at the time of deposition was much like the topography of today, rolling gentle hills and valleys with creeks and estuaries. The valley had a relatively shallow slope as evidenced by the calculated strike and dip. Based on the abundance of woody debris, the valley, or surrounding hills were likely forested.

My interpretation biased by several limitations of the data. The Olympia Bed stratigraphy layer is not always indicated as a separate geologic layer in boring logs. In many of the geotechnical and environmental boring logs, the Olympia Beds were not characterized as a separate stratigraphic unit; instead it was grouped with the upper or lower units and could be differentiated only by the presence of wood. However, the presence of wood will not always be available as a marker to identify Qob. Additionally data quality may be limited by the field experience and geologic knowledge of field staff that made the boring log observations. Because the primary goal of geotechnical borings is to identify basic lithology within the borehole, details of the stratigraphy may be overlooked.

There is an unexpected lack of data for Qob in SLU. It is probable that the layer extends beyond the limits of what I could document. Data from previous studies shows Qob deposits in regions surrounding the SLU study area. In particular, the unit can be found on Capitol Hill. Qob drapes the historical topography of Capitol Hill and terminates at I-5 (Figure 11). During my literature and boring log review, I noticed a lack of data below 30 feet. In particular the WA DNR website contained only 14 boring logs with depths of greater than 30 feet. Of these boring logs, I used only one due to the poor quality of information of the other boring logs. This lack of what I deemed good data may artificially limit the documented aerial extent of Qob presented in this study.

At present, the elevation of Qob deposits is mostly above sea level with the exception of the lower portion of bore hole BB-2 that sits at 3 feet below current sea level. During the deposition of the Olympia Formation from 14 to 60,000 yr B.P., the mean global sea level was between 10 and 120 m lower than present (Voris, 2000). Pleistocene sea levels at or below 10 meters (32.8 feet) would help to account for the deposition of the Olympia formation in a non-marine environment. The elevation of the Olympia Bed units found during boring log reviews can help to correlate the sea level at the time of deposition or the current depth below the surface (table 4).

During the advance of the Vashon Stade glacier, much of the Seattle area topography changed dramatically. The stratigraphy of the SLU region has many discontinuities that can be attributed to glacial erosion scour and glacier-sourced rivers. Radiocarbon dates from Borden and Troost's (2001) study of Qob in Tacoma suggest depositional ages ranging from 17,000 to greater than 46,000 yr. B.P. The age ranges determined from this investigation by Borden and Troost can be correlated to the SLU area based on similar evidence found from a radio carbon date that Kathy Troost PhD and Matt Smith LE, performed on woody samples for a project based in SLU. The age of the wood sampled was approximately 19,000 yr B.P. and can be correlated directly to the radiocarbon dates from samples taken in the Tacoma area.

The Olympia Formation in the SLU consists of grey silt with varying amounts of sand and gravel. One of the most prominent markers for the Olympia Formation in SLU is the deposition of woody debris within the unit. The wood found in the unit is commonly large branches and small logs in relatively good condition. The description of wood can be found in boring logs and excavations and the wood has very little decomposition as evidenced by the wood I observed at the excavation at 8th and Thomas. The introduction of this wood, and the wood's relatively fresh nature indicate that the wood was deposited then relatively quickly buried and saturated, which indicates the presence of a body of fresh water.

One possible explanation for rapid burial of large wood could be a lake seiche from a Pleistocene era Lake Union. Lake seiche induced by earthquakes have been known to produce waves up to 30 feet with waters reaching more than 300 feet inland and uprooting and breaking off large trees (e.g. McCulloch, 1968). With the Seattle Fault being a short distance away, an earthquake with a relatively large magnitude could cause Lake Union to shake and tilt for a prolonged period. North American precedence for prolonged lake seiche has been shown in places such as Alaska during the M 9.2 1964 earthquake, ground shaking caused waves that had 20- and 30-foot run up heights (McCulloch, 1968). The Alaskan 1964 event had an estimated magnitude of 9.2 which is several orders greater than the estimated 7.2 magnitude for historical estimates on the Seattle Fault, but SLU proximity to the Seattle Fault suggests high intensity shaking. A lake seiche could have a significant impact on areas with low vertical relief in relation to the lake (McCulloch, 1968). If lake sieche were the cause of the woody debris deposition within the Qob unit it is possible that the wood deposited would be placed in similar orientation due to the flow of the water. There is no current evidence that shows all wood debris within the Qob unit being in similar orientation and further study of the unit would be required.

Other possibilities that cannot be ruled out for the probable cause of deposition include landslides, debris flow. However not unlike lake sieche, no exact evidence suggest one mode over another. During boring log review, there did not exist sufficient evidence to suggest that landsides or debris flows were the mode of transport and/or deposition of the woody debris. The boring logs did not show evidence of sediment that did not belong to the Qob unit. The logs appeared to have relatively homogenous material characteristics and color and visual evidence observed at 8th and Thomas also suggested a material that was not reworked due to mass movement.

6.0 Conclusions

The erosive forces of glaciers have dramatically changed the region of Seattle. During the advance and retreat of glaciers over the past 2.4 m.y. many different sediment layers have been deposited and scoured away. During interglacial periods, sediments and organic material were deposited as local strata by fluvial, lacustrine or other natural erosional forces. The SLU area has been changed and reshaped by these natural forces.

The Olympia Formation was deposited between 15,000 to greater than 46,000 yr. B.P. in a climate that was relatively glacier free. (Borden and Troost, 2001). The SLU area where I found evidence of Qob, is a valley near modern Lake Union. The valley contained a stream where trees could grow in relative abundance, as evidenced by the organic deposits found within the unit. The trees and organic material were deposited within the unit over the 50,000 year interglacial period. The wood debris observed within the Qob unit either from my site visit or within the data collected from boring logs shows that the woody debris can be found throughout the unit and does not correlate to a single event.

I evaluated more than 600 boring logs as part of my review for this investigation and selected 23 bore holes to best represent the stratigraphy found within the my study area. During my investigation I was able to identify 7 bore holes that contained Qob deposits and visually confirm the existence of the deposits in an excavation located at 8th and Thomas. The confined area where evidence of the Olympia Formation exist, shows the deposits either were deposited only in this area or that the movement of glaciers and other erosive forces, erased evidence of the unit in other locations.

I used RockWorks 16 to model the selected boring log stratigraphy within my project area. The model illustrates the limited extent of Qob the western portion of SLU. The models indicated that a valley was present between bore holes HC-2, HC-4, HMW-3-13, and SW-1. Several younger stratigraphic units were not present in many of the bore holes containing Qob deposits, likely due to erosion.

7.0 Limitations

This investigation should not be used as a complete and comprehensive study due to the limitations discussed above.

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9.0 Figures

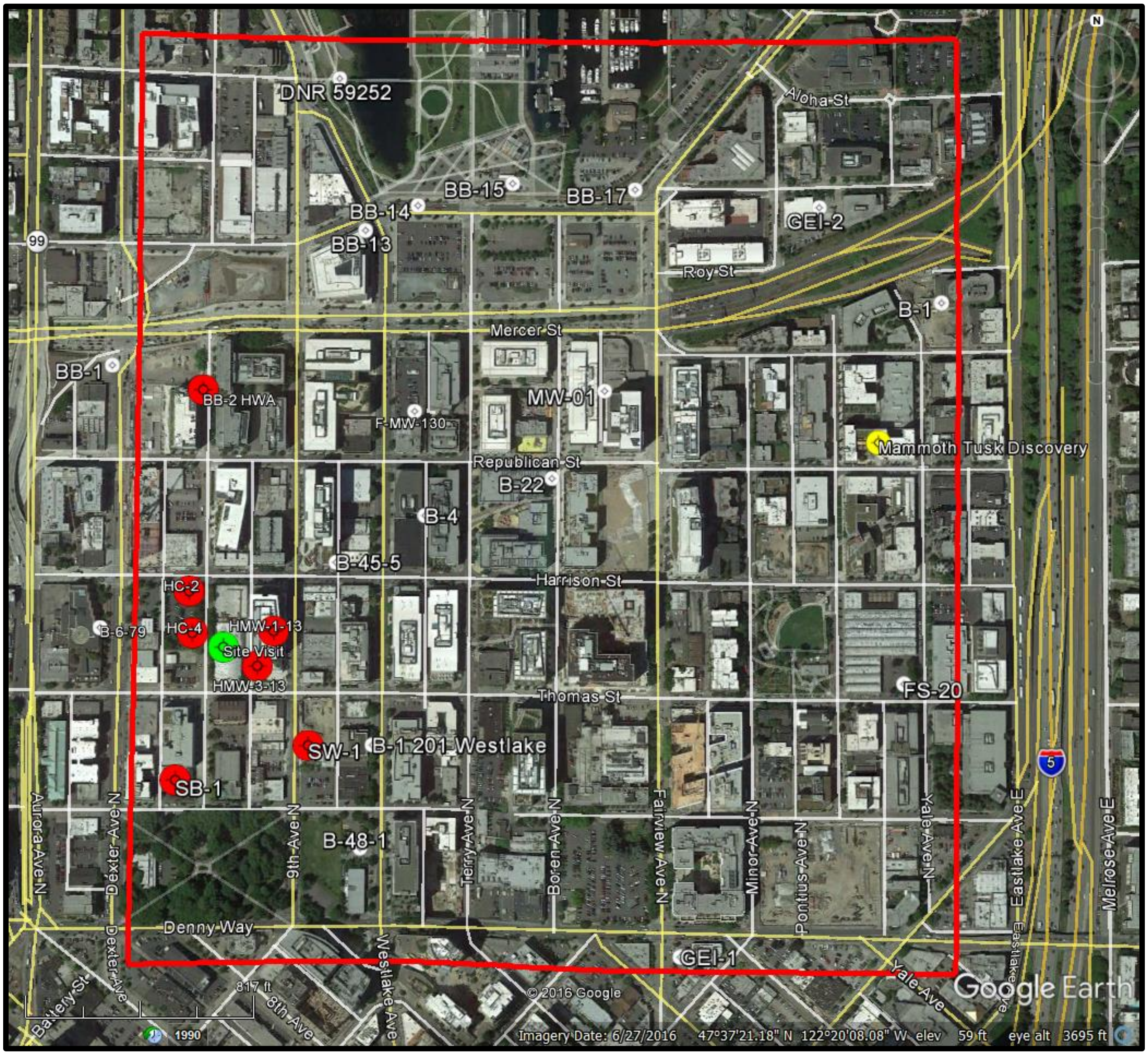

Figure 1. Site Map: Overview of the project area in the South Lake Union region of Seattle, Washington. The red perimeter depicts the project dimensions along Dexter Avenue on the West, Aloha Street on the North, Eastlake Avenue on the East, and Denny Way to the South. Bore hole icons (circles with cross marks) are shown in both white and red, with red icons indicating where organic-rich Qob was encountered, and white bore hole icons indicating no organic-rich Qob encountered. The green icon represents the location where a site visit was made to observe Qob deposits in situ, and the yellow icon represents where a mammoth tusk was discovered within the Qob unit. Image from Google Earth; bore hole locations plotted with Rockworks 16.

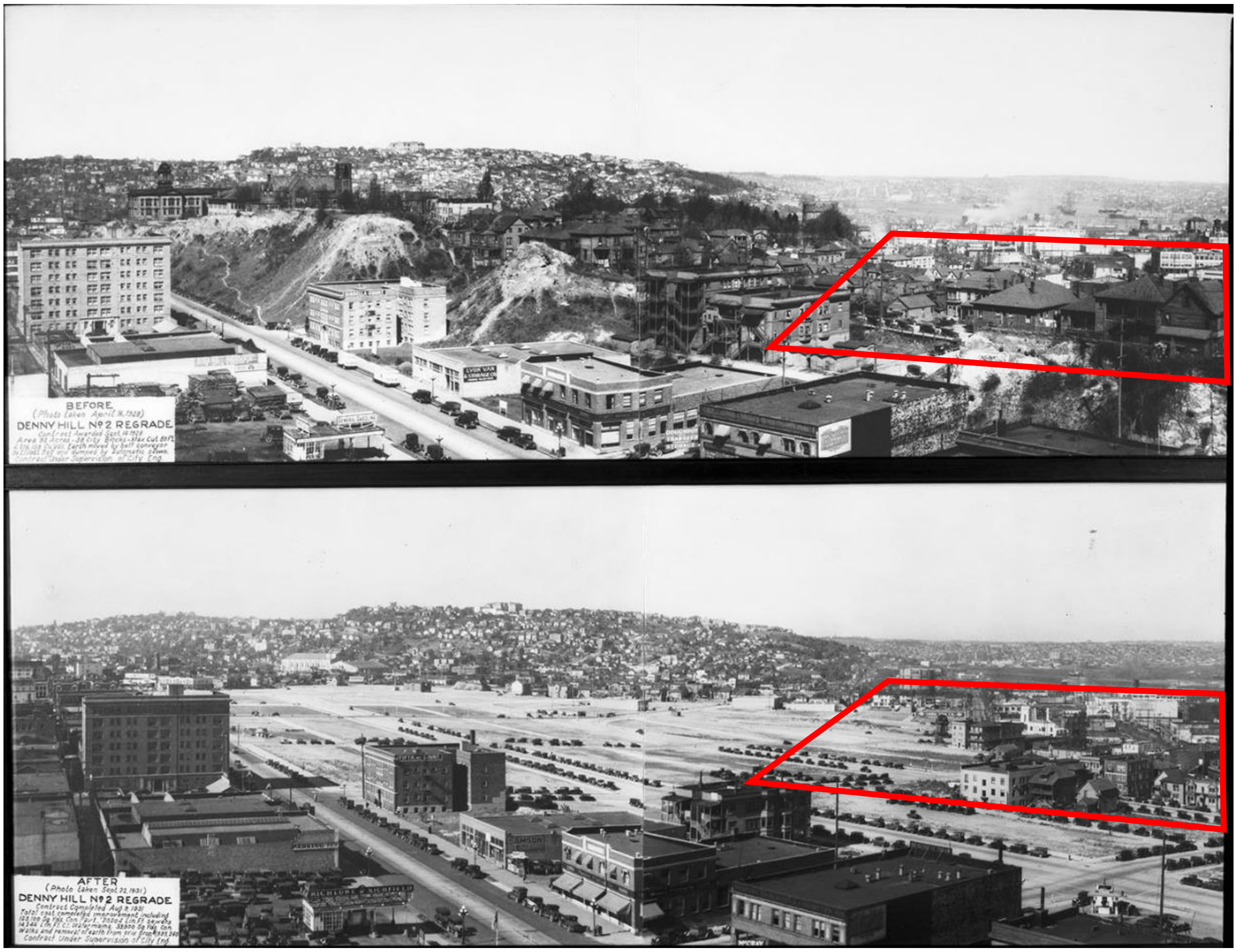

Figure 2. Historical South Lake Union Photos: Looking north at the before and after photos of the Denny Regrade. Picture is taken from the vicinity of Lenora Street and 5th Avenue. The general location of the study area is outlined in red. Photos by Lee, James Patrick, 1928 and 1931. (Lee, J. P., 1928 and 1931)

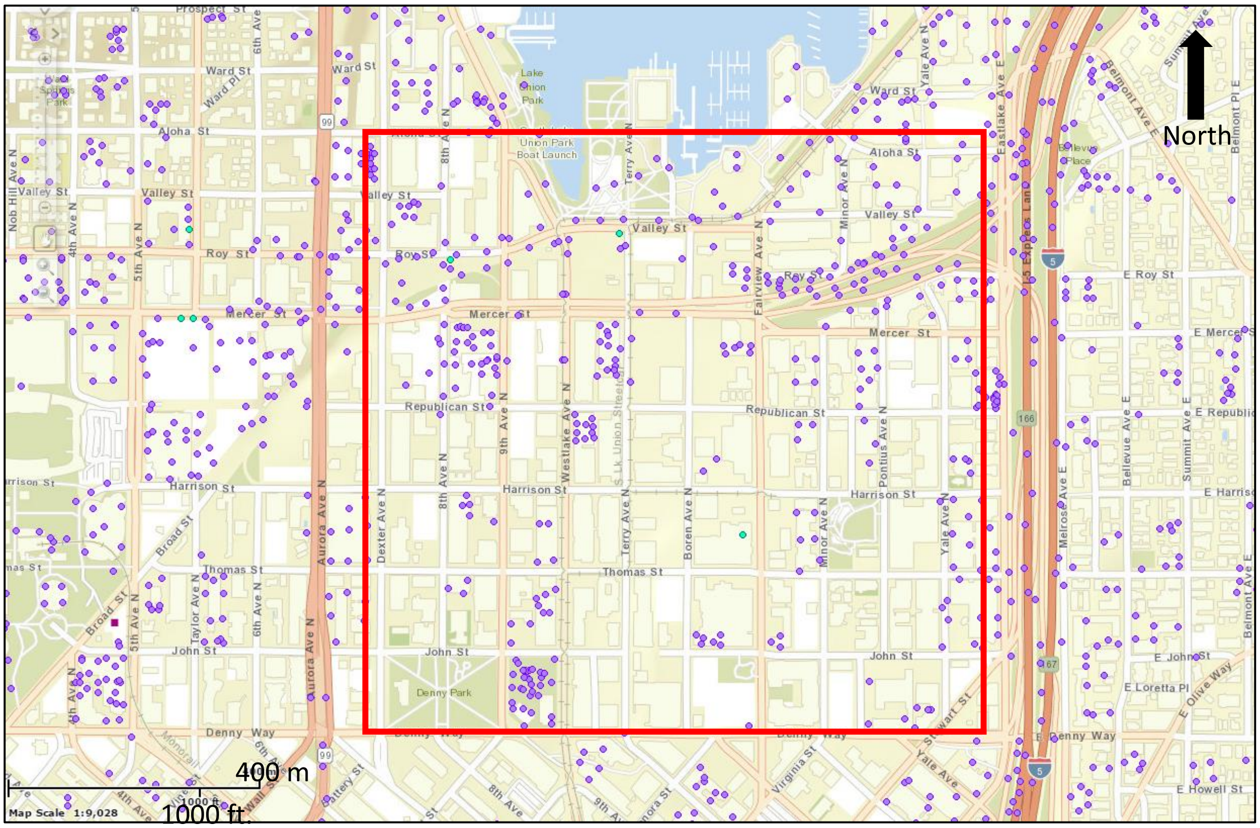

Figure 3. WADNR Boring Log Image: Location of geotechnical borings with subsurface data (purple dots) in the SLU region of Seattle, Washington. The extent of the study area is shown by the red outline. All data points within the red project outline were reviewed for evidence of Qob deposits. Data and map from the Washington Department of Natural Resources Geologic Information Portal for Subsurface Geology.

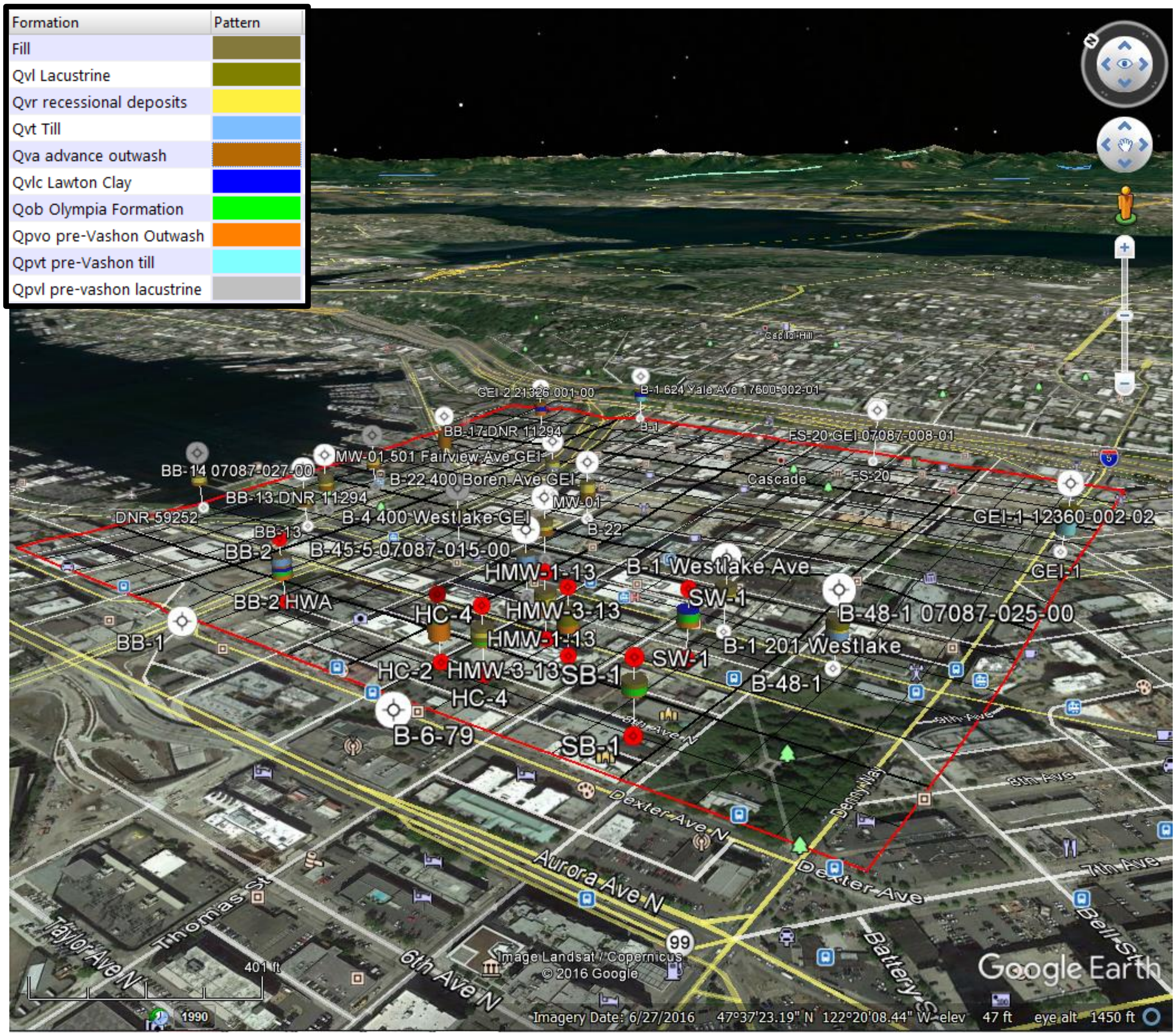

Figure 4. Google Earth Image of Boring Hole Locations: Oblique aerial view toward the northeast of SLU study area (red box) showing position (red or white symbols) and stratigraphy (colored cylinders) of all 23 boring logs selected for stratigraphic correlation. Colors correspond to stratigraphic units. Image from Google Earth after exporting all bore hole locations and project fence from RockWorks.

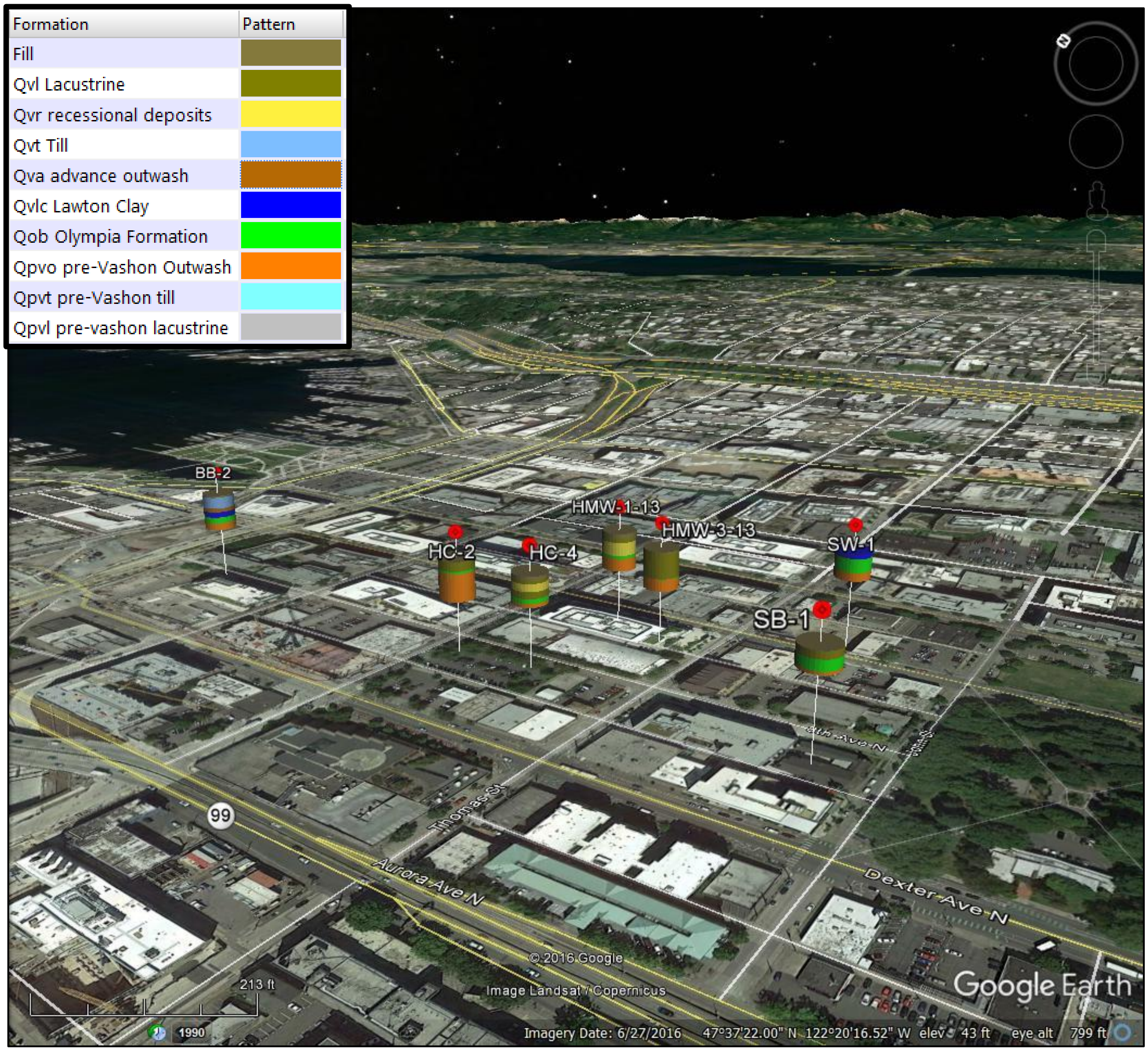

Figure 5. Google Earth Image of Boring Holes: Oblique aerial view toward the northeast of SLU study area showing position (red symbols) and stratigraphy (colored cylinders) of all 7 boring logs containing Qob and selected for stratigraphic correlation. Colors correspond to stratigraphic units. Image from Google Earth after exporting all bore hole locations and project fence from RockWorks.

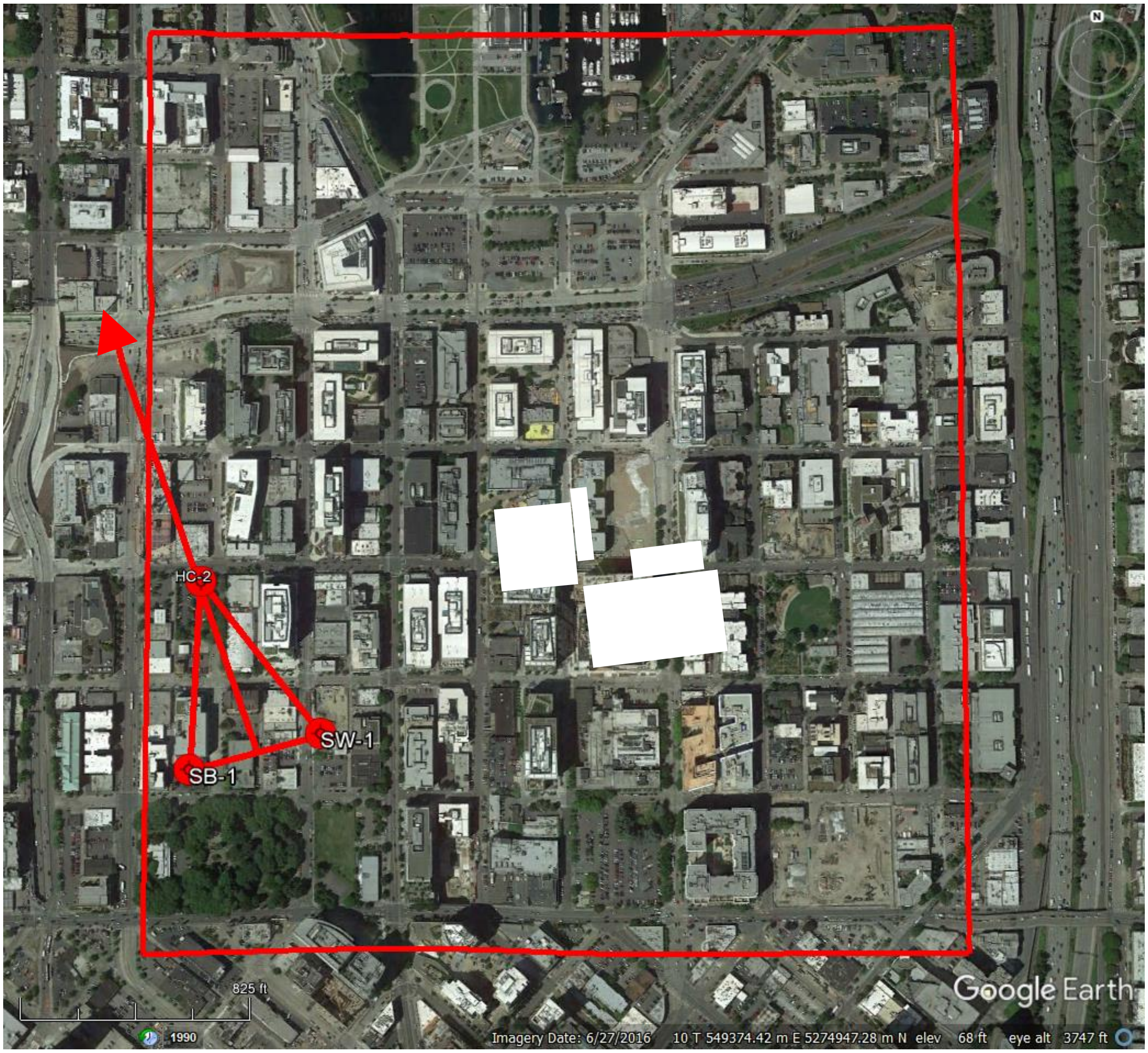

Figure 6. Top View of 3 Point Problem: Plan view of Google Earth with Boring Holes and dip direction. Red lines connect borehole containing Qob selected for the "three point problem" used to determine the dip and dip direction of the unit. The red arrow is 334.4° azimuthal direction of the 2.8° dip. Lake Union is located to the north of the furthest data point shown on the image. Approximate dimensions of the project are shown by the red outline and is approximately one square kilometer.

Figure 7. Site Recon Photos: Photographs taken at the excavation at 8th and Thomas, Seattle, Washington, on February 14th, 2017. Sediment layer below the lagging (wood crib wall) is Qob, as evidenced by the grey sandy silt and prominent wood. The bottom of the excavation is approximately 44 feet below ground surface. The wooden planks shown in the photograph are 12 inches in from top to bottom.

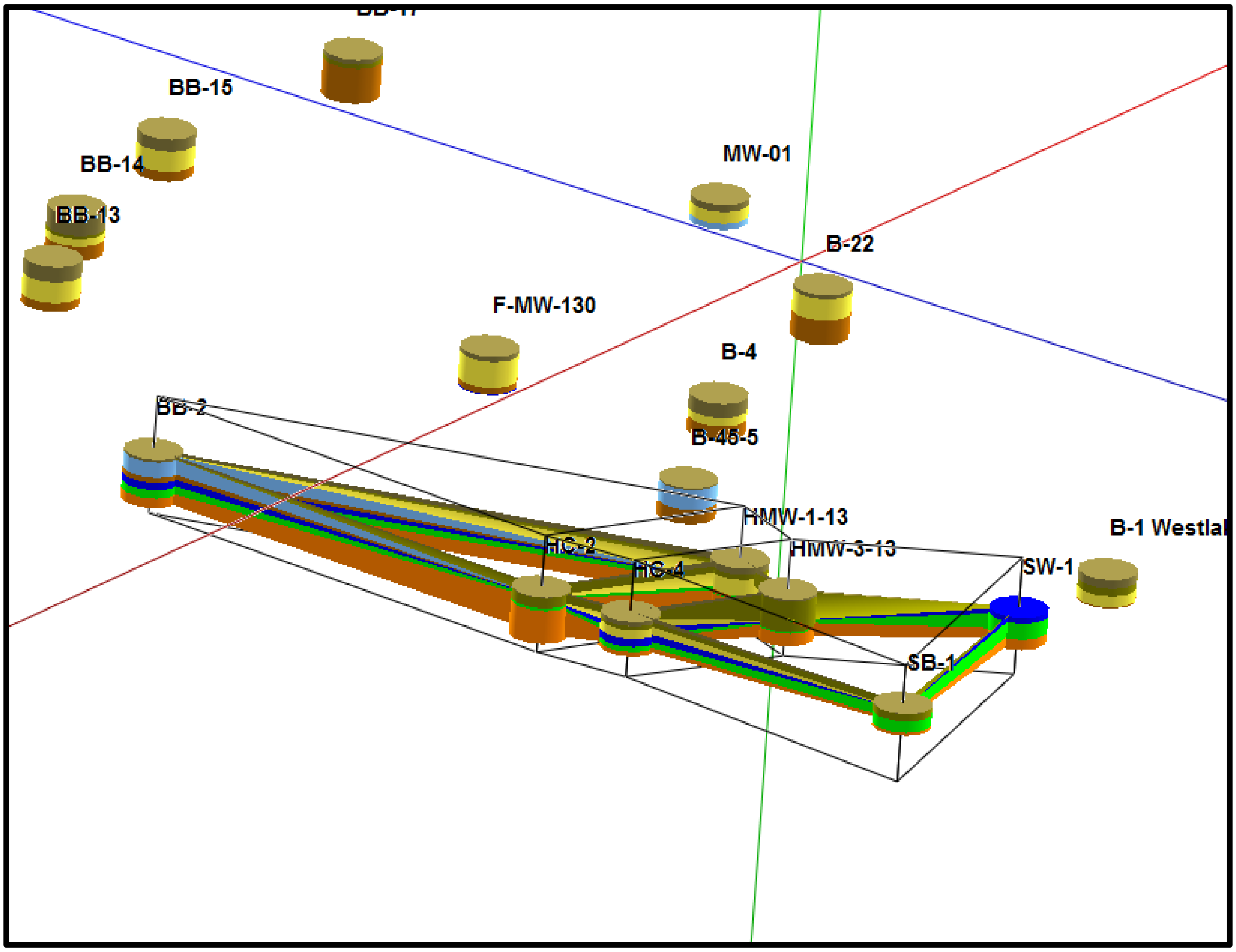

Figure 8. 2-D Cross Section Model: Oblique view of a 3-D Striplog model connecting all boreholes (colored cylinders) containing Olympia Bed (Qob). Model view is shown looking from the southwestern side of the project. Red, blue and green lines show coordinate axes, with blue indicating north-south (north to left) and green indicating up-down. Colors correspond to stratigraphic units; key to colors in Fig. 5. Qob is shown in bright green. The model displays the continuity and discontinuity found within the units.

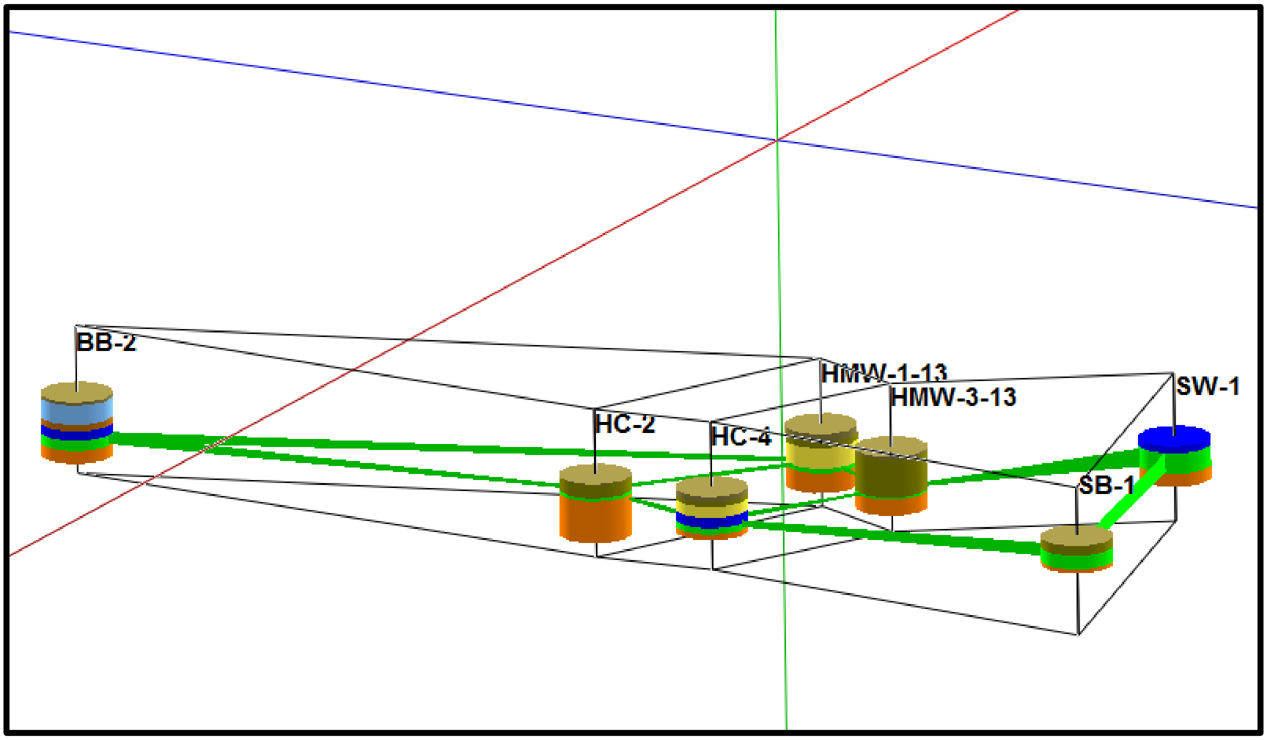

Figure 9. 3-D Model: 3-D Striplog model with only the Olympia Bed (Qob, green) deposits displayed. Image is looking from the southwest to the northeast, with the blue line indicating north to south. The model shows the Qob connectivity throughout the bore holes where Qob was observed.

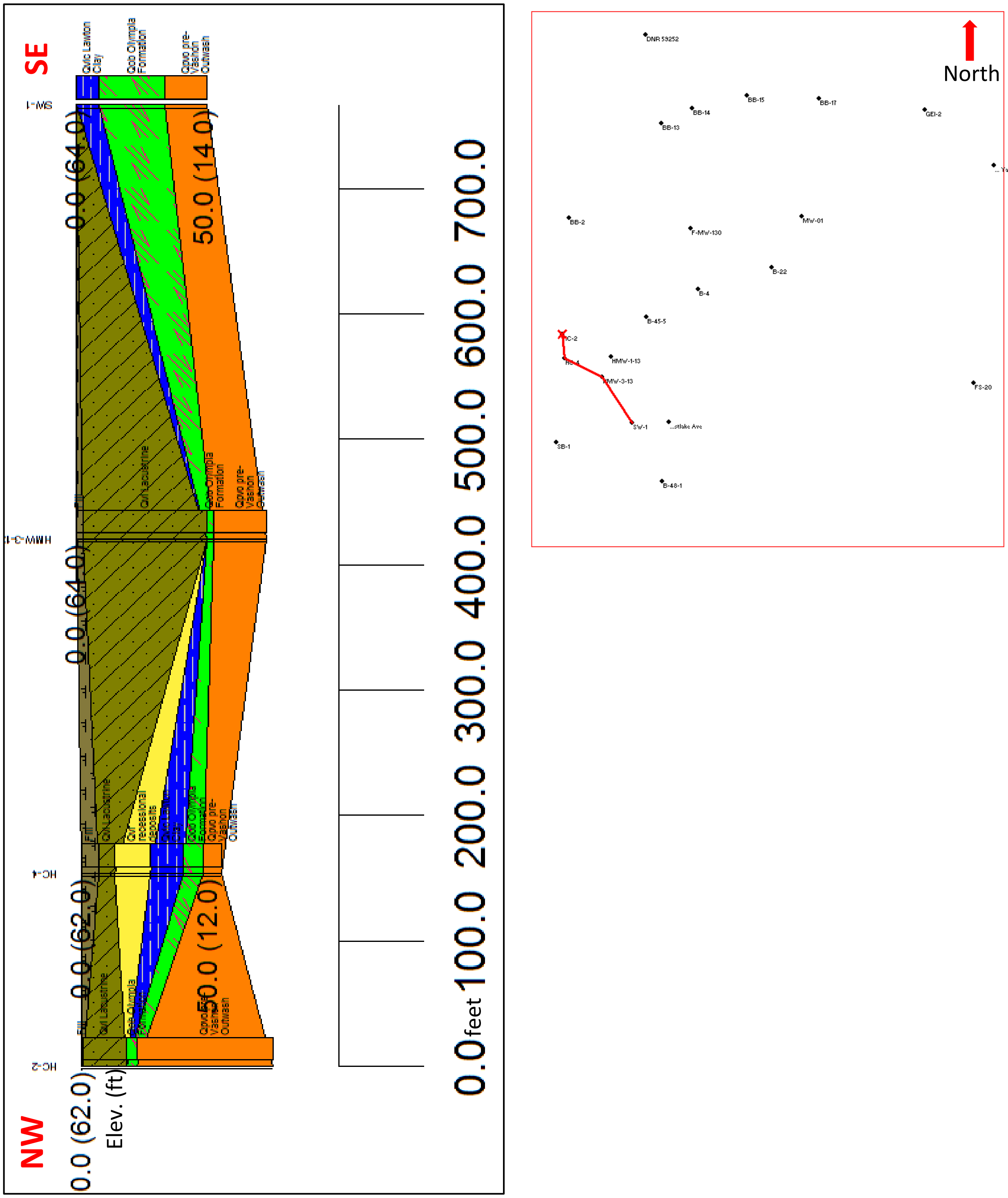

Figure 10. 3-D Model: Two-Dimensional Striplog cross section on the left was created with 4 bore holes containing the Olympia Formation (displayed in green). The cross section has surface elevations shown in parenthesis, depth below the surface is shown to the right of surface elevations. Vertical exaggeration is approximately 2.5:1 vertical to horizontal. The section selection map shown on the right indicates the bore holes selected in RockWorks 16. The image illustrates the subsurface valley feature and Qvr discontinuities.

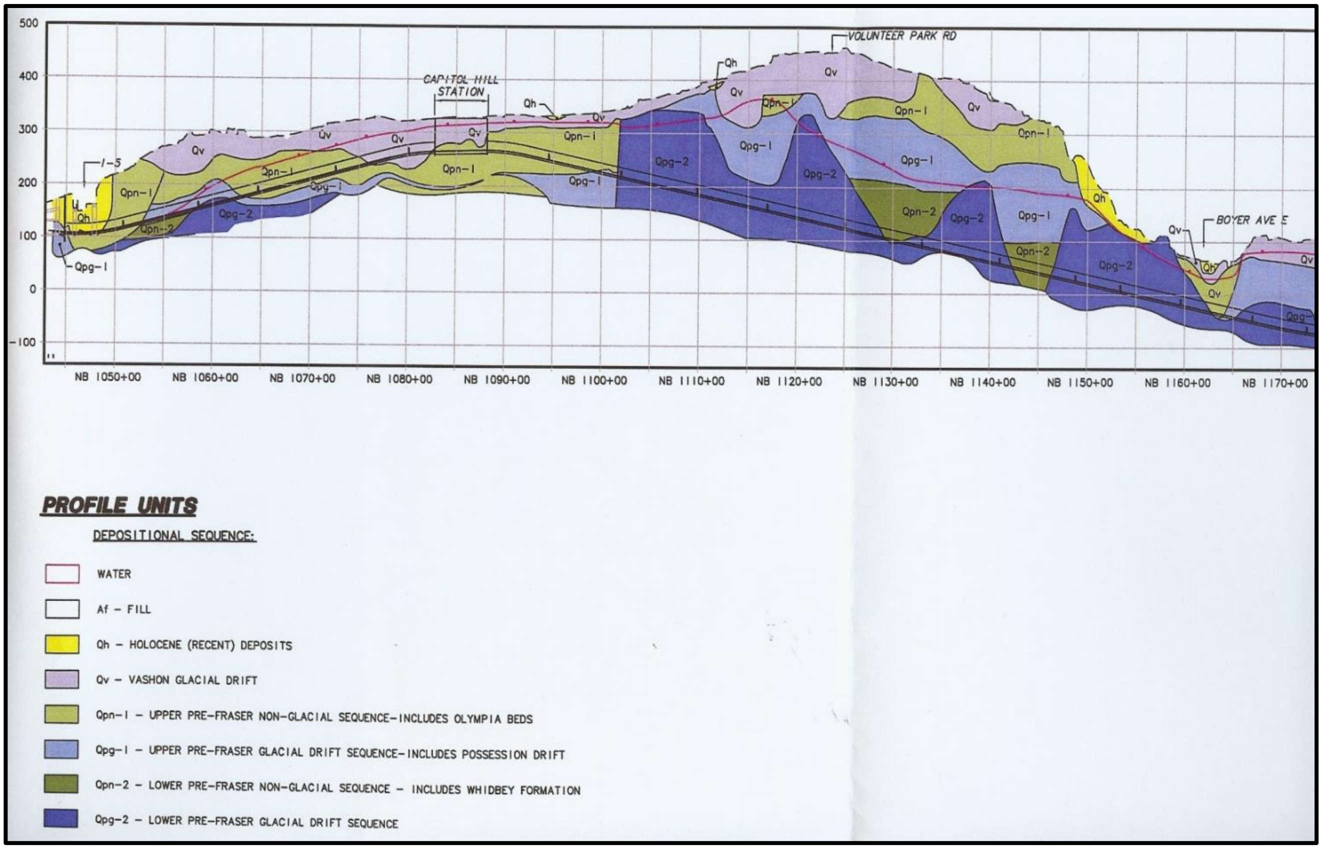

Figure 11. Capitol Hill Cross Section: Stratigraphy of Capitol Hill region of Seattle, east of SLU project area. Figure section compass reference is East on the right side going to the west side on the left. Interstate Highway 5 is shown on the far left. The Olympia Formation is grouped into the Qpn-1 sequence of deposition (light olive color), with the figure showing the terminus of Qpn-1 underneath I-5. Vertical and horizontal units are displayed in feet, one square on the figure is 100 feet. Figure Courtesy of Dave McCormack, Aspect Consulting.

10.0 Tables

Table 1. Order of stratigraphy units used in RockWorks 16 in Borehole Manager. All fields are customized based on the users desired model output.

Order	Formation	Pattern
1.0	Fill	
2.0	Qvl Lacustrine	
3.0	Qvr recessional deposits	
4.0	Qvt Till	
5.0	Qva advance outwash	
6.0	Qvlc Lawton Clay	
7.0	Qob Olympia Formation	
8.0	Qpvo pre-Vashon Outwash	
9.0	Qpvt pre-Vashon till	
10.0	Qpvl pre-vashon lacustrine	

Table 2. Example of the stratigraphy units used, and the assigned top and bottom depths to denote the start and end of each unit. Example is taken from Bore Hole B-1 at 624 Yale Avenue.

Depth to Top	Depth to Base	Formation
0.0	3.0	Fill
3.0	3.0	Qvl Lacustrine
3.0	3.0	Qvr recessional deposits
3.0	3.0	Qvt Till
3.0	3.0	Qva advance outwash
3.0	30.0	Qvlc Lawton Clay
30.0	30.0	Qob Olympia Formation
30.0	30.0	Qpvo pre-Vashon Outwash
30.0	51.5	Qpvt pre-Vashon till
51.5	51.5	Qpvl pre-vashon lacustrine

Table 3. Data used in calculating the strike and dip of Qob. Boring log holes used were, SB-1, SW-1, and HC-2.

	Azimuth	Distance	Elevation	Inclination(plunge)		
SB-1 High Elev	N/A	N/A	53.000	N/A		
SW-1 Middle Elev	184.000	532.900	40.000	1.397		
HC-2 Low Elev	255.000	494.000	29.000	2.781		
Linear 1			Linear 2			Theta
Cos(alpha)	Cos(beta)	Cos(gamma)	Cos(alpha)	Cos(beta)	Cos(gamma)	Angle(radians)
-0.070	-0.997	0.024	-0.965	-0.259	0.049	1.238
Cross-product	Cos(alpha)	Cos(beta)	Cos(gamma)	Pole	Pole	
3D	-0.045	-0.021	-0.999	Azimuth	Plunge	
Lower Hemi.	0.045	0.021	0.999	64.423	87.171	
Plane						
Strike (Azimuth	Dip	Quadrant				
334.423	2.829	W				

Table 4. Table shows the various contact depths for bore holes that contain Olympia Formation data.

Location Address (Seattle, WA.)	Bore Hole ID	Depth to Top of Qob (feet)	Depth to Bottom of Qob (feet)	Width (feet)	Sea level (feet)
781 Harrison St	HC-2	18	22	4	44 - 40
309 8th Ave	HC-4	40	48	8	22 - 14
325 8th Ave	HMW-1-13	44	50	6	17 - 11
300 8th Ave	HMW-3-13	51.5	54	2.5	12.5 - 10
766 John St	SB-1	12.5	30	17.5	70.5 - 53
216 9th Ave	SW-1	9	35	26	55 - 29
501 8th Ave	BB-2	49	62	13	10 - (-3)
Average		32	43	11	