Shear – and Compressional- Wave Velocity Measurements from Two 150-m-Deep Boreholes in Seattle, Washington, USA

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Introduction

The Puget Lowland region is located along the northwest coast of Washington State and lies within the tectonically active Juan de Fuca subduction zone. The urban centers and infrastructures of this region have been, and will be in the future, affected by earthquake ground shaking. Sources of potentially large (greater than **M** 6.5) earthquakes that would affect this region include: (1) thrust events along the Cascadia subduction zone, (2) deep earthquakes originating along the subducting oceanic plate, and (3) shallow crustal earthquakes on faults within the North American plate (Hartzell and others, 2002). During the last decade, substantial work has documented the location, extent, tectonic history, and potential seismic hazard of these major fault systems in the Puget Lowland (Bucknam and others, 1992; Pratt and others, 1997; Johnson and others, 1999, 2001).

Over the last one-half century the Seattle metropolitan area has experienced damaging ground shaking effects from multiple earthquakes. Earthquakes within the subducted oceanic plate [April 13, 1949 (*Ms* 7.1) and April 29, 1965 (*Ms* 6.5)], within 80 km (kilometers) of Seattle, produced widespread areas of Mercalli Intensity VII and localized VIII effects, particularly in West Seattle, that resulted in significant urban structural damage and 15 deaths (Algermissen and Harding, 1965; Mullineaux and others, 1967; Yelin and others, 1994; Williams and others, 1999). The February 28, 2001 (**M** 6.8) Nisqually earthquake (60 km southwest of Seattle) resulted in building damage, earthquake-induced ground failure and broad zones of liquefaction in the lower downtown area, Harbor Island and West Seattle (Troost and others, 2001; Frankel and others, 2002; Booth and others, personal communication, 2004).

Ground motion and site amplification are strongly influenced by the physical properties of near-surface geologic units through which the earthquake energy passes, as well as, by the underlying geometry of bedrock basins. Acquisition of near-surface shear-wave (V_S) and compressional-wave (V_P) data is thus important in understanding local and regional seismic hazard parameters. Previous studies have consistently shown that decreasing mean V_S velocity in the near-surface geologic materials generally correlates with an increase in the average amplification of earthquake ground motion (Brocherdt and Gibbs, 1976; Hartzell and others, 1996). Detailed near-surface seismic velocities are an important component in simulation modeling of urban ground motions and in the production of seismic hazard maps. Determination of near-surface V_S and V_P velocity also is motivated by the National Earthquake Hazards Reduction Program (NEHRP) model code provisions, which emphasize shallow S-wave velocity (Building Seismic Safety Council, 1994).

As part of a continuing program to gather velocity and geologic information in the Seattle metropolitan area, the U.S. Geological Survey (USGS) drilled and logged two 150-m (meters)-deep [500-ft (feet)] boreholes at Beacon Hill play field and Volunteer Park during the summer of 2002 (fig. 1). Sites were located with the intent of sampling representative glacial and interglacial deposits that are draped across two of the larger north-south-trending topographic highs in the Seattle metropolitan area. In general, substantially less information is available on internal thickness and unit velocity on these topographic highs than at the lower elevations and in areas of artificial fill (for example, Harbor Island, sport stadiums, and port industrial complexes). This preliminary report presents lithology profiles derived from cutting logs and core, plots of down-hole geophysical logs (natural gamma ray, spontaneous resistivity, temperature, and caliper), and a series of calculated borehole V_P- and V_S -wave velocity curves and models.

Figure 1. Composite geologic map of Seattle, Washington, (from Waldron and others, 1962; Shimel and others, 2003; Booth and other, written commun.2004; and Troost and others, written commun., 2004) showing geologic units grouped by degree of consolidation.

Geologic Setting

The Puget Lowland is a bedrock trough lying between coastal mountains (Olympic Mountains) and the Cascade Range. Bedrock, largely Tertiary in age, consists primarily of volcanoclastics and flows deposited in both marine and terrestrial environments that have been subsequently folded and faulted into a series of basins. These structural troughs have been largely filled with glacial and interglacial deposits up to 900 m (3,000 ft) thick. Bedrock is exposed only on the perimeter of the troughs and across the central Puget Lowland, where faulting has raised the bedrock above sea level. The modern topography was developed primarily by the last glaciation (the Vashon stage of the Fraser glaciation), with alluvial deposition and other post-glacial processes only slightly modifying the post-glacial surface. The predominant topographic features of the Lowland are a series of deep troughs, some of which are inundated by marine water of Puget Sound, and some at slightly higher altitude currently occupied by rivers, bogs, and lakes. A secondary local topographic feature is the series of predominantly north-south elongate hills that indicate glacial flow direction (fig.1).

Glaciers have advanced into the Puget Lowland at least seven times in the last 2 million years, each time partly eroding and partly depositing sediments. Therefore, the subsurface consists of a complex sequence of unconformities bounding the glacial deposits. Deposits that have been overridden by the Vashon-age ice sheet (or previous glaciers) are overconsolidated, having been buried in Seattle by approximately 1 km (3,300 ft) of ice. In contrast, much of the silty and sandy alluvium that fills the deep glacial troughs after the Vashon-age ice retreated about 13,500 years ago is loose and saturated to depths of 150 m (500 ft).

Glacial deposits in the Lowland variously consist of outwash, lacustrine sediments, till, and glaciomarine drift. Interglacial deposits consist of alluvium, colluvium, lacustrine sediments, volcanic deposits, and soils. The generalized surficial geology of the Seattle area (fig. 1) is based on preexisting mapping and interpreted surficial geology at both borehole sites. A composite stratigraphic column of Pleistocene glacial and interglacial events for the Puget Lowland area is presented in figure 2.

Figure 2. Comparison of the marine oxygen-isotope curve stages (MIS) using the deep-sea oxygen isotope data for ODP677 from Shackleton and others (1990), global magnetic polarity curve (Mankinnen and Dalrymple, 1979; Berendregt, 1995; Cande and Kent, 1995), and ages of climatic intervals in the Puget and Frasier lowlands. Ages for deposits of the Possession glaciation through Orting glaciation from Troost and others (2003c), Easterbrook and others (1981), Easterbrook (1986), Blunt and others (1987), and Easterbrook (1994). The Redondo interglaciation and Defiance Drift are informally named and dated by Troost and others (2003b). Additional ages from deposits of the Puyallup interglaciation from R.J. Stewart (written commun., 1999). Ages for the Olympia nonglacial interval from Armstrong and others (1965), Mullineaux and others (1965), Pessl and others (1989), and Troost (1999). Ages for the Coquitlam stade from Hicock and Armstrong (1985); ages for the Port Moody interstade from Hicock and Armstrong (1981). Ages for the Vashon stade from Armstrong and others (1965) and Porter and Swanson (1998). Ages for the Everson interstade from Dethieret and others (1995) and Kovanen and Easterbrook (2001), and Kovanen (2002). Many other glacial and interglacial depositional periods likely exist but not yet identified in the Puget lowland.

Drilling and Geophysical Logging

The Volunteer Park borehole (VPD) is located on the northern flank of Capital Hill, at an elevation of approximately 140 m (450 ft) (fig. 3). The borehole bottomed at an approximate elevation of -10 m (-33 ft) below mean sea level (MSL). The Beacon Hill play field borehole (BHP) is at an elevation of 95 m (320 ft) on the upper west flank of Beacon Hill and is approximately 5 km south of the Volunteer Park site (fig. 4). Both boreholes were located near the top and on the flank of two elongate hills that are cored by glacially overridden deposits of Vashon and pre-Vashon age.

Figure 3. Map showing the location of Volunteer Park in the Seattle, Washington area. The 153-m- (500-ft-) deep, 15-cm- (6.0-in-) diameter research drill hole was drilled using a Failing SD-300 drill rig. Photo shows site location, drill rig, and support equipment.

Figure 4. Location of the Beacon Hill play field borehole (13th and Holgate St). The 153-m- (500-ft-) deep hole was drilled in June 2002, downhole compressional- and shear-wave velocity logging was completed in September 2002. Photo shows downhole logging acquisition (photo by Joe Depner, Seattle, Washington).

Drilling and geophysical logging of both boreholes was done by the USGS, Water Resources Western Region Research Drilling Unit, Henderson, Nevada, using a Failing SD-300 drill rig (fig. 3). The upper 130-m (425-ft) section of each hole was drilled with a tri-cone rotary bit to produce a 6-in. (inches)[15.2-cm (centimeter)] diameter hole. The lower 23 m (75 ft) of both holes was continuous wire-lined cored in 3-m (10-ft) increments. Cores were recovered within plastic tube liners and sealed to prevent moisture loss. Following completion, holes were cased and grouted with 4.0-in.- (10.16-cm) diameter polyvinyl chloride (PVC) casing and sealed with locked well-observation caps.

Generally, the description for the upper 130 m of each hole are based on collected grab samples (cuttings) retrieved during drilling. Descriptions for the lower (130 to 152 m) section of each borehole are based on the analysis of recovered core. A detailed lithologic log for each borehole is presented on figures 5 and 6. The resulting data versus depth for a standard suite of borehole geophysical logs (natural gamma ray, spontaneous resistivity, temperature, and caliper) for the Volunteer Park and Beacon Hill play field sites, respectively, are shown on figures 7 and 8.

Figure 5. Lithologic log for the Volunteer Park borehole. See text for discussion.

Figure 6. Lithologic log for the Beacon Hill play field borehole. See text for discussion.

Figure 7. Standard suite of borehole logs obtained at the Volunteer Park site. From left to right, the logs presented are natural gamma, resistivity, temperature, and caliper.

Figure 8. Standard suite of borehole logs obtained at the Beacon Hill play field site. From left to right, the logs are natural gamma, resistivity, temperature, and caliper.

Downhole Seismic Logging

In September 2002, the Volunteer Park and the Beacon Hill play field boreholes were logged for V_P- and V_S-wave velocities. Accompanying the figure 4 location map (Beacon Hill play field site) is a photograph showing the typical equipment arrangement for obtaining borehole velocities. Procedures for acquiring borehole velocity data are discussed by Gibbs and others (1999), and significant details pertaining to this study are summarized in the following paragraph.

Data was acquired at 2.5-m (8.3-ft) depth intervals using a three-component geophone clamped to the wall of the grouted casing by an electrically controlled lever arm. Surface shear-wave energy was generated by impacts of an air-powered horizontal hammer on an anvil at the end of an aluminum box 2.3 m (7.5 ft) long positioned beneath the wheels of a truck (see figure 4 photograph) (Liu and others, 1988). To generate pulses of opposite polarity, the hammer was first driven in one direction and then in the opposite direction. Timing of arrivals was synchronized using a seismic switch attached to the hammer box. Compressional-wave energy was generated by striking a steel plate with a sledgehammer equipped with a seismic switch. The shear- and compressional-wave sources were offset from the borehole (same horizontal distance) to reduce energy wave interference caused by surface-wave travel down the grouted casing (Gibbs and others, 1999).

Data Processing and Analyses

Because the azimuth orientation of the recording three-component geophone (one vertical and two orthogonally oriented receivers) with respect to the energy source cannot be controlled on its descent down the borehole, it varies for each interval point measured (Gibbs and others, 1999). The following processing steps were used to compensate for this effect and to compute the final V_S- and V_P-wave interval velocity curves.

Processing

1) Convert data format from SEG-2 to Promax (seismic processing software).

2) Coordinate rotation of two horizontal components using eigenvectors of cross-energy

matrix to determine principal component direction.

3) Minimum phase band-pass filtering:
P-wave filter 40-80-200-400 Hz.
S-wave filter 10-20-200-400 Hz.

4) Interactively pick first breaks in Promax:
Pick P-wave arrival on first prominent trough.
Pick S-wave arrival on common but opposite break in traces for opposed-source impacts.

5) Picked travel times ported from Promax to Matlab (seismic processing software) for analysis. First-break travel time picks (P- and S-wave velocities) for both boreholes are plotted on figure 9.

Figure 9. First arrival time versus depth picks from individual shot records acquired at 2.5-m depth intervals. Compressional (P=open symbols) and shear (S=solid symbols) picks are plotted for Beacon Hill and Volunteer Park.

Interval Velocity Versus Depth Curves

1) Picked travel times are converted to vertical times.

2) Various velocity estimates are calculated (see colored velocity covers on figures 10 and 11). Average velocity (total depth / total vertical travel time)
Interval velocities (vint 1, vint 2, and vint 4) over 5, 10, and 20 m intervals.

Figure 10. Downhole compressional (P)- and shear (S)-wave velocity curves from the Volunteer Park site. Curves are calculated by averaging travel times over 5-m (blue), 10-m (black), and 20-m (red) depth intervals, and an overall average (green). Borehole velocity measurements were conducted to a depth of 153 m, but are plotted to 160 m depth.

Figure 11. Downhole compressional (P)- and shear (S)-wave velocity curves from the Beacon Hill play field site. Curves are calculated by averaging travel times over 5-m (blue), 10-m (black), and 20-m (red) depth intervals, and an overall average (green). Borehole velocity measurements were conducted to a depth of 153 m, but are plotted to 160 m depth

Plots of Vp- and Vs-wave velocity curves versus depth for the Volunteer Park site are shown on figure 10. Curves are average velocity (green) and for interval groups of 5 m (blue), 10 m (black), and 20 m (red). V_P and V_S-wave velocity curves versus depth for the Beacon Hill play field site are shown on figure 11. As more data points are grouped in the averaging process, thus sampling a wider depth interval, the range of velocity fluctuations is compressed.

Least-Square Modeling

Analyses of interval average velocity versus depth are based on grouping consecutive data points over selected depth intervals and do not account for changing lithologic properties or unit thicknesses. To correlate velocities with lithology, downhole travel-time plots were constructed using a least-squares modeling program (VELSLANT) which incorporates constant velocity layers that take into account refraction across boundaries between layers (Gibbs and others, 1999). See Gibbs and others (1999, page 11) for a detailed explanation of the VELSLANT least-squares modeling steps.

Travel time versus depth picks, interpreted boundary lines, and resulting residuals for both P- and S-wave least-squares velocity models for the Volunteer Park and Beacon Hill play field boreholes are shown on figures 12 and 13. Assignment of normalized standard deviations for travel time picks (confidence indicators) are color coded. Black dots signify picks of the highest confidence level. The standard suite of borehole geophysical logs, lithologic columns, and the shear-wave (Vs) least-squares velocity models for the Volunteer Park and the Beacon Hill play field sites are presented on figures 14 and 15. A summary plot of all V_P and V_S interval velocity and least-squares model curves versus depth along with the interpreted borehole stratigraphy for both sites are shown on figures 16 an17.

Figure 12. First-break residuals and layer-boundary residuals (color code indicates confidence of pick) derived from least-squares modeling (VELSLANT, Gibbs and others, 1999) for Volunteer Park P- and S-wave data. See text for discussion.

Figure 13. First-break residuals and layer-boundary residuals (color code indicates confidence of pick) derived from least-squares modeling (VELSLANT, Gibbs and others, 1999) for Beacon Hill play field P- and S-wave data. See text for discussion.

Figure 14. Volunteer Park shear-wave least-squares velocity profile with dashed yellow lines representing plus and minus one standard deviation. Generalized geologic log from borehole cuttings and downhole geophysical logs (fig.7) is shown for correlation with velocity profile. See figure 5 for detailed lithologic log.

Figure 15. Beacon Hill play field shear-wave least-squares velocity profile with dashed yellow lines representing plus and minus one standard deviation. Generalized geologic log from borehole cuttings and downhole geophysical logs (fig. 8) is shown for correlation with velocity profile. See figure 6 for detailed lithologic log.

Figure 16. Volunteer Park borehole summary plot showing all compressional (P)- and shear (S)-wave velocity curves, least-squares velocity model (fig. 14), and lithology from borehole cuttings and core.

Figure 17. Beacon Hill play field borehole summary plot showing all compressional (P)- and shear (S)-wave velocity curves, least-squares velocity model (fig. 15), and lithology from borehole cuttings and core.

Discussion

Volunteer Park Borehole

Interpretation of drillhole cuttings, recovered core and regional geology mapping indicate that the 152-m (500-ft) Volunteer Park borehole penetrates an advance outwash of the Vashon stade (geologic map unit Qva), a thick glaciolacustrine deposit from a previous glaciation (Qpogl), and finally deposits from an interglacial interval (Qpon).

Qva "Esperance Sand"-Advance Outwash Deposits

Drilling at the VPD site penetrated 52 m (157 ft) of Vashon advance outwash (Qva), which also is known locally as the Esperance Sand member of the Vashon Drift (Mullineaux and others, 1965). At VPD, the Qva consists of silty sandy gravel and fine, medium, and coarse sand, with gravel and silty sand. The sand is horizontally bedded to cross-bedded, having been deposited by streams issuing from the advancing ice sheet. Within this unit, the upper sandy gravel grades from gravelly near the ground surface to relatively clean sand in the middle section, and then into a silty-clayey section at its base.

For purposes of discussion, the uppermost velocity layer (for example surface to 3 m depth) will be ignored, as it is defined by a single data point and is believed to represent a mixture of compacted soils and Qva material. With respect to seismic velocity structure, the 52-m-thick Qva unit can be subdivided on the basis of V_P and V_S curves, which show good correlation with both borehole geophysical logs and the lithology logs (figs. 5, 14, and 16). The V_P-velocity model shows three distinct subdivisions. An upper (surface to 21 m depth) sandy gravel to gravelly sand unit has an average Vp of approximately 575 meters/second (m/s). Beneath this gravel-rich unit, from 21 to 45 m depth, a middle unit of silt free, fine to medium sand has an average Vp of approximately 1,125 m/s. From 45 to approximately 52 m depth, a lower (basal) Qva unit is predominantly composed of silty sand with a trace of fine gravel. This lower, fine-grained "dirty" unit has a Vp velocity nearly three times higher (3,050 m/s) than the other overlying Qva units. The reason for the high Vp velocity of this 7-m-thick layer is not known at this time.

The V_S -velocity model for the Qva unit also shows three distinct subunits. The upper gravel rich unit (3 to13 m depth) has a Vs velocity of 250 m/s. The middle unit (13 to 23 m depth), composed of less gravel and more clean sand, has a Vs velocity of 390 m/s. The lower Qva section (23 to 52 m depth) is relatively consistent with only minor fluctuations in areas where logging indicates an increase in gravel content. This unit has an averages V_S velocity of 580 m/s.

Qpogl-Glaciolacustrian Deposits

Drill cuttings, core and borehole geophysical logs (figs. 5 and 7), and velocity models (figs. 14 and 16) indicate a relatively abrupt transition in lithologic materials at the base of the sandy Qva unit. The caliper log (fig. 14) shows a marked change in the erodablity of the upper most part of this Qpogl unit, possibly indicating an erosional contact with reworked material over a few meters.

This unit (Qpogl), composed of thick, hard, blue-gray, silty, high-plasticity clay, is glaciolacustrine in origin (pre-Olympia in age, greater than 60,000 years old) and likely marks the transition from a nonglacial to a glacial environment. Bed orientations range from horizontal to 45 degrees in dip with fractures and sand lenses. From figures 14 and 16, it is evident that, although there are small variations in V_P-wave velocity and a relative small stepped increase in Vs-wave velocity from 460 to 500 m/s at a depth of 80 m, this section (52 to134 m) is relatively homogeneous with respect to lithology and seismic velocity. The V_P velocity average is approximately 1,715 m/s and the V_S velocity average is 480 m/s.

Qpon-Nonglacial Deposits

The interval between 134 and 153 m (442 and 500 ft) (for example, the bottom of the borehole) consists of interbedded silty clay, clayey silt, and sandy silt, with minor organic stringers (fig. 5) and is interpreted to be an interglacial deposit. This unit must be greater than 80,000 years old based on its lithologic position and may represent a low-energy fluvial or lacustrine environment. The silt and clay interbeds vary from low to high plasticity. The bedding ranges from subhorizontal to steeply dipping.

Within this section, V_P and V_S-velocity models are similar because they both show higher velocities for the silty clay and clayey silt beds above and below a slower sandy bed. V_P velocity for the thickest sandy bed is approximately 1,525 m/s with the average velocity of the finer-grained beds being approximately 2,000 m/s. V_S velocity of the sandy bed is 460 m/s with the finer-grained lithologies having an average velocity of 560 m/s. The overall average V_P velocity is 1,780 m/s with a V_S velocity of 500 m/s (figs. 14 and 16). The slightly higher VP and V_S velocities for this section in comparison to the overlying Qpogl section, which consists for the most part of similar lithologic materials, may result from its age and the presence of sandy beds, which would have allowed better dewatering during consolidation.

Beacon Hill Play Field Borehole

Interpretation of borehole cuttings and regional geology indicate that the subsurface consists of a sequence of the Vashon advance outwash (Qva), Lawton Clay (Qvlc), glaciolacustrine deposits from the Possession glaciation (Qpdl), and older interglacial and glacial deposits (Qpon, $Qpog_t$, and Qpogl). VPD and BHP have some similarities. Both boreholes penetrated thick Vashon advance outwash near the ground surface, and both have thick glaciolacustrine silty clay near the middle depths of the boreholes. Compared to the Volunteer Park site, the Beacon Hill borehole has better stratigraphic and chronologic control as a result of recent mapping and dating investigations (Troost, and others, 2003c).

Qva “Esperance Sand”-Advance Outwash Deposits

Immediately beneath the ground surface is approximately 5 to 7 m of fill and disturbed soil deposited during construction of the playground. From 7 to 38 m depth, the borehole penetrated gravelly sand of the Vashon advance outwash (unit Qva). Similar to VPD, borehole geophysical logs and cuttings (figs. 6 and 8) correlate well with V_P and V_S curves (figs. 15 and 17) supporting a velocity model for the Qva section that consists of three layers, an upper gravelly, slightly silty sand layer (7-12 m), a middle clean, well-graded sand with minor amounts of gravel (12-26 m), and a lower, silty sand with some gravel (26-38 m).

V_P and V_S least-squares models (figs. 15 and 17) show similar unit thickness and a velocity increase for each unit. The upper, middle, and lower units have V_S velocities of 360, 485, and 675 m/s, respectively. V_P velocities for these same units are 875, 1,500, and 1,750 m/s, respectively. The lower Qva sand unit in both boreholes (figs. 15 and 17) form a distinct V_P- and V_S-velocity boundary with respect to the overlying, more gravel-rich to clean and well-graded Qva material and a significant velocity inversion with the underlying dense silty clay glaciolacustrine units.

Qvlc “Lawton Clay”-Glacialacustrine Deposits

Glaciolacustrine deposits, the Lawton Clay member of the Vashon Drift (Mullineaux and others, 1965) (map unit Qvlc), underlies the Qva. The contact between these units is sharp on geophysical logs, V_P- and V_S-velocity curves, and borehole cuttings log indicating a probable erosional contact. The Qvlc [38 to 42 m (127 to 137 ft) depth] is predominantly laminated to massive silty clay with trace sand and gravel (figs. 6, 8, 11, and 15). Lawton Clay was not identified in the VPD borehole, either because it may be indistinguishable from unit Qpogl or was not deposited on the higher elevation pre-Vashon surface at that site.

The Lawton Clay was deposited during the transition from a nonglacial to glacial environment about 15,000 years ago in the Seattle area and represents the earliest part of the Vashon Drift glacial sequence. Both Vp and Vs velocities for the Qvlc unit are among the lowest values recorded within this borehole. The Vp velocity varies from 400 to 800 m/s over this 4-m-thick interval. The Vs-wave velocity is consistently 420 m/s. These velocities are similar to the lower range of values determined for the underlying Possession glacialacustrine deposit (Qpdl).

Qpdl-Glacialacustrine Deposits of the Possession Glaciation

Underlying the Qvlc unit is a 70-m-thick [42 to12 m, (137 to 370 ft) depth] section of Possession glaciolacustrine deposits (map unit Qpdl), about 70,000 years old (Troost and others, 2003c). The Qpdl deposit at Beacon Hill is lithologically similar to the Qpogl section in the Volunteer Park borehole; however, it is presently unclear if they are of equivalent age. At BHP, the Qpdl consists of hard silty clay with slightly sandy zones having a trace of gravel. Geophysical logs and borehole cuttings (figs. 6, 8, and 15) indicate a change in the lithologic character in the Qpdl unit at approximately 80 m depth. Except for an approximate 10-m-thick section where the V_P velocity drops to 1,000 m/s, the V_P velocity is a relatively consistent 1,710 m/s. The V_S velocity model shows a reduction in velocity from 520 m/s in the upper part of the unit to a low of 400 m/s in the lower part of the unit, with an overall average of approximately 450 m/s. The V_S velocity in the lower section is comparable to the velocity of the Qvlc unit. Both V_P and V_S velocity changes occur at a depth that correlates with significant changes in the natural gamma, resistivity, caliper, and temperature logs. The drop in velocity may indicate that the silts and clays did not drain as quickly as those in the upper parts of the units.

Qpon-Nonglacial Deposits

The interval between 112 and 128 m (370 and 420 ft) is interpreted as a series of interglacial deposits consisting of interbedded silt, clayey sand, sandy silty clay, and sandy silt (fig. 6). These deposits are at least 80,000 years old and represent a low-energy fluvial or lacustrine environment. The clayey interbeds are of low plasticity.

Both Vp and Vs velocities are uniform within this unit. The Vp velocity is 1,800 m/s and the Vs velocity is 580 m/s. These velocities are slightly higher than the high-end range of velocities determined for the overlying Qpdl unit, although the litholodic composition of the units is similar. This probably is a reflection of the greater age of the Qpon unit and/or increased consolidation.

Qpog$_t$-Till, Qpon-Nonglacial, and Qpogl-Glacialacustrine Deposits (128 m to bottom of hole)

Borehole lithologic cuttings and borehole geophysical logs correlate with a distinct velocity boundary at the base of the Qpon unit (128 m). From 128 to 146 m (420 to 480 ft) depth, the lithology is a slightly clayey, silty, gravelly sand with lenses of clayey gravel, and sandy clay (fig. 6). This sequence is interpreted to be a glacial till (Qpog$_t$). The age of this till has not yet been determined. The till contains clay and silt lenses and beds dipping 30 to 40^o. The glacial till unit overlies a 5-m-thick unit (Qpon) between 146 and 151 m (480 and 498 ft) depth, which is interpreted to be interglacial deposits consisting of interbedded silt, clayey silt, and sandy silt with clay laminae and traces of fine organic debris (fig. 6). These deposits are at least 190,000 years old and represent a low-energy fluvial or lacustrine environment. From a depth of 151 m to the bottom of the hole at 153 m, cuttings and core indicate glaciolacustrine deposits (Qpogl) consisting of hard silty clay with dropstones. The high-plasticity clay has many slickenside surfaces and fractures. Reduced drilling penetration rates beginning in the overlying unit indicate that these materials are very dense and hard, possibly from overburden stresses induced by ice contact and being overridden by at least two ice sheets.

Velocity modeling indicates that this section of the borehole (146 to 153 m) appears to be seismically homogenous. The V_P velocity for the section is 2,255 m/s, and the V_S velocity over the same section is 930 m/s. Both the V_P and V_S velocities interpreted for this section are the highest encountered within this borehole, or for materials of similar composition found in the lower section of the Volunteer Park borehole.

Conclusions

In both the Volunteer Park (VPD) and Beacon Hill play field (BHP) boreholes, the surficial deposit is the coarse-grained Vashon Drift outwash (Qva “Esperance Sand”). This unit, thicker at the VPD site, overlies thick [86 and 74 m (282 and 243 ft), respectively] and relatively homogenous sections of glaciolacustrine clay to silty clay in each borehole. In both boreholes, a nonglacial unit is identified beneath the glaciolacustrine deposit. Whereas the VPD borehole terminates in this nonglacial deposit, the BHP borehole penetrates an additional 18 m of pre-Olympic till (age unknown), 5 m of nonglacial material, and finally terminates in a glaciolacustrine unit that is at least 190,000 years old in age.

The Vashon Drift advance outwash varies in thickness from approximately 48 m (148 ft) at VPD to 26 m (85 ft) at BHP. Based on lithology, borehole geophysical logs, and borehole Vp and Vs models, the Qva unit can be subdivided into three zones: an upper, silty to sandy gravel zone; middle zone of fine to coarse relatively clean sand with local gravel; and a lower zone of dense, very silty sand. Shear-wave velocity models at the two sites show an increase in velocity of 43 to 54 percent, respectively, between the upper and the lower Qva layers (250 to 580 m/s at VPD and 370 to 675 m/s at BHP). The only geologic interface to have a higher velocity impedance is found near the bottom of BHD where nonglacial deposits, underlain by till, jump in V_S velocity from 580 to 930 m/s. Based upon results from both boreholes, overall Qva V_S velocity is estimated to be 505 m/s. These values are nearly identical to the Vs low of 250 m/s and an average V_S of 500 m/s for the Qva unit [reported by Williams and others (1999, 2001)], using a surface refraction/reflection method.

In both boreholes, the coarse-grained glacial outwash unit is underlain by thick glaciolacustrine deposits. Both V_P and V_S velocities for this section show minor variability. At the BHP borehole, the glaciolacustrine deposit of the Vashon Drift, Lawton Clay (Qvlc) member may be present (38 to 42 m). The seismic velocities for this unit are V_P 600 m/s and V_S 450 m/s. Williams and others (1999, 2001), using a surface refraction/reflection method, also determined a V_S of 400 m/s for the Lawton Clay member. Although the V_S for the Lawton Clay is one of the lowest recorded in either borehole, its velocity is similar to that determined for the underlying glaciolacustrine deposits of the Possession glaciation in the Beacon Hill borehole and for similar lithology in the Volunteer Park borehole. These glaciolacustrian deposits have a Vs average of 500 m/s (480 to 520 m/s range) at VPD and 450 m/s (390 to 520 m/s range) at BHP, with an overall estimated Vs of 475 m/s.

Beneath the glaciolacustrine deposits both boreholes encounter pre-Olympia nonglacial deposits (Qpon). In general, lithologic composition and seismic velocity for this unit is similar in both boreholes. The V_S for VPD and BHP is 500 and 580 m/s, respectively, with an estimated average value of 550 m/s. The average V_P for these nonglacial sediments is 1,800 m/s.

Borehole BHP encountered a hard dense till unit ($Qpog_t$) at a depth of 128 m. The highest shear-wave velocity impedance boundary encountered in either borehole is found at this nonglacial deposit till interface. The average Vs increases abruptly from 580 m/s (nonglacial) to 930 m/s (till). Williams and others (1999, 2001), using a surface refraction/reflection method, determined a range of 360 m/s (near-surface and weathered) to 755 m/s (deeper) for the Vashon till. These values for till-type material fit well with that determined for the till unit measured near the bottom of the Beacon Hill borehole. The higher Vs velocity probably reflects both its older age and greater degree of compaction.

The pre-Olympia till unit is underlain by a relatively thin unit of nonglacial material; the borehole terminates in a glaciolacustrine deposit. An insignificant number of downhole-velocity data points were obtained beneath the till.

The average shear-wave velocity structure for the materials encountered in both boreholes is presented in figure 18. Similar lithologies in both boreholes have similar shear-wave velocities with the velocities from the Beacon Hill site being slightly faster. The greatest variability of velocity is observed between the Qva zones. A velocity inversion (a transition from higher to lower velocity) occurs at the boundary between the lower Qva unit and the underlying glaciolacustriane unit in both boreholes. The overall average shear-wave velocity for Qva is 505 m/s. This average velocity is approximately the same velocity as determined for glacialacustrine and nonglacial units in both boreholes (fig. 18). Another significant velocity boundary is observed in the Beacon Hill play field borehole, where there is an increase of approximately 38 percent between nonglacial units and a till near the bottom of the borehole.

Figure 18. Summary of average shear-wave velocity of the major geologic units measured by downhole methods at Volunteer Park and Beacon Hill play field. Units are in their natural occurring descending stratigraphic position. Qva (Vashon Drift advance outwash) is subdivided into three units based upon least-squares models. Yellow bar indicates the overall average Vs velocity for the entire Qva unit in both boreholes.

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