CHEMICAL BUILDING SEISMIC TRENCHES
BRIGHTWATER WASTEWATER TREATMENT PLANT SITE
SNOHOMISH COUNTY, WASHINGTON

Submitted to
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Wastewater Treatment Division
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MACTEC

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EXECUTIVE SUMMARY

King County constructed three seismic trenches in June, July, and August 2006 to help determine the locations of two new chemical storage buildings at the Brightwater Treatment Plant site. The two chemical buildings will be approximately 1,200 feet apart and have secondary containment systems to prevent any spills from getting away from the building. Previous seismic studies determined that Lineament 4, in the northern portion of the site where no new buildings are planned, was an active trace of the Southern Whidbey Island fault (SWIF). No evidence of active faulting suggested that traces of the SWIF might be present where the chemical storage buildings were planned. However, King County committed to move the chemical storage buildings if active faults, as defined by the International Building Code, were found under the proposed locations. The seismic study described in this report was designed to determine if the chemical storage buildings needed to be moved to avoid active faults. The 2003 International Building Code defines an active fault as on that has a historic slip rate of 1 mm per year or more and evidence of having moved during Holocene times (within the most recent 11,000 years before present).

The planned location of the North Chemical Building currently is a paved road with buried utilities in active service. The seismic trench for the North Chemical Building was shifted to a position that would intercept traces of the SWIF parallel to Lineament 4 that, if present, would likely pass through the chemical building location.

Two sets of seismic trenches were constructed to examine the proposed site of the South Chemical Building. Additional trenches in each set allowed the Seismic Study Team to follow up specific features and to resolve questions. To avoid a then-active drain line at the planned location for the South Chemical Building, the first set of trenches was located near the building site rather than on it, similar to the north trench. The Team subsequently dug a second set of trenches at the building site itself, after the drain line was no longer in use.

The Seismic Study Team found evidence in the seismic trenches that no active faults as defined by the 2003 International Building Code are present and concluded that the chemical buildings could be built safely in their planned locations. The seismic trenches constructed for the South Chemical Building showed no evidence of faulting since glaciers retreated from the Seattle area about 16,570 years before present. The seismic trench constructed for the North Chemical Building showed very dense glacial till deposits compacted by the weight of glacial ice. Cracks in the glacial till deposits were filled with sand and silt that was also very dense and interpreted to be compacted by the weight of glacial ice. Therefore, the seismic trench for the North Chemical Building showed no evidence of faulting since glaciers were present in the Seattle area more than

about 16,570 years before present. The seismic trench findings are consistent with published information indicating that suspected active traces of the SWIF do not pass through the Brightwater site where treatment plant facilities are planned.

INTRODUCTION

The Brightwater Wastewater Treatment Plant site is located in southern Snohomish County near its boundary with King County (Figure 1). Representatives of the two counties entered into a Development Agreement dated October 11, 2005, which required King County to “construct two additional trenches across portions of the site in between lineament 4 and the postulated lineament X (located on the southern portion of the site), in order to prevent the placement of certain chemical facilities over unknown seismic faults and to minimize the risk of a chemical spill or release during a seismic event.”

Presented in this report are the results of geologic examination of trenches excavated at the Brightwater site during June, July, and August 2006. These trenches are part of geologic/seismic studies undertaken at the site since 2004 when the Southern Whidbey Island fault (SWIF) was identified near the site by the U.S. Geological Survey (USGS). In the earlier investigation, two trenches were excavated on the site in September and October 2004 at locations selected by a USGS geologist with concurrence by King County and its consultants. The trenches were located along a northwest-trending lineament (Lineament 4) identified by USGS scientists using aeromagnetic and LiDAR data in a study published as USGS Open-File Report 2004-1204 (Blakely et al., 2004). Evidence of seismic activity was interpreted from exposures in both trenches. The USGS interpretation of these trenches was published as USGS Open-File Reports 2005-1013 (Sherrod et al., 2005a) and 2005-1136 (Sherrod et al., 2005b), whereas King County’s consultant’s interpretation was published at Technical Appendix A in the Supplemental Environmental Impact Statement (SEIS). King County’s seismic trenching consultant is MACTEC Engineering and Consulting (MACTEC).

Sections of figures from Blakely et al. (2004) and Sherrod et al. (2005a) are reproduced on Figure 2. Panel A on Figure 2 shows aeromagnetic data on a LiDAR hillshade base map with lineament and scarp locations, as well as glacial flutes (glacially scoured upland ridge lines). Panel B on Figure 2 shows locations of the two USGS seismic trenches excavated in 2004, as well as lineaments and scarps in the LiDAR data. These two panels on Figure 2 suggest that Lineament 4 crosses the north part of the site, but that no other lineaments project across the site where treatment facility buildings are planned. Furthermore, the glacially scoured upland ridges are useful geomorphic features indicating where the landscape has not been disrupted to the northwest or southeast of the Brightwater site since the glacial ice sheet receded across the site area.

Purpose and Scope

The purpose of the Chemical Building seismic trench investigation is to describe the geology exposed in the trenches with specific reference to the possible presence of active faults under or within 50 feet of the building footprints. The trenches were excavated at locations defined by King County and its consultants and with equipment provided by Hoffman Construction and its grading subcontractor Northwest Construction. The scope of services provided for this investigation consisted of overseeing excavation of the trenches; cleaning and scraping the trench walls to better expose the geology; interpreting, logging, and documenting the exposed geology; interacting with representatives of King County, their consultants, Snohomish County, and the USGS; and preparing this report.

Active Fault Definition

The Development Agreement dated October 11, 2005, states: "For purposes of this Development Agreement, the definition of an "active fault/active fault trace" shall be the definition contained in the 2003 International Building Code [2003 IBC], Section 1613.1, which provides:

> "A fault for which there is an average historic slip rate of 1 mm per year or more and geologic evidence of seismic activity within Holocene (past 11,000 years) times. Active fault traces are designated by the appropriate regulatory agency and/or registered design professional subject to identification by a geologic report."

This definition has two parts, both of which must exist for a fault to be an 'active fault'. The first part of the definition requires an average historic slip rate of at least 1 mm per year. A slip rate of 1 mm per year is equivalent to a displacement of nearly 4 inches in 100 years, 1 foot in about 300 years, and 3 feet in about 900 years.

The second part of the active fault definition requires evidence of seismic activity within the Holocene, which is taken by the 2003 IBC to be the past 11,000 years of earth history. Evidence of seismic activity consists of discrete displacements along fault planes and warping or folding over a relatively narrow zone. Glacial deposits at the Brightwater site are more than 11,000 years old, as discussed in subsequent sections of this report. Therefore, if glacial deposits overlying a possible fault are unfaulted and undeformed, then any underlying faults are inactive by the 2003 IBC definition. However, determination of the age of any faulting or deformation in glacial deposits requires that post-glacial deposits or features be present.

Tectonic Faults and Glacial Faults

A fault is a fracture in the crust of the earth along which rocks on one side have moved relative to those on the other side (http://www.consrv.ca.gov/CGS/rghm/ap/). This definition of a fault was taken from the Alquist-Priolo Earthquake Fault Zones web page on the California Geological Survey web site. Faults that present hazards to buildings and other facilities are those across which movement or shifts can occur at the ground surface. Faults that present hazards to buildings typically are tectonic faults or earthquake faults. *Tectonic faults* are faults created by internal forces in the earth that may be related to large-scale processes occurring over long periods of time that are responsible for forming large-scale features such as mountain ranges and volcanoes. *Earthquake faults* are tectonic faults which are considered to be capable of moving during future earthquakes. Some earthquake faults have produced displacements of the ground surface during historic time, and it was observation of ground-surface displacements produced along faults during some major historic earthquakes that led geologists to realize that earthquakes and fault displacements were related. Most earthquake faults are the result of repeated displacements over a long period of time. Therefore, faults with evidence of displacement within the past 11,000 years are considered to be *active faults* even if they have not displaced the ground during earthquakes in historic time.

Not all faults are tectonic faults. A “fracture in the crust of the earth along which rocks on one side have moved relative to those on the other side” can be created by forces external to the earth that may be related to erosion, precipitation, or the weight of something heavy placed on the ground. Such faults are *non-tectonic faults* and may have special names that do not include the word *fault*. Landslides and sink holes are two examples of features which have non-tectonic faults. The main scarps and lateral flanks of landslides are *faults* by the general definition, but clearly they are not earthquake faults. Some landslides have been created by strong earthquake shaking, but the main scarps and lateral flanks of earthquake-induced landslides are not considered to be earthquake faults.

Sometimes differentiating tectonic faults from non-tectonic faults is difficult. The main scarp and lateral flanks of a landslide have a fairly distinctive pattern on a slope that allows the landslide deposit to be identified as a slope movement. However, if the entire landslide deposit could not be observed, then the upper few feet of a portion of the landslide main scarp would have the same appearance as a tectonic fault. Additional geologic features and characteristics would need to be observed and considered to interpret the landslide main scarp correctly. The terms *scarp* and *flank* are used instead of *landslide fault* because they clearly are created by non-tectonic processes.

Glaciotectonism , according to Bibliography of Glaciotectonic References by James S. Aber (http://www.geospectra.net/glatec_biblio/), “refers to deformation of the Earth's crust brought about as a consequence of glaciation. All manner of structures may be produced: folds, faults, fractures, intrusions, etc. Many distinctive landforms may be created by glaciotectonism; these include: ice-shoved hills, push moraines, hill-hole pairs, drumlins, cupola hills, etc. Such features are widespread in regions of former glaciation as well as in proximity to modern glaciers. Glaciotectonic structures and landforms are especially common in parts of northern North America, western and central Europe, and northern Asia--both on land and on adjacent continental shelves.” The northern part of North America, including the Puget Sound region, was subjected to repeated glaciations, including the most recent Vashon glaciation, which retreated from the Seattle area approximately 16,500 calibrated years before present. A subsection of the FINDINGS AND INTERPRETATIONS section this report describes a variety of complex structures caused by glacial processes, including *glacial faults*.

Glacial faults are unlike landslide scarps and flanks in the sense that a landslide deposit has a set of geomorphic features that are related to each other and commonly present to some degree in many landslides. Glaciers and ice sheets can create highly complicated structures, including non-tectonic faults, which are related to other glacial features in highly complicated ways. In some cases, interpretation that a fault is a glacial fault is based on local features (e.g., small displacement on a surface that dies out or terminates within glacial deposits). In other cases, interpretation that a fault is a glacial fault must be based on qualities that are absent, instead of those that are present (e.g., orientation of glacial fault varies over short distances, or glacial fault does not persist over moderate distances).

Age of Glacial Deposits

Ages of advance and retreat of glacial ice in the Puget Sound region from Porter and Swanson (1998) are presented on Figure 3 to illustrate glacial deposit ages, as well as demonstrate the relationship among radiocarbon years B.P., calibrated years B.P. (cal yr B.P. where ‘present’ is defined as 1950 A.D.), and calibrated calendar years. Porter and Swanson (1998) interpolated radiometric dates from the region and interpreted that ice advanced across the Seattle area approximately 17,590 cal yr B.P., reaching a maximum extent approximately 16,950 cal yr B.P., and retreating by about 16,570 cal yr B.P. A shaded area in Figure 3 denotes the Holocene Epoch as less than 10,000 radiocarbon yr B.P., which corresponds to less than approximately 11,340 cal yr B.P.

Trench Orientations and Locations

The October 11, 2005, Development Agreement states: “King County shall prepare the following trenches:

> “i. For the proposed location of the south chemical storage building (the acids chemical storage building), King County will construct a trench at the proposed footprint of the acids chemical storage building. The exact length and orientation of this trench shall be determined by King County based upon the existing geological information and the recommendations of the US Geological Survey, Snohomish County and King County seismic consultants.
>
> “ii. For the proposed location of the north chemical storage building (the alkaline chemical storage building) because the construction of a trench in the exact location of the proposed building footprint is not reasonable or feasible given the current uses, the existing roads and underground utilities at that location, a trench shall be constructed east of the proposed alkaline chemical storage building footprint. The exact length and orientation of this trench shall be determined by King County based upon existing

> geological information and the recommendations of the US Geological Survey, Snohomish County and King County seismic consultants.
>
> “iii. In the event that the investigative protocol described above discloses the presence of an “active fault/active fault trace” meeting the 2003 IBC definition within the foundation footprint of one or more of the chemical storage buildings, the Parties agree that King County will move the chemical storage building(s) fifty (50) feet back from the active fault/fault trace, unless such location renders the chemical storage building’s purpose in interacting with the treatment works infeasible. In that event, King County shall locate the building as far away from the active fault/fault trace as feasible, but in no case may the location be less than 25 feet from the location of the identified active fault trace.”

It is our understanding that representatives of the USGS declined to become involved with the foundation trenching for specific buildings and made no recommendations regarding orientations or locations of seismic trenches.

The SWIF projects across Snohomish County in a southeast direction; therefore, a northeast orientation was used for seismic trenches at the Brightwater site because it is approximately perpendicular to the trend of the SWIF.

The Development Agreement stipulated that King County excavate one trench at each of two chemical storage buildings on the Brightwater site; the building locations are shown on Figure 4. Each Chemical Building is approximately 60 feet long and 40 feet wide. The long dimension of the South Chemical Building is oriented east, perpendicular to Route 9, whereas the long dimension of the North Chemical Building is oriented north, parallel to Route 9. The South Chemical Building straddled a north-trending fence line that separated two lots used by an automobile wrecking company for storing car bodies, as can be seen on the aerial photograph on Figure 4. The North Chemical Building is located in a paved roadway, as can be seen on Figure 4, under which buried utilities are located.

King County agreed to excavate a trench at the proposed footprint of the South Chemical Building. The trench for the North Chemical Building could not be located at the proposed building footprint because of the paved road and buried utilities that are currently in service; therefore, the north trench location was shifted to the east of the building to a location and orientation that would intercept any active fault traces on the trend of the SWIF through the building.

The reasoning used for selecting lengths and orientations of the seismic trenches is illustrated on Figure 5. The purpose of excavating seismic trenches at or near the Chemical Building locations is to check for the possible presence of active traces of the SWIF. The trend of Lineament 4 in the north part of the Brightwater site is approximately N 35° W (equivalent to S 35° E). Therefore, the local trend of the SWIF is taken to be about the same as the trend of Lineament 4. The seismic trenches were oriented approximately perpendicular (N 55° E) to the trend of the SWIF. The chemical building footprints are shown on Figure 5 with shaded red rectangles that are 40 feet wide by 60 feet long. The rectangle with the long direction oriented east has a slightly longer dimension (75 feet) perpendicular to the SWIF than does the north-trending building. The 50-foot setback is consistent with the requirements of the October 2005 Development Agreement; this dimension is shown on Figure 5 on both sides of the building footprint projection. Thus, a trench length of 175 feet would be sufficient to expose the geology across either chemical building footprint and allow for a typical 50-foot active-fault setback on each side. Each of the chemical building seismic trenches excavated during June, July, and August 2006 was approximately 200 feet long.

Shifting a trench location some distance away from a building footprint may be done with reasonable confidence that the presence or absence of faulting exposed in the trench is representative for the building location because significant fault traces persist over distances of at least several hundred feet. This is a so-called ‘building shadow’ along the trend of a possible fault. Thus, a seismic trench can provide useful geologic information for a swath parallel to the possible fault trend across an entire site. For many projects, it is desirable to excavate seismic trenches outside building footprints to minimize disturbance of the foundation soils that will provide support for the future buildings. Careful attention to compaction of trench backfill soils is required for projects where seismic trenches are excavated across building footprints.

During planning of the trenches, an active, south-trending surface-water drain line was discovered within the footprint of the South Chemical Building. This drain line was located on the north and west sides of the auto wrecking lot adjacent to the east side of the South Chemical Building (Figure 4). Because the drain line was active, King County and its consultants decided to shift the trench location to the east of the building, as was done for the North Chemical Building trench. The active drain line would have discharged water directly into a trench at the time the trenches were excavated; however, this drain line was taken out of service as part of site preparation in July after trenching occurred. Two northeast-trending trenches were excavated in June and July 2006 at locations approximately 240 feet to the southeast of each of the chemical buildings (labeled Trench South 1 and North Trench on Figure 4).

An additional trench was excavated at the footprint of the South Chemical Building in August 2006 at the request of Snohomish County after the surface-water drain line had been taken out of service. The additional trench is labeled Trench South 2a on Figure 4. During excavation of Trench South 2a, geologic features were observed that needed to be evaluated further to determine their lateral persistence. Consequently, a parallel trench (Trench South 2b on Figure 4) was excavated approximately 60 feet to the southeast.

Figures 6, 7, and 8 contain photographs which provide a general overview of excavations for Trench South 1, the North Trench, and Trench South 2, respectively.

Trench South 1 was excavated from the northeast toward the southwest beginning on June 20, 2006. A track-mounted excavator with a smooth-tooth bucket was used to construct a trench with sloping sides (Figure 6 photos A and B) because of stability and safety concerns. The initial target depth for the trench was about 15 feet. After the first part of the excavation had been made, a MACTEC engineering geologist determined that glacial deposits existed at a relatively shallow depth. This determination resulted in a transition of the excavation to a shallower depth toward the southwest. Ground water was encountered at a depth of about 10 feet in the northeast part of the trench. The bottom of the trench was sloped toward the southwest and a sump pump was used to pump accumulated water into a portable Baker tank that had been positioned next to the trench. Working conditions in the bottom of the trench were complicated by the water combined with loose soil material generated during the process of cleaning the sidewalls. A small backhoe was used to clean out the bottom of the trench and integrate drainage from the deeper northeast end with the remainder of the trench so that dewatering could be accomplished from a single sump at the southwest end (Figure 6, photo A). Laborers assisted MACTEC geologists with trench-wall cleaning in all trenches excavated during the summer of 2006.

A narrow uniformly sloping bench was constructed along the southeast wall for much of the length of Trench South 1 (Figure 6 photos B and D), and nearly vertical faces were created above and below the bench to facilitate geologic logging. Features ultimately interpreted to be related to liquefaction were exposed at several locations. A bench approximately 15 feet long and 6 feet wide was excavated by hand at one location (Figure 6 photo F) where a planar feature interpreted to be caused by liquefaction injection was encountered. The extent of excavator-caused disturbance in the upper part of the sloping sides of the trench required additional effort to clean them for geologic examination. Therefore, a small backhoe was used to excavate a four-foot-deep trench parallel to and about 25 feet northwest of the initial trench (Figure 6 photos C and D). The northeast end of the initial excavation was too wide to allow the four-foot-deep trench to extend all the way to the northeast limit of the South Trench area. Therefore, the northwest wall of the excavation was cleaned and logged as a northeast continuation of the four-foot-deep trench (Figure 6 photo E).

The North Trench was excavated by a track-mounted excavator with a smooth-tooth bucket from the southwest to the northeast on June 22, 2006. The southwest end of the trench was on a steep north-facing slope that separated two lots (Figure 7 photo A). Concrete ‘ecology blocks’ were present along the west end of the slope. A number of ecology blocks were removed to permit excavation of the North Trench. A MACTEC engineering geologist observed excavation of three test pits along the trench alignment to determine the nature of and depth to glacial deposits. Excavation was terminated a few feet below the depth where glacial deposits were encountered (Figure 7 photo B). Several backfilled utility lines and one active drain line were crossed by the trench. The North Trench was excavated with sloping sides; where very compact glacial till was encountered at shallow depth, the lowest three or four feet of trench wall was vertical; the walls above the vertical part were sloped for stability and safety.

The North Trench walls were cleaned for geologic observation, and the bottom was cleaned where cracks were observed on the walls. The backfilled utility line excavations and one test pit near the northeast end of the trench prevented the geology from being continuously exposed along the southeast trench wall; in these areas, the opposite side of the trench (the northwest side) was logged to provide a nearly continuous view of the geology along the trench. A small side pit was excavated adjacent to the north side of the trench (Figure 7 photo C) to further evaluate a planar feature interpreted to be caused by liquefaction injection that was exposed in the North Trench.

Trench South 2a was excavated from the southwest toward the northeast beginning on August 19, 2006. A MACTEC engineering geologist observed excavation of two test pits to determine the nature of and depth to glacial deposits. Stratified deposits were encountered in the test pits and a target depth of 12 feet was selected. A track-mounted excavator with a smooth-tooth bucket constructed a terraced trench with four benches consisting of three-foot-high risers and four-foot-wide treads (Figure 8 photos A and B). Near the midpoint of the trench, the depth was increased to 15 feet and an additional bench was needed for stability and safety (Figure 8 photos A and B).

The geology exposed on opposite walls of the Trench South 2a appeared to have differing amounts of gravel, and a liquefaction feature near the bottom of the trench at one location seemed to have some vertical persistence on the southeast wall, but a different character on the northwest wall. A decision was made by King County and its consultants to excavate a trench parallel and adjacent to Trench South 2a. Excavation began on August 23, 2006, by removing the top three feet of soil from the trench area (Figure 8 photo C) because it consisted of fill soil and material disturbed by the automobile wrecking yard land use. Trench South 2b extended to a depth of 12 feet below grade. The upper three feet of fill soils and disturbed materials was removed from the common ridge between the two trenches. Therefore, the northwest wall of Trench South 2b consisted of three three-foot-high benches (Figure 8 photos D, E, and F).

FINDINGS AND INTERPRETATIONS

Summary

Descriptions of the geology exposed in the Chemical Building seismic trenches are presented in Appendix A. Results of radiocarbon analyses of samples collected from Trench South 2a and Trench South 2b are presented in Appendix B. The geology exposed in the seismic trenches excavated near the Chemical Building locations at the Brightwater site demonstrates the extreme local variability associated with glacial and subglacial erosional and depositional environments. A summary of the geology exposed in the Chemical Building seismic trenches is presented in this section of the report, along with discussions of pertinent studies of glacial and subglacial environments.

The North Trench is located approximately 1,000 feet north of Trench South 1 and about 800 feet north of Trench South 2, as shown on Figure 4. Trench South 2 is less than 200 feet northwest of Trench South 1. The North Trench exposed only very compact glacial till and crudely stratified till-like diamict[1] deposits, whereas Trench South 1 exposed till, diamict, and stratified glaciofluvial deposits. Trench South 2a exposed stratified glaciofluvial, outwash, and possibly glaciolacustrine deposits, whereas only 20 to 30 feet away, Trench South 2b exposed glacial erratic boulders, an esker-like gravel deposit, locally contorted and sheared silty subglacial deposits, outwash, and possibly glaciolacustrine deposits.

Review of Scientific Analysis of Glacial Deposits

Published information regarding glacial deposits includes descriptions and interpretations of deformation. This section of the report includes a review of a few references of detailed studies on Long Island, NY, and relevant sections of textbooks.

Complicated folded and faulted glacial deposits of the most recent ice age at locations on Long Island, NY, have been documented by geologists at the State University of New York at Stony Brook. Klein and Davis (1999) documented numerous complicated small folds which they expected to be caused by simple glacial push that would result in folds with relatively uniform appearance at exposures over moderate distances. Instead, they found substantial local lateral variation in distribution and thickness of sedimentary facies. Klein and Davis (1999) interpret these variations to be caused by significant deformation by glacial ice during the time that sediment was being deposited in a subglacial environment (synglaciotectonic deposition or syndepositional glaciotectonic activity). One diamict they observed was 3 times thicker at one location than at another location 300 feet away. At a third location about 400 feet away, a thick gravel and sand layer was present under the diamict unit. These lateral variations in stratigraphy over distances on the order of a few hundred feet suggested to Klein and Davis (1999) that they were caused by separate, probably seasonal, glacial advances rather than a single, prolonged glacial advance.

Tingue et al. (2004) conducted ground-penetrating radar (GPR) surveys on Long Island, NY, in the general area studied by Klein and Davis (1999) and found glaciotectonic folding and thrusting. Small hills were found to be anticlines in the GPR stratigraphy, and thrust-faulted folds were interpreted to be complex glacial push structures within subglacial deposits. The faulted folds which appeared to be truncated at their upper surfaces were interpreted to have been sheared off by a sediment-rich ice sheet in local advance during overall glacial recession. Mildly folded cobbly diamict near the ground surface was found to overlie strongly folded diamict deposits.

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[1] Diamict refers to deposits of unsorted, unstratified, matrix-supported sediment of unknown or undifferentiated origin. Also called diamicton.

Cangelosi et al. (2006) continued to evaluate the area discussed by Klein and Davis (1999). They defined a tunnel valley with a dendritic pattern of tributary valleys and found complicated glacial stratigraphy with tributary valley-filling sediments they thought were too thick to be explained by post-glacial subaerial processes because the modern topographic drainage area is too small to produce the volume of sediment they observed. They explained the distribution and thickness of sedimentary deposits as having formed in an active subglacial environment in response to glaciofluvial processes.

Bennett and Glasser (1996) noted that subglacial melting supplies sediment to the sole of a glacier where it may be transported subglacially before it finally lodges. Debris will be released preferentially into depressions or hollows in the glacier bed. Subglacial cavities occur where glaciers flow over irregular topography composed of bedrock or other materials strong enough to resist the shearing action of the moving ice. Bennett and Glasser (1996) describe five ways that sediment can accumulate in cavities at the sole of a glacier:

1) Roof release – sediment dropping from the base of the glacier which is the cavity roof,
2) Till slurry – deformable till being squeezed from the base of the glacier into the cavity,
3) Clast expulsion –resistance to downward ice pressure on clasts being lost as they pass over the cavity.
4) Till-curls – sediment-rich ice at the base of the glacier peeling away from cleaner ice, and
5) Fluvial deposition – melt water at the base of the glacier flowing into the cavity and depositing its sediment load.

Bennett and Glasser (1996) explain that the properties of cavity-filling subglacial sediment may vary considerably, as implied by the range of processes described above. They also show a photograph of faulted sand layers within outwash sediments, noting that the faults formed during subsidence caused by melting of buried ice in or beneath the outwash sediments. Subsidence over buried ice can produce synclines or sag structures, and can occur during deposition of outwash sediments, or after deposition is completed.

Martini et al. (2001) describe water flow on, within, and below glaciers, noting that melt water discharge changes seasonally or even daily depending on melting rates, conditions within the glacier, and on whether continuously open conduits are present. They state that water can sometimes pond in lakes under ice sheets or in tributary valleys cutoff by glaciers until it is deep enough to float the glacier or generates enough hydrostatic pressure to break through it. The water then forces its way out under pressure as a sheet or channelized flood. The glacier settles down as hydrostatic pressure is dissipated and the flood is terminated. They show a diagram indicating ‘high-pressure water jets’ can occur at the base and front of the glacier. Martini et al. (2001) do not mention liquefaction of subglacial deposits at locations where high-pressure water exists, but cohesionless deposits might be expected to liquefy under such water pressures and differential loading of glacial ice.

Martini et al. (2001) state that water flowing on, within, and below glaciers basically follows the same processes as water flowing in open channels or full pipes. The resulting glacial and subglacial deposits have similar fluvial structure and overall composition to stream deposits. Sediments deposited in contact with glacier ice have three distinctive qualities:

1) They have an extreme range of and abrupt change in particle size with clasts that have the same composition as nearby till,
2) They contain fragments of till,
3) They show deformations caused by ice melt out – ice push or slumps – because they were deposited against or over ice.

Martini et al. (2001) show a photograph of glacially faulted and folded ice-contact stratified deposits caused by differential subsidence that occurred in response to melting of a buried ice block under the stratified deposits. Deformation, including glacial faults, is common in subglacial ice-contact deposits.

Review of Scientific Analysis of Puget Sound Region Glacial Deposits

The dates of advance and retreat of the most recent glacial ice sheet across the Puget Sound region were described by Porter and Swanson (1998), as discussed in an early section of this report. This section of the report contains additional descriptions of the local glacial deposits.

The local glacial deposits of the Vashon Stade of the Fraser glaciation (Puget Lobe of the Cordilleran ice sheet) were the subject of Booth’s (1984) dissertation at the University of Washington. He describes the Vashon till as a diamict with a silty sand matrix that ranges from less than 3 feet to more than 100 feet thick. In some places, the upper part of the Vashon till consists of melt-out or ablation till consisting of debris released by melting ice during deglaciation. Booth (1984) states that the melt-out or ablation till commonly grades into deposits that are distinctly water-worked because they are stratified as recessional drift forming a discontinuous blanket.

Booth (1984) determined that the Vashon till forms a mantle on the upland areas, whereas recessional deposits are largely confined to channels that pass through the upland topography without obscuring it. Scattered exposures of pre-Vashon deposits and bedrock indicate that Vashon till largely blanketed preexisting topography that was not greatly altered by the ice. Booth (1984) found that Vashon till is significantly thinner on up-glacier sides of hills that have at least 100 feet of relief relative to the down-glacier sides.

Booth (1984) describes some exposures of Vashon till that are composed of compact, crudely to well-bedded, clast-supported deposits with extremely variable proportions of silty matrix. These exposures include sorted sand or gravel interstratified with diamict, commonly far from a plausible long-term ice margin. He interpreted these deposits to be subglacial fluvial sediments representing either reworked recently deposited basal till or sediments actively transported in subglacial or englacial passageways.

Laprade (2003) observed deposits of sorted sand or gravel interstratified with diamict described by Booth (1984) and noted that they have characteristics that are similar to both till and outwash, and often are referred to as ‘till-like’ on boring logs. Laprade (2003) reported that these deposits are found on the down-glacier sides of hills and ridges leading to a conclusion that the depositional environment was one of relatively low pressure, possibly a void, beneath the Puget Lobe of the Cordilleran ice sheet. In this low-pressure environment, sediments that normally would be compacted as lodgment till were subglacially reworked into highly variable to chaotic composite masses of “classic” till, friable till, silty or “dirty” outwash, and sandy or “clean” outwash.

Laprade (personal communication, 2006) prefers to map these subglacial deposits collectively as Vashon diamict deposits (Qvd), an informal geologic unit designation. These deposits somewhat resemble descriptions by Troost et al. (2005) for Vashon ice-contact deposits (Qvi) or Vashon subglacial meltout till deposits (Qvtm). The suite of eight geologic units used by Troost et al. (2005) for Vashon deposits in the Seattle area is reproduced in Table 1.

Data from the Brightwater Site

The general geologic setting of the Brightwater site in the vicinity of the Chemical Buildings is dominated by glacial deposits. The site generally slopes westward toward Little Bear Creek where modern alluvial and wetland deposits have accumulated on the glacial landscape. Site grading done for past land uses created terraces of cut-and-fill pads, and fill deposits are present in many locations. Surface-water control features on the site consist of buried pipes that collect water from the upper elevations on the east and convey it to lower elevations on the west. Soil profile features may be preserved locally, but in many places the soil horizon has been disturbed or it never formed to a degree that could be recognized.

Geologic materials exposed in the Chemical Building seismic trenches range from isolated subrounded blocks of granitic rock to flat-lying silty clay, with stratified sand and gravel units and deposits of chaotically deformed diamict. The geologic materials appear to match reasonably well the geologic unit descriptions of the Vashon deposits in the Seattle area by Troost et al. (2005; see Table 1). Some details of the geology exposed in the trenches are presented below, with more detail being provided in Appendix A. In general, it appears that Vashon advance outwash is present in Trench South 1 and Trench South 2b. Vashon till is present in Trenches South 1, 1a, 1b, and 1c, and the North Trench, and till fragments small enough to have been transported subglacially are present in Trenches South 2a and 2b. Vashon subglacial meltout till and/or Vashon ice-contact deposits appear to be present in Trenches South 1, 1a, 1b, and 1c and Trenches South 2a and 2b. Vashon recessional outwash and possibly recessional coarse-grained and lacustrine deposits appear to be present in Trenches South 2a and 2b. Gravelly deposits in the uppermost part of Trenches South 2a and 2b below deposits of fill are interpreted to be Vashon recessional outwash deposits. After deglaciation was complete in the Seattle area about 16,570 cal yr B.P., the volume of water flowing in streams in the glacially eroded valleys was likely too small to transport gravel at the elevations of the Chemical Building seismic trenches. Some gravel on the slopes could have been reworked by gravity-dominated processes to produce gravelly colluvial deposits, but these deposits would be thin. The seismic trench locations appear to be too distant from the slopes east of the site to have been areas of significant mass wasting, such as landslides or debris flows.

Geologic Summary of Seismic Trenches

South Trench Location

The ‘South Trench’ location consisted of two trench areas: Trench South 1 and Trench South 2, as shown on Figure 4. Trench South 1, excavated in June and logged in June and July 2006, was located approximately 240 feet southeast of the South Chemical Building and consisted of four exposures (see Appendix A):

a. Southeast side of main trench (Trench South 1)
b. Supplemental trench excavated northwest of main trench (Trench South 1a)
c. Wall in northeast corner of excavation (Trench South 1b)
d. Benched excavation (Trench South 1c)

Trench South 2, excavated and logged in August 2006, consisted of two adjacent trenches. Trench South 2a was located through the South Chemical Building, whereas Trench South 2b was located adjacent to the southeast corner of the South Chemical Building. Appendix A contains detailed trench logs, discussions of the stratigraphy and structure exposed in these trenches, and photographs of selected features.

Trench South 1, 1a, 1b, and 1c

Geologic materials exposed in Trench South 1, 1a, 1b, and 1c consisted of till and diamict that were deposited in a subglacial environment. The stratigraphy in all exposures was complex, with bodies of diamict or till interspersed with deposits of stratified gravelly sand, thinly bedded silt, and massive sand deposits. All deposits must have been overridden by ice because they were uniformly very dense. The interpretation that the deposits were overridden is consistent with a subglacial environment that includes interspersed diamict bodies with other deposits of stratified sediments.

Liquefaction features were observed in Trench South 1 and Trench South 1c (Figure 9). The sandy deposits in which these features were observed are too dense to be able to liquefy in their current condition; therefore, the liquefaction must have occurred before the deposits were compacted by overriding ice no less than about 16,950 cal yr B.P. The liquefaction features in Trench South 1 consist of disrupted sandy silt and injection features. Most liquefaction features in Trench South 1 were located west of about Sta. 0+40 in a sandy unit underlying a body of diamict. The sandy unit locally had prominent reddish brown iron oxide and black manganese oxide mineralization. The disruption associated with these liquefaction features was minor and it terminated at the contact with the overlying diamict deposit.

A curvi-planar feature was observed cutting through massive sand and diamict at about Sta 0+28 in Trench South 1 and on the opposite side of the excavation in Trench South 1c (Figure 10); an undeformed deposit of very dense stratified gravelly sand-sandy gravel was observed to overlie the curvi-planar feature on both sides of the trench (Figure 11). The cause of the curvi-planar feature is unclear; it could be caused by loading related to subglacial processes or secondary earthquake effects, such as liquefaction. It is less likely that the curvi-planar feature is related to tectonic faulting because of the character of fine sand and silt filaments along the feature and its variable strike and dip (N55°W/55°SW in Trench South 1 and N05°W to N20°W/38°W in Trench South 1c) over a short distance.

This curvi-planar feature coincided approximately with down-to-the-west irregularities in the base of a diamict unit in Trench South 1c, but the base of the diamict unit in Trench South 1 was more regular at the location of the curvi-planar feature (Figure 12). The character of the massive sand under the diamict was different on opposite sides of the curvi-planar feature in Trench South 1c. The curvi-planar feature had the appearance of a fluidized zone associated with injection of silt and fine sand in a dike-like form perhaps along a minor fracture caused by differential subsidence generated by ice melt out or liquefaction of the massive sand deposit 30 to 60 feet to the west. The fluidized zone consisted of wavy, thin fine sand and silt filaments that were continuous along the plane without evidence of shearing (Figure 13). The change in strike and dip over a short distance is consistent with subglacial deformation in response to differential settlement caused by ice melt out or the liquefaction a short distance to the west. The curvi-planar feature extended through the diamict deposits and was truncated by a very dense subglacial gravelly sand-sandy deposit in both Trench South 1 and Trench South 1c.

It is clear that the curvi-planar feature formed in a subglacial environment and cannot be an active feature by the 2003 IBC for two reasons: 1) the thin sand and silt filaments comprising it appear to be uniformly as dense as the deposits on either side, leading to a conclusion that the feature was in place when the deposit was overridden by glacial ice no less than about 16,570 cal yr B.P., and 2) the deposit containing the curvi-planar feature is overlain by undeformed, very dense, stratified gravelly sand-sandy gravel that was itself overridden by ice no less than about 16,570 cal yr B.P.

Trench South 1a exposed continuous, unfaulted stratigraphy containing bodies of till with bedded sandy coarse gravel, massive sand, and thinly bedded sand (Figure 14). A massive silty sand unit with scattered gravel between Sta 0+42 and 0+57 was medium dense. This medium dense unit was near the ground surface and overlying all other deposits except fill and possibly a weak soil horizon; all other deposits exposed in Trench South 1a were uniformly very dense, indicating that they were overridden by ice no less than about 16,590 years ago. Therefore, we interpret the medium dense silty sand with gravel to be Vashon recessional outwash or possibly, but less likely, colluvial deposits derived from localized erosion of the subglacial deposits and redeposition on the gentle slope.

Trench South 1b in the northeast corner of the excavation exposed approximately 65 lineal feet of stratigraphy that was uniformly very dense and included bodies of diamict indicating deposition in a subglacial environment. Two small glacial faults with approximately one inch of down-to-the-east normal separation were observed in a sand unit at Sta 0+47 to 0+50 (Figure 15). The small faults could be traced upward to an undeformed contact with stratified diamict. The small glacial faults are consistent with ice melt out features described by Bennett and Glasser (1996).

Trench South 2a

Trench South 2a exposed subglacial and recessional outwash deposits dominated by silty gravel. Small bodies of diamict were present at a few locations. Thinly bedded fine to coarse sand and silt which were exposed in the southwest end of the trench had some appearances of being deposited in a quiet-water, possibly glaciolacustrine, environment. Gravel-filled channels cut into non-gravelly or less-gravelly deposits (cut-and-fill structures) were common (Figure 16).

Four types of deformation were observed in Trench South 2a: inclined beds, liquefaction, small glacial or liquefaction faults, and a buttress unconformity feature, all of which are older than 16,570 cal yr B.P. Inclined beds (Figure 17) existed in the northeast half of the trench and had the appearance of low-amplitude anticlines and synclines. They could be glacier-push folds or ice melt-out sags, described by Klein and Davis (1999) or Bennett and Glaser (1996). Whatever their origin, gently dipping recessional deposits overlie the inclined beds between Sta 0+15 and Sta 0+90 (Figure 18) clearly indicating that the folding process ceased during glacial recession, no less than about 16,570 cal yr B.P.

Liquefaction features are present in Trench South 2a Sta 0+97, Sta 1+49, Sta 1+57, and Sta 1+70. The liquefaction feature at Sta 0+97 is most pronounced below elevation 260 feet and displays disturbed sand containing moderately large fragments of laminated silty sand that were rotated as if they became incorporated into a fluidized mass of sand (Figure 19). Deposits directly above this liquefied zone appear to have sagged with approximately one foot of elevation difference across the liquefied zone. A small north-trending, steeply dipping liquefaction fault less than 1” wide was exposed at about elevation 262 on the bench above the liquefied zone (Figure 20). This small liquefaction fault was adjacent to a zone of sand disturbed by liquefaction and appeared to be overlain by unfaulted gravelly sand. A reddish brown marker sand was disrupted by the liquefied zone at Sta 1+00 and elevation 262, but it appeared to project through the liquefied zone and across the small fault with a sag shape that matched the lower sag. Another small liquefaction fault at about elevation 264 appeared to be approximately in line with the lower small liquefaction fault (Figure 21) and positioned on the northeast edge of a coarse gravel deposit. This gravel deposit did not appear to be filling a stream channel, and it had a small zone of disturbed sand suggesting that the gravel deposit is filling some type of a liquefaction feature. Gently inclined, but undeformed sand and gravel deposits are present above the coarse gravel deposit indicating that the liquefaction and other disturbing processes are no younger than the age of the upper recessional outwash deposits which are no younger than 16,570 cal yr B.P. The deposits described above are on vertical faces separated by benches that are several feet wide; therefore, the trench log does not represent a single vertical plane. Lateral variability in the nature of the deposits and liquefaction features is reflected in the logs of the terraced trenches (Trench South 2a and Trench South 2b).

A dike of liquefied sand was exposed at Sta 1+49 in Trench South 2a and a liquefaction-appearing feature was exposed at Sta 1+70 (Figure 22). The deposits above the feature at Sta 1+70 were in a ‘V’ shape that suggested it might be the root ball of a tree that was uprooted as the tree fell.

Several small glacial faults with less than 1” of displacement were exposed at Sta 0+72 in Trench South 2a (Figure 23). These glacial faults have limited vertical extent and terminate upward and downward. They probably are caused by subglacial processes, but secondary earthquake processes cannot be ruled out. They are covered by unfaulted deposits that are no younger than 16,570 cal yr B.P.

A buttress unconformity feature was exposed in Trench South 2a at Sta 1+57 (Figure 24). This feature was visible on both sides of the trench with a strike and dip of N05°E/32°W. Sediments on opposite sides of the feature appeared similar, but specific stratigraphy could not be correlated. Layers below the feature were continuous across its downward projection. The east edge of the feature had some appearance of a stream channel erosion cut. Layered sand deposits within the feature were inclined at the angle of repose, suggesting that it was a free-face as the sand accumulated in a colluvial wedge configuration. The base of the feature appeared to curve into and become a bedding plane in the stratified sandy and silty deposit. Sandy gravel deposited in channels that cut into the sandy and silty deposit with the buttress unconformity are undeformed where they overlie an upward projection of the feature. Therefore, whatever processes caused the feature, they have not been active since 16,570 cal yr B.P. which is the age when deposition of the recessional outwash was complete.

Trench South 2b was excavated adjacent to the southeast of Trench South 2a to provide an opportunity to evaluate the persistence of the liquefaction zone exposed in Trench South 2a at Sta 0+95. The station numbers used in Trench South 2b are approximately the same as the station numbers used for Trench South 2a. Elevations were set in the field by the Hoffman Construction surveying subcontractor. The distance between the lowermost faces in the two trenches was about 40 feet. The trenches were nearly parallel at a trend of about N55°E (which is equal to S55°W).

Trench South 2b

The stratigraphy exposed in Trench South 2b and Trench South 2a was similar, but with some notable differences. Glacial erratic boulders, a diamict body adjacent to an esker-form gravel deposit, a buttress unconformity, and local deformation were exposed in Trench South 2b. The glacial erratic boulders were encountered at Sta 0+96 and Sta 1+10 (Figure 25), clearly indicating a subglacial origin of the deposits below the boulders. A body of diamict exposed at Sta 0+75 in Trench South 2b was larger than any diamict bodies exposed only a short distance away in Trench South 2a. An esker-form gravel deposit was exposed at Sta 0+65 near the diamict body (Figure 26).

A buttress unconformity was exposed at Sta 1+22 (Figure 27). This feature separated steeply inclined gravel and sand from nearly horizontal sand and silt layers. Contorted beds and small glacial or liquefaction faults were located in the sand and silt layers on the west side of this unconformity (Figure 28). A continuous, undeformed sand layer was present below the unconformity at its downward projection showing that it is not a fault. This unconformity is located approximately 10 feet west of the larger of the two glacial erratic boulders, but the influence of the boulder on the unconformity is unknown. High-pressure water jets, as described by Martini et al. (2001), or normally pressurized water at the base of the glacier most likely flowed around the erratic boulders with variable turbulence and eddy currents. The trend from the unconformity to the liquefaction zone at Sta 0+97 in Trench South 2a is about N08°W, but the relationship between the liquefaction feature and the unconformity is unknown. In any event, the unconformity is not an active feature because its upward projection is overlain by undeformed subglacial or glacial outwash deposits.

Remarkable local deformation in silty sand deposits was exposed between the two glacial erratic boulders and adjacent to the smaller boulder at about Sta 0+93 (Figure 29). The stresses responsible for this deformation must have been compressive and could have been caused by glacial push in which the larger boulder resisted movement of the smaller boulder. In any event, the compressive stresses must have been local and acted only at the time of deposition because undeformed stratigraphy was present below and above the deformed deposits. Therefore, the most recent displacement on any of the small glacial faults at about Sta 0+93 is older than about 16,570 cal yr B.P.

North Trench Location

The ‘North Trench’ consisted of a main trench and a small pit excavated on the northwest side at Sta 1+10. The North Trench was excavated in June and logged in June and July 2006, whereas the small pit was excavated and logged in July 2006. Geologic materials exposed in the trench were diamict, stratified diamict, and injected sand and silt. Fill soils were present over the glacial deposits and in backfill along trenches excavated for drain lines. All natural materials had been overridden by ice because they appeared to be uniformly very dense, including fine sand dikes and fracture fillings.

Fractures were observed in the diamict at a number of locations. Troost et al. (2005) note in the summary description of the Vashon till that it is commonly fractured. Some cracks branched into two parts that diverged in direction (Figure 30). One crack was observed to have a very small (0.01 foot) component of left-lateral separation (Figure 31). Other cracks were simple tension cracks (Figure 32).

One curvi-planar feature striking west-northwest and dipping southwest was exposed at about Sta 1+08 (Figure 33). This feature was adjacent to thin fine sand dikes with local pockets of fine sand. The pit was excavated to create a larger exposure of this curvi-planar feature. The curvi-planar feature appears to be a fluidized zone because it consists of wavy, thin sand and silt filaments that are continuous along the plane without evidence of shearing (Figure 34). The curvi-planar feature in the North Trench had some similarities to the curvi-planar feature exposed in Trench South 1c.

During excavation of the small pit with a smooth-tooth bucket, the MACTEC engineering geologist paid particular attention to the density of the diamict and the injected thin sand and silt filaments in the curvi-planar feature. All materials, including the sand and silt filaments, appeared to be uniformly very dense. We interpret this degree of density to indicate that the deposit was overridden by ice.

The exposures of diamict in the North Trench revealed cracks and a curvi-planar feature that is interpreted to be injection of liquefied sand and silt in a fluidized zone. The lack of stratified subglacial or recessional outwash deposits overlying the diamict in the North Trench require that the density be used as an indicator of the age of injected or fluidized zones and crack fillings. The Puget Lobe of the Cordilleran Ice Sheet advanced across the Seattle area approximately 17,590 cal yr B.P. reached its maximum extent approximately 16,950 cal yr B.P., and completed its retreat approximately 16,570 cal yr B.P. (Porter and Swanson, 1998).

During the site visit made by the USGS scientists on July 6, 2006, Dr. Brian Sherrod commented on the fractures in till exposed a few years ago in a trench across the Catfish Lake scarp of the Tacoma fault (Sherrod et al., 2003). The Catfish Lake scarp is a prominent, through-going topographic feature oriented slightly south of due east that interrupts the trend of glacially scoured features in the landscape northwest of Tacoma, as shown on Figure 35. The orientation of glacially scoured ridge lines mark the flow direction of glacial ice as it advanced across the Puget Sound region. The glacially scoured ridges in the Catfish Lake scarp area visible on Figure 35 are oriented toward the south-southwest. Sherrod et al. (2003) states that “Profiles created using LiDAR grids in a GIS system show that scarp heights vary from less than a meter to about 3 m in height”.

Glacially scoured ridges in the Brightwater site area are also shown on images presented on Figure 35. The glacially scoured ridges are oriented slightly east of due south in the Brightwater site area. The trend of the SWIF in the site area is toward the southeast at approximately S35°E which is the trend of Lineament 4. Booth (1984) interpreted the upland areas scoured by the Vashon glaciation to be largely unmodified by post glacial processes. The hillshade depiction of the LiDAR data for the Brightwater site is shown Figure 36 with an open rectangle representing the trend of the SWIF through the North Trench location.

DISCUSSION AND CONCLUSIONS

Based on detailed examination of the seismic trenches excavated at the Brightwater site in June, July, and August 2006, we found no evidence of active faults that meet the 2003 IBC definition passing through, or within 50 feet of, the foundations of the two Chemical Buildings. The primary geologic evidence to support this conclusion consists of

1. Unfaulted and undeformed stratigraphy deposited in a subglacial or recessional outwash environment that must be no younger than 16,570 cal yr B.P. (Trenches South 1, South 1a, South 1b, South 1c, South 2a, and South 2b)
2. Uniform dense conditions in diamict adjacent to fractures and fracture-filling materials (North Trench)
3. Continuous glacially scoured ridges depicted in LiDAR images of the landscape adjacent to the site
4. Absence of LiDAR scarps in the glacial landscape adjacent to the site.

Geologic evidence of minor deformation, cracking, liquefaction, and small glacial faults were observed at several locations. These pre-Holocene deformation features were overlain by unfaulted and undeformed stratigraphy in the trenches excavated for the South Chemical Buildings. The North Trench exposed fractured diamict buried only by historic fill soils. The trend of the SWIF projected through the Chemical Buildings was used to select locations of trenches that would intercept southeast-trending fault traces that might be associated with the SWIF. The glacially scoured upland ridges around the Brightwater site have remained largely unmodified since the ice melted from the area approximately 16,570 cal yr B.P. Therefore, active faults (with post-glacial displacement of the ground surface) would have produced scarps across the glacially scoured landscape, including the upland ridges. The Catfish Lake scarp (Sherrod et al., 2003) is an excellent example of a post-glacial displacement of less than 1 m to about 3 m (Figure 35). The glacially scoured ridge to the southeast of the site shows no suggestion of a scarp in the LiDAR image at the same scale as the image of the Catfish Lake scarp (Figure 35). An open rectangle oriented parallel to the trend of the Lineament 4 and positioned on the North Chemical Building is shown on the LiDAR hillshade image of the site area (Figure 36). The glacially scoured ridge located southeast of the site appears to be continuous in the LiDAR data without interruption by a southeast-trending scarp. This observation is consistent with the conclusion based on geologic logging of the North

Trench that cracks and injection features exposed in that trench do not represent active faults or other deformation of seismic significance the North Chemical Building.

Geologic evidence of liquefaction was observed at several locations in Trench South 1 and one location in Trench South 2a. Very dense conditions in the sand deposits displaying the liquefaction evidence support a conclusion that the liquefaction occurred during glaciation as the sediments were being deposited and before they were overridden by ice. Therefore, the liquefaction features in very dense sand is pre-Holocene in age and not active by the 2003 IBC definition. Unfaulted and undeformed deposits of subglacial or recessional outwash origin were present over the liquefied deposits exposed in Trenches South 1, South 1a, South 1b, South 1c, South 2a, and South 2b.

Liquefaction-induced folding with minor faulting has been documented in lake deposits in Utah that are approximately 15,000 years old (Keaton and Anderson, 1995). Their article is reproduced in Appendix C, the relevant part of this article for the Brightwater project is on pages 462 to 464. The construction excavation log on Figure 7 in the article in Appendix C shows small-scale reverse and normal faults that may have some component of lateral slip and impressive folding with essentially no dikes or injection features of liquefied sand or silt. Surface faulting is not suspected to be a factor contributing to the deformation at this site of liquefaction-induced folding, which is more than one mile from the Wasatch fault, probably more than five miles from the West Valley fault. Strong earthquake shaking in the immediate vicinity of the construction excavation undoubtedly occurred repeatedly during the past 15,000 years, including at times when the location was submerged by lake water, as well as after the lake receded. The amplitude of the fold in Appendix C Figure 7 between Sta. 29 m and Sta. 35 m is greater than 2 m. Sand layers in this fold are overturned.

The description of liquefaction features at the site in Utah serves to demonstrate the character of deformation that can be produced by liquefaction without surface faulting. The synclines or sags in Trench South 2a at the Brightwater site are similar in amplitude and wave length to those in the article in Appendix C. The synclines and sags in Trench South 2a are more uniform and symmetrical than the liquefaction-caused overturned fold and could have been produced by liquefaction or by ice melt out.

Age of Deposits

The Puget Lobe of the Cordilleran Ice Sheet advanced across the Seattle area approximately 17,590 cal yr B.P. reached its maximum extent approximately 16,950 cal yr B.P., and completed its retreat approximately 16,570 cal yr B.P. (Porter and Swanson, 1998). The well-documented age-range of glacial deposits in the site area is sufficient for determining the minimum age of deformation features that are buried by undeformed glacial deposits. However, an attempt was made to determine radiocarbon ages of deposits in Trenches South 2a and 2b by collecting five samples. The first sample collected was determined in the field to be mineral instead of organic, so it was not submitted for dating. The second and third samples, collected from Trench South 2a and

Trench South 2b, respectively, were submitted to Beta Analytic, Inc., in Miami, FL, for pretreatment and radiocarbon analyses using accelerator mass spectrometry (AMS) techniques. During pretreatment of sample 2, it became clear that the sample was mineral instead of organic, so it was discarded. Sample 3 was carbon, but at the end of pretreatment, Beta Analytic advised us that under microscope examination some of the small fragments appeared to be shiny and have a conchoidal fracture unlike late Quaternary charcoal but similar to coal. The decision was made to try to avoid the shiny fragments and to date the other materials. Nonetheless, the radiocarbon age of >37,500 years B.P. (Beta-220275) was calculated (see Appendix B). The old carbon in this sample probably was eroded from Tertiary formations containing thin coal seams (Minard, 1985) which crop out in the Maltby area, upglacier from the Brightwater site, but east of the ice flow path.

Two more samples were collected from a silt layer single in Trench South 2a. Fragments that appeared to be organic were collected (sample 4) and a 5 cm long, slender fragment that appeared to be a delicate twig was collected separately (sample 5). Both samples were submitted to Beta Analytic. Sample 5 was subjected to pretreatment and suitable plant fragments were obtained. Beta Analytic advised us that under microscope examination the fragments appeared to be more like a thick blade of grass than a twig, but it did not have the appearance of a modern root. Nonetheless, the conventional radiocarbon age of 70±40 years B.P. (Beta-220382) was calculated, which corresponds to 140 to 20 cal yr B.P. or 270 to 210 cal yr B.P. (see Appendix B). The two ranges of calibrated ages are based on the INTCAL98 calibration curve for conventional radiocarbon ages, which is shown graphically in Appendix B for this analysis. This sample contained modern plant material but it came from a layer of silt that clearly was in-place and that had not been disturbed by drain-line construction. Neither did the layer appear to have been an animal burrow. We thought that this layer was deep enough to be below root depth, but root contamination is the most plausible explanation for its modern age.

Thus, radiocarbon dates from the Chemical Building seismic trenches were inconsistent with regional dates from Vashon glacial deposits (Porter and Swanson, 1998). Therefore, the ages of the formations exposed in the Chemical Building seismic trenches must be estimated on the basis of the interpreted depositional environment and successful radiocarbon ages determined for the Puget Lowland by Porter and Swanson (1998) which are shown on Figure 3. Trench South 2b exposed two boulders too big to have been transported by any mechanism other than glacial ice. Glacial advance in the Seattle area occurred approximately 17,590 cal yr B.P., reaching a maximum extent approximately 16,950 cal yr B.P., and retreated by about 16,570 cal yr B.P. Therefore, advance outwash deposits, till, and diamict or subglacial meltout till overridden by ice of the Vashon stade of the Fraser glaciation at the Brightwater site must be no older than about 17,590 cal yr B.P. and no younger than about 16,950 cal yr B.P. Recessional outwash deposits, glaciolacustrine, and subglacial meltout till not overridden by ice of the Vashon stade of the Fraser glaciation at the Brightwater site must be no younger than about 16,570 cal yr B.P. but probably no older than 16,950 cal yr B.P.

Therefore, unfaulted glacial deposits (advance, till, subglacial, and/or recession) are meaningful for the conclusion that active faults as defined by the 2003 IBC do not pass through the seismic trenches.

Unfaulted Stratigraphy

Under the IBC definition, an active fault is one that has 1) a historic slip rate of 1 mm/year or more and 2) evidence of having moved during the Holocene (the most recent 11,000 calibrated years before present). The features identified in the recent trenching do not meet either part of this definition. First, no part of the SWIF has generated surface displacement during a historic earthquake nor has historic creep been documented; therefore, no part of the SWIF is an active fault by the slip rate definition. Second, no faults or other features exposed in Trench South 1, 1a, 1b, or 1c or Trench South 2a or 2b are active by the Holocene age criterion because all questionable features can be accounted for by non-tectonic processes and are overlain by undeformed subglacial or recessional outwash deposits, indicating that the undeformed deposits are greater than 11,000 calibrated years before present (no younger than 16,570 cal yr B.P.).

Cracks in diamict exposed in the North Trench, including sand fillings and one injection feature, were uniformly very dense, supporting a conclusion that the deposit was overridden by glacial ice after the cracks and injection feature were in place. Glacial outwash deposits are not present at the North Trench location; clearly unfaulted and undeformed deposits are not available at this location. Figure 36 shows open rectangles oriented parallel to Lineament 4 and centered on the Chemical Buildings. These open rectangles fall on a uniform glacially scoured upland ridge located southeast of the Chemical Buildings. It is apparent that no significant scarp disrupts the glacially scoured upland ridge at this location.

Comments and Responses to Reports and Letter

Scientists employed by the USGS were invited by King County Wastewater Division to visit the site on Thursday, July 6, 2006, while Trench South 1, 1a, 1b, and 1c and the North Trench were open. Drs. Craig Weaver, Brian Sherrod, and Ralph Hagerud made a visit on that day, and Dr. Weaver prepared a site visit report which he sent to King County. The USGS Site Visit Report contains statements and opinions regarding the geology exposed in the trenches. Appendix D contains comments relevant to the USGS report.

Dr. Robert Yeats, retained by the Sno-King Environmental Alliance (SKEA) spoke with Dr. Sherrod shortly following the USGS visit to the trenches and prepared statements in an electronic letter addressed to “Dear SKEA folks.” Appendix E contains comments relevant to Dr. Yeats’ letter.

Dr. Yeats was also retained by the City of Woodinville to provide information about the seismic hazard at the Brightwater site based on an interpretation of geotechnical borehole data. He prepared a report under Earth Consultants International (ECI) dated August 21, 2006. The geotechnical borehole data was developed by King County's geotechnical consultants Shannon & Wilson and CH2M Hill. Conclusions and interpretations about the geology with specific reference to surface fault rupture hazards included in the ECI report are part of the scope of services being provided by MACTEC Engineering and Consulting. Therefore, representatives from each of these three companies collaborated to prepare responses to the comments in the August 21, 2006, ECI report, which are contained in Appendix F.

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Table 1. Description of geologic units for Vashon (younger glacial) deposits for the Seattle area modified from Troost et al. (2005).

Geologic Unit	**Name**	**Summary Description**	**Thickness**	**Density/ Hardness**	**Permeability Factors**
Qvr	Recessional outwash deposits	Stratified sand and gravel, moderately sorted to well sorted, and less commonly silty sand and silt. Deposited in outwash channels that carried south-draining glacial meltwater during ice retreat away from the ice margin. Also includes deposits that accumulated in or adjacent to recessional lakes. Discontinuous. May include thin lag on glacial till uplands although deposits less than about 1 m (3 ft) think not shown on map. Locally divided into:	~1 to 6 m; typically in channels	Loose to dense	Horizontally bedded to cross bedded, uniformly to well graded, channelized, coarse lag deposits common
Qvrl	Recessional lacustrine deposits	Laminated silt and clay, low to high plasticity, with local sand layers, peat, and other organic sediments, deposited in slow-flowing water and ephemeral lakes. Locally includes high-plasticity clay with swell potential. Lenses and layers of ash and diatomite may be present. Gradational with Qvr	5 m typically on uplands; up to 16 m at heads of recessional channels	Very soft to stiff	Horizontally bedded; sandy channels may breach lacustrine deposits
Qvrc	Recessional coarse-grained deposits	Predominantly sand and gravel, clean to silty, horizontally to cross bedded, deposited in outwash channels and deltas	4 to 10 m	Loose to dense	Interspersed silt and open-work gravel layers
Qvi	Ice-contact deposits	Intercalated till and outwash, irregularly shaped bodies of till and outwash. Outwash consists of sand and gravel, clean to silty, horizontally bedded to steeply dipping. The till consists of matrix-supported gravelly sandy silt that may or may not have been glacially overridden. Gradational with Qvr and Qvt	3 to 15 m; on patches on the upland	Loose to very dense	Intermixed irregularly shaped bodies of till and coarse-grained deposits

Table 1 (continued). Description of geologic units for Vashon (younger glacial) deposits for the Seattle area modified from Troost et al. (2005).

Geologic Unit	Name	Summary Description	Thickness	Density/ Hardness	Permeability Factors
Qvt	Vashon till	Compact diamict of silt, sand, and rounded to well-rounded gravel, glacially transported and deposited under ice. Commonly fractured and has intercalated sand lenses. Generally form undulating, elongated surfaces. Upper 1 m of unit generally weathered and only medium dense to dense. Locally divided into:	Typically 1 to 10 m	Very dense	Vertical fractures, sand lenses, and crude subhorizontal bedding common
Qvtm	Subglacial meltout till	Deposits consist of compact diamict (gravel and sand in a silt matrix) with large, often tabular, sand and gravel bodies, cobbles common. Coarse-grained layers may exceed 50% of the volume of the deposit. Locally identified as ‘sandy till’, locally gradational with Qvt and Qva	Typically 1 to 10 m	Dense to very dense; sand commonly is less dense	Vertical fractures, sand bodies, irregular bedding are common
Qva	Advance outwash deposits	Well-sorted sand and gravel deposited by streams issuing from advancing ice sheet. May grade upward into till. Silt lenses locally present in upper part and are common in lower part. Generally unoxidized to only slightly oxidized. Grades downward into Qvlc with increasing silt content	Locally over 60 m thick; widespread	Dense to very dense	Predominantly medium grained sand, horizontally to cross bedded, hard silt beds common throughout
Qvlc	Lawton clay deposits	Laminated to massive silt, clayey silt, and silty clay with scattered dropstones deposited in lowland proglacial lakes. Marks transition from nonglacial to earliest glacial time, although unequivocal evidence for glacial or nonglacial origin may be absent. Deposits of correlative age and texture may be included in older fine-grained units where evidence of age and/or depositional environment is absent.	> 30 m; generally present in pre-Vashon valleys below 240 feet in elevation	Very stiff to hard	Vertical fractures, fine sand partings common near top and bottom of unit