

Geology and landslide geomorphology of the Burpee Hills, Skagit  
County, Washington, USA

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## Abstract

Landforms within the Skagit Valley record a complex history of land evolution from Late Pleistocene to the present. Late Pleistocene glacial deposits and subsequent incision by the Skagit River formed the Burpee Hills terrace. The Burpee Hills comprises an approximately 205-m-thick sequence of sediments, including glacio-lacustrine silts and clays, overlain by sandy advance outwash and capped by coarse till, creating a sediment-mantled landscape where mass wasting occurs in the form of debris flows and deep-seated landslides (Heller, 1980; Skagit County, 2014). Landslide probability and location are necessary metrics for informing citizens and policy makers of the frequency of natural hazards. Remote geomorphometric analysis of the site area using airborne LiDAR combined with field investigation provide the information to determine relative ages of landslide deposits, to classify geologic units involved, and to interpret the recent hillslope evolution. Thirty-two percent of the 28-km<sup>2</sup> Burpee Hills landform has been mapped as landslide deposits. Eighty-five percent of the south-facing slope is mapped as landslide deposits. The mapped landslides occur predominantly within the advance outwash deposits (Qga<sub>v</sub>), this glacial unit has a slope angle ranging from 27 to 36 degrees. Quantifying surface roughness as a function of standard deviation of slope provides a relative age of landslide deposits, laying the groundwork for frequency analysis of landslides on the slopes of the Burpee Hills. The south-facing slopes are predominately affected by deep-seated landslides as a result of Skagit River erosion patterns within the floodplain. The slopes eroded at the toe by the Skagit River have the highest roughness coefficients, suggesting that areas with more frequent disturbance at the toe are more prone to sliding or remobilization. Future work including radiocarbon dating and hydrologic-cycle investigations will provide a more accurate timeline of the Burpee Hills hillslope evolution, and better information for emergency management and planners in the future.

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## Introduction

In the last few decades, major advances in remote geomorphic mapping have led to new methods for identifying deep-seated landslides. In particular, airborne laser mapping (light detection and ranging, or LiDAR) has enabled production of high-resolution topographic images of the ground surface (e.g. Haugerud, 2014). In areas where LiDAR is available, a thorough desk review in concert with field investigation is a powerful combination for identifying steep and convergent slopes that are prone to landslides (Miller, 2004; McKean and Roering, 2004; Glenn et al., 2006; Schulz, 2007; Burns et al., 2009). Convergent slopes are generally less stable, spoon-shaped features on a landform, that contributes debris downslope and often into a stream network (Lu and Godt, 2013). In Washington State, landslide hazards have gained renewed public attention after the State Route (SR) 530 Landslide occurred near Oso, Washington on March 22, 2014 (Keaton et al., 2014; Gerstel and Badger, 2014). This event demonstrated the hazard from deep-seated landslides in glacial sediments of the North Fork Stillaguamish River Valley (LaHusen et al., 2014) and has spurred scientific investigations of deep-seated landslides in other regional river valleys, including this study. This investigation focuses on mapping the geology and occurrence of landslides in a neighboring valley to the north, the Skagit River Valley.

The Skagit River Valley is an 8,000-km<sup>2</sup> watershed in the North Cascades Range, approximately 160 km north of Seattle, and approximately 80 km north of the SR 530 Landslide. Both the Skagit and North Fork Stillaguamish valleys drain the North Cascade Range west into Puget Sound. The Skagit River Valley has similar morphology and depositional history to the North Fork Stillaguamish River Valley, including: glacial stratigraphy, low relief glacial terraces, undercutting of basal slopes by river bank erosion and rivers truncating distal toes of known landslide deposits. This study focuses on the Burpee Hills, adjacent to the town of Concrete, Washington (Fig. 1). The Burpee Hills is 28-km<sup>2</sup> bound on the northern edge by Grandy Creek, on the eastern edge by Lake Shannon reservoir created by the Lower Baker River Dam, and on the south by the Skagit River and SR 20.

My work helps lay the foundation for future studies in the region by producing a relative chronology of landslide deposits and by comparing geology to slope morphology in order to elucidate the history of landsliding on the Burpee Hills. If complemented by hydrologic and fluvial geomorphologic investigations, these findings will serve to inform better land-use-planning standards and increase preparedness for communities along the slopes of the Burpee Hills. The following tasks were completed during this work: (1) to identify and map landslides using LiDAR-derived digital elevation models (DEM); (2) to develop a generalized geologic map of the Burpee Hills based on new observations and compilation of existing data; (3) to evaluate the slope profiles of identified landslides, based on slope angle and shape; (4) to test a relationship between glacial stratigraphy and slope morphology of the Burpee Hills landform by comparing slope profiles of mapped landslides to generalized stratigraphy; and (5) to use slope roughness to determine relative ages of landslide events at the margins of the Burpee Hills.

## *Motivation for this study*

After the SR530 Landslide near Oso, Washington, Washington Governor Jay Inslee, formed the Joint SR530 Landslide Commission to evaluate Washington State landslide preparedness and to make recommendations for future events in the Puget Lowland (Gerstel and Badger, 2014; Lombardo et al., 2014). The GEER report (Keaton et al., 2014) and the Joint SR530 Landslide Report (Keaton et al., 2014; Lombardo et al., 2014) both advocate for statewide landslide mapping efforts and increased public awareness of potential landslide hazards. With that in mind, this project intends to advance landslide mapping of the Skagit River Valley.

Landslides have been documented throughout Skagit County since the early 20<sup>th</sup> century (Heller, 1978; Skagit County, 2014). Most of these landslides have been categorized as shallow debris flows and have often coincided with high precipitation events (Skagit County, 2014). Few deep-seated landslides have been reported in recent history, but there is geologic evidence to suggest their occurrence in the past, as I report below. Therefore, to inform inhabitants of Skagit County of the hazards of landslides, it is necessary to improve landslide maps in order to provide data for probability of landslide occurrence. Although a number of studies have addressed landslides in the Seattle area (e.g. Tubbs, 1974; Laprade et al., 2000), little work is specific to the Skagit Valley (e.g. Heller, 1980). Data collected and maps produced by Paul Heller (1980) have provided a foundation for this investigation. The maps produced in this project are intended to be used as a screening tool for landslide prone slopes within the Burpee Hills, and to help inform the community of landslide hazard potential.

## **Background**

### *Geologic Setting*

The Burpee Hills are on the western flank of the North Cascade Range of Washington State (Fig. 1). The geology of the North Cascade region is the result of a complex history of orogeny, volcanism and glaciation which has created and altered the rugged landscape. Within the North Cascades region, the Skagit Valley has distinct bedrock, surficial deposits and morphology that are important to understand regional landslides. Tabor and Haugerud (1999) described the bedrock geology of the North Cascade region as consisting of several distinct bedrock terranes. The Skagit River cuts through crystalline core complexes from Ross Dam to Bacon Creek dominated by the Skagit Gneiss complex (Riedel et al., 2011). The north-south trending Fraser-Straight Creek Fault divides the North Cascades into east and west sections (Lasmanis, 1991). The Skagit River crosses the Fraser-Straight Creek Fault at Marblemount, Washington and enters a bedrock terrane dominated by greenschist, phyllite and the Chilliwack Group (metamorphosed sedimentary rocks) (Misch, 1966; Tabor and Haugerud, 1999; Riedel et al., 2011). Due to less resistant bedrock (Chilliwack Group) to west of the fault, the river valley is approximately three times

wider than it is to the east of Marblemount (Riedel et al., 2011). The Burpee Hills landform is within the wider western section of the Skagit River valley at the confluence of the Baker River and Skagit River (Fig. 2).

#### Bedrock Geology

The Burpee Hills landform is approximately 25 km west of the Fraser-Straight Creek Fault. The Anderson Creek Fault, a mid-Paleozoic, high angle fault is inferred along Grandy Creek on the northern boundary of the Burpee Hills (Fig. 3) (Tabor et al., 2003). The western section is referred to as the Northwest Cascades System (Tabor et al., 2003). The Northwest Cascades System is comprised of four major stacked thrust sheets that have been displaced by extensional faults (Tabor et al., 2003). The Excelsior and Welker Peak Nappes are the thrust sheets that surround the study area. The thrust sheets are composed of the Chilliwack Group of Cairnes (1944) and are formed in an arc setting and composed of metamorphosed basaltic and andesitic volcanic rocks, sandstone, siltstone and shale (Tabor et al, 2003). The Chilliwack Group ranges in age from Silurian to Permian. The thrust sheet also includes the overlying Cultus Formation, which is a regionally overturned, Triassic to Early Jurassic marine and dacitic volcanic unit (Brown et al., 1987). The Bell Pass mélange overlies the Chilliwack Group and Cultus Formation and includes gneiss and schist, locally mapped as the Yellow Aster Complex of Misch (1966) and range from Pennsylvanian to Jurassic in age, although zircon yield mid-Paleozoic ages (Tabor et al., 2003). Oligocene to Holocene Cascade magmatic arc-root plutons altered the older Paleozoic to Tertiary bedrock in the North West Cascades erupted on phases of the Chilliwack Group (Tabor et al., 2003).

Volcanism related to Glacier Peak and Mount Baker contributes ash and volcanic sediments to the lower Skagit River watershed. The volcanic activity of Mount Baker for the past 1.3 Ma has shaped the Baker Valley and subsequently the Skagit Valley by deposition of volcanic ash, which is found downstream of the study area (Hildreth et al., 2003; Riedel et al., 2011). The subsequent lahar deposits have been extensively mapped in the 1:24,000 map of the Lyman Quad to the west of the study area (Dragovich et al., 2003).

#### Glacial History

Multiple glaciations throughout the Pleistocene have shaped the modern valley, including alpine glaciation from the North Cascade Mountains and continental glaciation from the Puget Lobe of the Cordilleran Ice Sheet (Waitt and Thorson, 1983; Booth, 1986; Riedel, 2007; Booth et al, 2004; Riedel et al., 2011). There are general similarities in depositional history, geomorphology and regional geology between the Skagit, Sauk and Stillaguamish River valleys, because they were physically interconnected drainage networks during the Pleistocene. The Skagit River drained south during the Pleistocene via the Sauk and Stillaguamish Rivers while Vashon stade sediments blocked the Skagit valley to the west of the Sauk (Tabor et al., 2002). Eventually the incision by the Baker River and other local flow breached the blocking sediments and the Skagit began to drain to the west (Heller, 1978; Tabor et al., 1994). The modern Skagit River flows west toward the Puget Sound. The modern Sauk and Baker Rivers are the main tributaries to the Skagit



Valley. Although the Sauk drains to the north from Glacier Peak (Riedel et al., 2011) the headwaters of the North Fork Stillaguamish River interact with the Sauk River as it flows through Darrington, Washington.

The current stratigraphic framework found in the Burpee Hills is dominated by the deposition of sediment during the last glacial maximum of the Cordilleran Ice Sheet with a duration ranging from 14,000 years B.P. to 17,000 years B.P., known as the Vashon Stade of the Fraser Glaciation (Armstrong et al., 1965; Tabor and Haugerud, 1999; Porter and Swanson, 2008). The provenance of clasts along the Baker River establish flow directions of the alpine and continental ice include: south flowing down the Baker River valley (alpine), east up the Skagit Valley (continental) and from the northwest to southeast (continental ice sheet at last glacial maximum) (Heller, 1980; Riedel, 2010; Riedel et al., 2011). There is evidence that the Vashon stade covered the parts of the Skagit Valley including the Burpee Hills with an ice surface elevation of 1500 m (Booth, 1987; Booth et al., 2003). As the Puget Lobe advanced east, up the west-flowing Cascade valleys it left ice-marginal deposits referred to as moraine embankments (Booth, 1986).

The Burpee Hills landform can be described as a glacial terrace or moraine embankment, which stratigraphically overlies the bedrock. Based on the geologic map by Tabor et al. (2003), bedrock is present at the base of the south bluff of the Burpee Hills and is identified as Pre-Devonian intrusive rocks known as the Yellow Aster Complex (Misch, 1966). Overlying the bedrock is a Quaternary (Fraser-age) sequence including: continental advance glacial sediments including dense glacio-lacustrine deposits overlain by glacio-fluvial sand and gravel deposits, capped by continental glacial till (Heller, 1980; Riedel, 2011). This glacial terrace is an erosional remnant landform formed by incision of the Skagit Valley into the glacial outwash deposits aggraded during the advance of the Puget Lobe of the Cordilleran Ice Sheet (Ritter et al., 2011). The Burpee Hills is thought to be part of a kame terrace or a traceable lateral moraine on the north side of the Skagit Valley formed while the Puget Lobe advanced (Heller, 1980; Riedel et al., 2011). According to Riedel et al., (2011), there are notable unconformities in stratigraphic sections exposed along the western shores of Lake Shannon Reservoir. The unconformities are between the continental glacial advance silts and clays and the overlying glacial till. These sections were not observed in this study.

The post-glacial environment is important to the modern geomorphology of the Burpee Hills landform. At the end of the last glacial maximum, Glacial Lake Baker was contained northeast of the Burpee Hills within the current Baker River Valley. As the Puget Lobe retreated and Glacial Lake Baker drained to the east, outlets opened including Lake Tyee Channel (Riedel et al., 2011) and eroded through glacial sediment, establishing the outlet to Baker Valley and the northern edge of the modern Burpee Hills landform. Glacial Lake Baker persisted throughout the post-glacial Holocene until at least 4 ka (Scott and Tucker, 2006; Riedel et al., 2011).

## *Previous Work glacial stratigraphy and landsliding*

Previous work has been conducted to understand the complex geologic history of the Puget Lowland, specifically the evidence of glaciation and glacial features (Armstrong, 1957; Easterbrook, 1963; Armstrong et al., 1965; Easterbrook, et al., 1967; Heller, 1978; Waitt and Thorson, 1983; Easterbrook, 1986; Booth, 1987; Porter and Swanson, 1998). Subsequent studies were done to constrain the ages of the dominant glacial history in the Puget Lowland (Booth et al., 2004, Troost and Booth, 2008).

The study of the Pleistocene glaciation initiated studies of landforms and methods to identify unstable areas throughout the Puget Lowland (Tubbs, 1974). Heller (1978) produced the first landslide-susceptibility maps of the Skagit Valley by mapping landslides and regional geology and by identifying the types of landslides produced within certain geologic conditions. Heller (1978) classified the slopes of the Burpee Hills and identified failure mechanisms allowing for classification of deep-seated and surficial landslide failure along the Burpee Hills. The landslide types identified by Heller (1978) include (1) shallow debris slide, (2) debris flows with larger flow run out and (3) slump flow, or deep-seated landslides. Each of the failure mechanisms was described in relation to slope percent and related strata. In this study, I focus on the slump flow or deep-seated landslides that have occurred along the south-facing slopes of the Burpee Hills.

## **Section 1: Geologic Analysis of Burpee Hills**

The overarching goal of this section is to evaluate relationships between geology and landslide potential. In order to do so, it is necessary to compare the elevations of head scarp to the thickness of each measured geologic unit. Field mapping, remote mapping, and compilation of prior work on the Burpee Hills landform are used to document the underlying geology. A geomorphometric approach is used to identify landforms with distinct deep-seated landslide morphology.

### *Methods*

#### Desk Review

Prior to fieldwork, I delineated features in the Burpee Hills landform based on geomorphology. To accomplish this, it was necessary to create slope and convergence raster maps from the existing digital elevation model (DEM) for the study area. These raster data sets were then used to identify head scarps and individual landslides. I also utilized National Agriculture Imagery Program (NAIP) aerial imagery from 2006-2009 to locate previous landslides and investigate how they have changed in recent history. I accessed borehole data from the Washington State Department of Ecology (DOE) to correlate measured geologic units and to create a generalized geologic map. I created parcel maps and location maps using aerial imagery and Skagit County data to locate accessible outcrops and other sites of interest within the field area.

### Field Work

During fieldwork for this project, I used GPS and a laser range finder to map outcrops exposed along Burpee Hills Road, Baker Lake Road and Challenger Road (Fig. 2). There are a total of six outcrops measured on the Burpee Hills, five along Burpee Hills Road on the eastern portion of the landform, and one along Grandy Creek Road on the western portion of the landform (Fig. 2). At each outcrop I measured unit thickness of each differentiable unit based on grain size, sorting, grain shape and density. I measured elevation at each outcrop. I observed the relative stratigraphic position of each geologic unit, how it was layered on top of the underlying sediment (i.e. unconformities). I noted the direction each measured section faced and the prominent vegetation on each outcrop. Samples were collected where accessible. The units were described and grouped by distinct changes in grain size, lithology and density (Appendix). I investigated each outcrop for presence of ground water seepage, piping and other signs of subsurface flow. At each measured section, I made a measurement of slope angle and position with Brunton compass and took photos to document prominent features.

### Lab Methods

In the lab, I described geologic samples according to the Unified Soils Classification System (ASTM D2488-09a, 2009). I used grain size, grain-size distribution, sorting and shape to describe and classify each sample. From the descriptions (Appendix), I compared the deposits at each measured section to known descriptions of glacial sediments of the Puget Lowland (Armstrong, 1957; Armstrong et al, 1965; Clague et al., 1980; Thorson, 1980; Easterbrook, 1986; Booth, 1994; Booth et al., 2003). I compiled each of the measured sections into a generalized geologic representation for the entire Burpee Hills based on the DOE well log data and previously collected data (Heller, 1980).

### Digital Mapping Methods

A digital elevation model (DEM) with 2-m resolution derived from airborne LiDAR was acquired from Puget Sound Lidar Consortium. The DEM is projected in the NAD1983 State Plane Washington North FIPS 4601 coordinate system measured in feet. All other layers used in this study, including the 1:100,000-scale geologic map (Tabor et al., 2004) sourced from the Washington State Department of Natural Resources WA-DNR, were projected to match the DEM. In order to create a generalized geologic map of the Burpee Hills, I assumed the concepts of crosscutting relationships and original horizontality apply to the glacial sediments unconformably overlying the bedrock. The bedrock exposed in the Burpee Hills landform was mapped in my generalized geologic map within the boundaries defined by Tabor et al., 2003 with 20-m confidence interval as defined by the data source (Haugerud et al., 2009).

I acquired data from historic landslide maps, stratigraphic sections and geologic maps (Heller, 1978; Heller, 1980; Heller, 1981), to create a generalized geologic map. The geologic contacts were mapped at the 1:24,000 scales to capture the thickness of each unit per my field measurements. There is local variation between the units; therefore

the contacts between the measured geologic units in the generalized geologic map were delineated within 20 m to 50 m location confidence (i.e., certain the contact exists in a 20-m or 50-m buffer from where it is plotted). The contacts between units are marked as concealed (dotted) or visible throughout the extent of the generalized geologic map based on field measurements (Fig. 5) (as recommended by Haugerud et al., 2009).

The surficial unit sketches (Appendix) made in the field were digitized in Adobe Illustrator CS6 to create stratigraphic columns of each of the six measured sections. Standard USGS symbols were used to represent each stratigraphic unit (Federal Geographic Data Committee, 2006).

## *Observations*

### Geologic Descriptions

The Burpee Hills is made of an approximately 205-m sequence of glacial sediments. Based on the assumptions made the bedrock is overlain by three distinct units (Fig. 5; Table 1). There is one exposure of bedrock within the Burpee Hills formation and is located on the southern slope along Challenger Road, State Route 20 (Fig. 2) and the Cascade Recreational Trail. The minor outcrop of Devonian bedrock is mapped along the southern face of the Burpee Hills according to the 1:100,000 scale geologic map (Tabor et al., 2003). The glacial deposits that form the landform are thicker to the east and consist of: (1) a basal unit is a dense to very dense, fine-grained, laminated deposit dominated by silt and clay. The lowest elevation deposits have the highest measured density. (2) The basal unit is unconformably overlain by a medium to coarse-grained, cross-bedded, gravelly sand, with minor cobbles and boulders. This unit has meter scale features that vary across the landform. (3) The third unit unconformably overlies the second and is characterized as coarse to very coarse-grained, gravel with cobble to boulder-sized clasts forming an undulating terrace top. See Appendix for more details about each measured lithology.

Field observations provided data for analysis of geology of the Burpee Hills and helped build the generalized model of the underlying geology (Fig. 4). There is meter-scale variation within each outcrop and each contains three or four distinct units (Appendix). I chose to combine geologic units into larger than meter-scale features because the approximately 2-m resolution of the DEM would not be able to reconcile variations in terrain finer than that scale. For this reason, I decided to forego measuring features smaller than 1-meter in thickness. This resulted in the fine-scale variation of cross-beds, alternating fine and coarse-grained sediment, etc. not included in this study. There are five identifiable sediment types (Fig. 4) found within the sandy-gravel of the second unit. These sub-units are combined in the generalized stratigraphy (Fig. 5).

The USCS classifications of the observed sediments (e.g. CL) of each unit were compared to the descriptions of the corresponding stratigraphic designation (e.g. Qgl<sub>v</sub>) (Dragovich et al., 2003; Tabor et al., 2003). Based on the descriptions from

previous studies in the North Fork Stillaguamish Valley (NFSV) and the Skagit Valley (Heller, 1981) I found strata that matched my observations and designated a stratigraphic designation based on the sediment characteristics (Gerstel and Badger, 2014; Keaton et al., 2014). I also referenced elevation and thickness of each stratigraphic designation to compare the variation between the valleys and relate the observed classifications of the sediment to the appropriate stratigraphic unit.

### *Results of mapping*

Useful metrics for measuring and understanding geology of the Burpee Hills and analyzing slope characteristics within each unit include previous mapped landslides (Heller, 1980), measured sections and combining meter-scale geology into larger units. Elevations at each measured section were useful in creating the generalized geologic map. Slope degree and percent were used to compare slope to previous studies and determine the stability of the slopes.

### Geology

Compilation of data from the DOE, previous studies (Heller, 1979; Heller, 1980; Riedel, 2007; Riedel, 2011) and the field observations for this study provided the data for a generalized geologic map (Fig. 5). This map presents the main units that are found in the Burpee Hills. The generalized stratigraphy represented in the Burpee Hills here as a package of an approximately 205-m thick deposit (Riedel et al., 2011). The measured sections of this study represent a minimum 175-m of exposed unconsolidated glacial sediment (Fig. 5). The glacio-lacustrine deposit has a minimum thickness of 8 m (Table 1) and is observed only in the western outcrop AOBH-1 (also section 5 of Heller, 1979). Due to the lack of exposure along the eastern portion of the Burpee Hills the glacio-lacustrine unit (Qgl<sub>v</sub>) was mapped with 50-m location confidence and as a concealed contact. According to the principle of original horizontality and under the assumption of cross-cutting relationships I extrapolated the average thickness of this layer across the elevation where it was exposed on the western part of the outcrop. There is evidence for the appearance of glacio-lacustrine sediment along the western shoreline of Lake Shannon Reservoir and the eastern facing edge of the Burpee Hills (Riedel et al., 2011). It is unknown if the unit is laterally contiguous across the entire landform; further subsurface investigation is necessary to determine the extent. The overlying advance outwash is also Fraser-age and from the Vashon Stade of the Puget Lobe of Cordilleran ice sheet. The average measured thickness at each measured section is approximately 13 m (Table 1). This unit varies in composition throughout the measured sections of the Burpee Hills landform and includes the following USCS classifications from fine grained to coarse grained sediments: SM, SP-SM, SW-SM, SP and GW-GC (Fig. 4). The measured sections that contain advance outwash occur at successive elevations, therefore it can be inferred that the total thickness of the advance outwash incorporates the measured thicknesses at each measured section (Appendix). The outwash occupies the largest range in elevation and spans approximately 160-m thick across the Burpee Hills. This unit was mapped with the location confidence of 20-m and has a basal contact that is concealed. The unit is thickest on the southern face of

the landform and varies in thickness throughout the deposit. It is composed of several facies from fine to very coarse-grained sediment and is definitively identified in measured sections by cross-beds with a varying height from 0.5-m to 2-m. The advance outwash (Qga<sub>v</sub>) is overlain by a thin, deposit of glacial till forming the terrace surface of the Burpee Hills (Qgt<sub>v</sub>). This unit has a minimum thickness of 3 m and is exposed at two measured sections along Burpee Hills Road (Appendix: AO\_BH\_1a and AO\_BH\_2a).

The area at the base of the southern facing slopes is mapped as Quaternary alluvial (Qa, Fig. 5). The alluvium may contain reworked colluvium from previous landslide deposits, but was not sampled in this study. On the northern slope of the Burpee Hills the mapped area is labeled Qoa, Quaternary older alluvium. This is the location of the postglacial Lake Tyee channel which drained Glacial Lake Baker after the ice sheet retreated (Riedel et al., 2011). Although this unit was not sampled during this study, I observed Grandy Creek flowing to the southwest through the paleo-channel which marks the northern boundary of this study area.

The generalized geologic map provides the context for slope investigation. The elevations are extracted from the DEM for each mapped geologic unit to quantify the relationship between geology and topography. This is important for comparison to the other regional river valleys including the North Fork Stillaguamish Valley (NFSV). The unit identified as Quaternary alluvium (Qa) occurs at the lowest elevation (74 m) along the southern edge of the Burpee Hills landform (Fig. 5). This recent alluvial sediment is mapped along the right bank of the Skagit River. Based on the geologic map the successive unit, glaciolacustrine deposit (Qgl<sub>v</sub>), has a lower exposed elevation of 100 m. This unit is represented as the basal unit in AOBH\_1 and is the basal glacial unit mapped on the Burpee Hills representing the oldest Pleistocene deposit in this landform (Fig. 4). Overlying the glacio-lacustrine sediment is the Vashon Stade advance glacial outwash (Qga<sub>v</sub>) with a lower contact elevation of 115 m. The overlying glacial till (Qgt<sub>v</sub>) has a lower contact elevation of 300 m. The glacial till has an average thickness of 5 m, based on measurements at AO\_BH\_1a and AO\_BH\_2a. The highest ground surface elevation measured is 305 m (Fig. 4).

### Slope

The formation and stability of natural slopes is a product of erosional processes related to geology, climate and amount of time the landform has been exposed. The slope is an important metric for understanding geomorphology especially in quantifying geometry of slope and angles along slope profiles. The slope profiles and slope geometries are useful for determining the dominant downslope processes of the landform. The slope derived from the DEM of the Burpee Hills is compared to geology to show variation in morphology of features develops in different soil types (Fig. 6). These features provide evidence to identify mass movement processes and infer how slopes erode. Determining the type of mass movement processes is especially important along the south facing slopes of the Burpee Hills directly above the Town of Concrete. When a mass movement process is inferred it is used to

predict rates of movement and frequency of landslide occurrence, factors that are very important for citizens, planners and emergency managers.

The slope is measured remotely by deriving slope values in degrees from the DEM (Fig. 7). The lowest slope angles occur within the Qoa in the paleo-channel formed on the northern distal edge of the Burpee Hills (Fig. 6). From the morphology seen in the LiDAR imagery, one can see this unit is confined with a valley and does not have significant topographic variations. The Quaternary alluvium (Qa) has an average slope 8°. This deposit occupies the right bank of the Skagit River floodplain on the southern distal edge of the Burpee Hills and has little local variation in slope. The overlying glacio-lacustrine deposits (Qgl<sub>v</sub>) have an average slope value of 21°. The evidence of hummocks within this mapped unit suggests the glacio-lacustrine sediment is not well exposed across the outcrop and frequently covered by landslide deposits, or colluvium. The overlying mapped advance outwash (Qga<sub>v</sub>) has an average slope of 26°. The near vertical exposure of the glacial till (Qgt<sub>v</sub>) has the highest slope (33°), whereas the glacial till mapped as the terrace top or glacial upland (Qgt<sub>u</sub>) has little slope variation and an average value of 8° (Fig. 7). It is important to distinguish units of the generalized geologic map based on average thickness and geomorphologic features to accurately represent the slope changes along the landslide prone areas of the Burpee Hills.

## **Section 2: Landslide Analysis of Burpee Hills**

There are a minimum of 30 remotely mapped landslides presented in this study located along the south-facing slopes and east-facing slopes of the Burpee Hills. The geomorphology, extent, size and landslide mechanisms are evaluated and compared to the mapped geology of the area and to the neighboring river valley to the south, the North Fork Stillaguamish River, where the noteworthy SR530 (Oso) landslide occurred on March 22, 2014.

### *Methods*

#### Field Methods

One landslide exposed along Burpee Hills road was measured and observed during field work. The scarp elevation, the aspect, width, and other prominent features of the landslide (i.e., vegetation, landslide deposit) were measured. Other landslide data were sourced from Skagit Valley natural hazard documents and other previous work (Heller, 1979; Skagit County, 2014).

#### Digital mapping Methods

I conducted a remote geomorphometric analysis on the Burpee Hills landform following the methods of Berti et al. (2013), Roering et al. (2013) and Haugerud (2014). I delineated scalloped scarp features along the Burpee Hills landform that resembled deep-seated landslide features identified in the neighboring North Fork Stillaguamish River Valley (Haugerud, 2014). Landslide deposits without the scarp

were outlined separately at 1:20,000. The landslide deposit polygons were then used to define the zones for terrain roughness analysis. To establish a roughness value of the Burpee Hills, the standard deviation of slope was analyzed using a focal statistic window of 15 x 15 cells, which best captured the average size of hummocks (30-m x 30-m) within the study area (LaHusen et al., 2015; Berti et al., 2013). Gullies were removed from the landslide deposit polygons and thus from the roughness analysis because they exhibit different morphology from landslide deposits (Sean LaHusen, personal communication, 2016). Roads were also buffered out of the landslide deposit polygons so they do not artificially affect the surface roughness values.

A second set of landslide polygons that include landslide scarps was used in slope profiles. This polygon layer included the head scarp and run out distance, to evaluate a relationship between average height and average run out length of the deep-seated landslides and also the relationship to the subsurface geology. Other geomorphologic analyses, including the area of each mapped landslide, a slope profile, which included head scarp elevation, total runout length and total height of each landslide (Table 4). These data along with the standard deviation of slope, which measures the surface roughness based on hummock size, can be used to define relative age of landslide deposits. The remotely collected data also include a height to length ratio (H: L), which is useful for understanding the mobility of a landslide, and thus the potential destruction caused by its path. Data reported includes the H: L ratio, where height (H) is defined as the elevation difference between the head scarp and the base elevation of the landslide deposit and L is defined as the length from the head scarp to the landslide toe (Corominas, 1996; Legros, 2002; Iverson et al., 2015; LaHusen et al., 2015).

Slope profiles were measured using ArcMap 10 software for each measured landslide. For 30 of the mapped landslides of the Burpee Hills, slope profiles were measured from head scarp to distal toe of the landslide deposit. The slope profiles show the relationship to run out distance, scarp elevation and the relative elevation of geologic sediments related to slope profile. The slope profiles measured are limited to the mapped landslides (Fig. 8) and occur on the south facing and east facing slopes of the Burpee Hills.

## *Observations*

### Mapped Landslides

Landslides were mapped from the DEM on the southern and eastern slopes of the Burpee Hills (Fig. 8). The criteria used to map the landslides include: a visible head scarp above hummocky terrain, convergence around the head scarp, and evidence of prior downslope movement. In this study, 30 landslides were remotely mapped within the Burpee Hills Landform using the aforementioned criteria (Fig. 9). The Burpee Hills have a distinct scalloped edge along the terrace top, formed by the head scarps of the mapped landslides. Several factors complicated mapping the landslides including landslide size and extent, the presence of long, trench-like gullies, and remobilization features. I mapped four remobilization features within larger mapped



landslides. The remobilization features are identified by the presence of a secondary scarp feature and disturbed sediment downslope that have distinctively different morphology from the initial landslide scarp (LaHusen et al., 2015). Gullies exhibit significantly different morphology from the landslides, as sinuous, steep valleys in the Burpee Hills. Gullies were excluded from the mapped landslide areas. The mapped landslides occupy 28% of the total area of the Burpee Hills and 85 % of the south face. The average landslide area is 0.26 km<sup>2</sup> [smallest: 0.03 km<sup>2</sup>, largest: 0.73 km<sup>2</sup>]. Generally, the area of a landslide increases from west to east along the south face of the Burpee Hills (Fig. 8). The average elevation ranges for the landslides are between 54 m – 308 m. The elevation increases from west to east across the south face of the Burpee Hills.

The mapped geologic unit involved in each mapped landslides range from the largest area to smallest area: Qga<sub>v</sub> [5.1 km<sup>2</sup>], Qgl<sub>v</sub> [2.0 km<sup>2</sup>], Qa [0.24 km<sup>2</sup>], Qgt<sub>v</sub> [0.17 km<sup>2</sup>], Qgt<sub>v</sub> (u) [0.11 km<sup>2</sup>]. The advance outwash deposits are the main unit involved in the overall remotely mapped landslides. Of the 30 mapped landslides, 50% of the total landslides have glacial till and underlying advance outwash involved in the features. All of the mapped landslides have the glaciolacustrine (Qgl<sub>v</sub>) unit mapped within their extent, but the presence of the unit decreases as one moves from west to east along the south and east faces of the Burpee Hills. LS1 involves a small amount of sand overlying the glaciolacustrine, where LS24 includes mostly advance outwash and overlying till. It is likely that glaciolacustrine sediment underlies the run out in each of the mapped landslides along the south facing slopes. The Quaternary alluvium (Qa) also underlies or truncates the runout of the landslides on the south-facing slope [LS 16, 8].

#### Slope-Profile Characteristics

The shape of the measured slope profiles (Fig. 9b) is useful in interpreting failure characteristics and relationship to geology (Miller and Sias, 1998; Gerstel and Badger, 2014). Slope profiles and normalized slope profiles for all 30 of the identified landslides are shown in (Fig. 9a; Fig. 9b). Generally the slope profiles exhibit an upwardly concave surface indicative of a rotational landslide feature (e.g. Lu and Godt, 2013). Hummock features are commonly seen in the measured slope profiles beyond 70% of the total run out distance (Fig. 9b). Overall the highest number (15) (50%) of the measured slope profiles have the head scarp within the glacial till (Qgt<sub>v</sub>) (Fig. 18). A total of [14] (47%) of the measured slope profiles have the head scarp originating in the advance outwash (Qga<sub>v</sub>). Just [1] landslide (1%) has a head scarp that occurs within the elevation range of the glaciolacustrine unit (Qgl<sub>v</sub>). In total, 8 slope profiles have a head scarp elevation below 200 m. These 8 slope profiles also have the shortest run out distance (less than 300 m) and occur on the western edge of the south-facing slope. There is one slope profile with a head scarp elevation of 245 m. The remaining 21 slope profiles have a head scarp elevation between 275 m and 360 m. These landslides have longer more variable run out distances ranging from 140 m to 680 m.

Total height (H), run-out distance (L) and H: L ratio and are reported in Table 4. H: L ratios are a description of the mobility of a landslide. Small ratios imply long run out

distances, thus affecting a larger downslope area; whereas larger ratios indicate shorter run out distances and affect a much smaller area. Although the H: L ratio has been discredited as an adequate measure of bulk frictional resistance, it is a useful tool to identify areas that may be affected by large run out landslides [small H: L ratio and a specific upland source area] (Legros, 2002; Iverson et al., 2015). Average H: L ratio of the 30 mapped landslides at Burpee Hills is 0.27. The largest H: L ratio measured occurs with LS 28 and is 0.71. The smallest H: L ratio measured is within LS 3 and is 0.14 (Table 4).

### *Roughness and Relative Ages of Landslides*

According to previous studies, surface roughness can be used to delineate landslide features, to quantify past landslide movement, and to create maps of active landslides (McKean and Roering, 2004; Van Den Eeckhaut et al., 2005; Booth et al., 2009; Berti et al., 2013). In this study, surface roughness is a useful metric to define a timeline of landslide events relative to one another. Higher roughness values suggest a shorter time since landslide deposition; lower roughness values correspond to a longer time since landslide deposition. This metric can be related to absolute ages and used to predict frequency of landslide events in an area (e.g. the North Fork Stillaguamish River (NFSR)) (LaHusen, 2015). There are no absolute ages values for the Burpee Hills therefore surface roughness cannot be directly correlated to a numerical age but it can be useful to classify the relative age of each landslide relative to the total mapped landslides on the landform. Surface roughness provides a tool to determine the sequence of landslide occurrence in the Burpee Hills. There were a total of 30 landslide deposits mapped for the roughness analysis, and four remobilization features were mapped within the extent of the original 30 landslides.

The roughness output is shown in Figure 11 and represents the relative age of the landslide deposits mapped in Figure 10. The highest roughness values occur where the Skagit River is closest to the Burpee Hills landform, where the Baker River meets the Skagit River downstream of Lower Baker Dam and in the forested slopes of the Burpee Hills adjacent to Lake Shannon. Of the 30 landslide deposits mapped for the roughness analysis, two deposits had the highest roughness values [D: 6.5 -7.2] (Fig. 11). The high roughness values indicate 7% of the mapped landslide deposits are younger than the other mapped landslides. Fourteen of the 30 mapped landslides have a roughness value range [C: 5.7 - 6.5], suggesting 46% of landslides occurred after D but before A and B range roughness values. Roughness range C occurs most frequently across the Burpee Hills and landslides with this range are in closest proximity to the Town of Concrete, including homes, infrastructure and major roads. Twelve of the 30 landslides mapped have a roughness value range [B: 4.9 – 5.7] suggesting 40% of landslides occurred after A, but earlier than C and D range roughness values. Finally, two of the total 30 landslides have a mean roughness value range [A: 4.1 – 4.9] suggesting that 6% of the total landslides mapped are older than the other mapped deposits and were deposited before the others. Thus the majority of the landslides mapped along the slope of the Burpee Hills landform occur at a C

roughness range. Therefore the south-facing slopes of the Burpee Hills are prone to landslides and they have occurred in the recent past.

The proximity of the Skagit River to the valley wall impacts the variations in erosion along the toe of the mapped landslides. Along the western portion of the Burpee Hills (Fig. 11) the east bank of the river is over 700 m away from the south-facing slopes. At this proximity to the Skagit River, roughness values range from 4.9 to 6.5. With one landslide deposit value with highest roughness (6.5-7.2), likely a result of remobilization of a previous slide in the area (Fig. 11). However, approximately 3 km to the east the Skagit River is within 100 m of the toe of the slope. Where the Skagit River is within 100m of the slope the average roughness values range from 5.7 to 7.2.

The standard deviation of slope values were compared to area of the mapped landslides and proved to have no significant relationship (Fig. 13a). The lack of relationship between the landslide area and slope based roughness index (SDS) suggests that the roughness index is not dependent upon the size of the landslide area. The H: L ratio values were calculated and compared to standard deviation of slope, which proved no significant relationship (Fig. 13b). This suggests that the SDS is not dependent upon the mobility of a mapped landslide in this study. However there is potential source of error where some of the mapped landslide deposits are likely truncated by the Skagit River or smaller streams.

## **Discussion**

### *Depositional History of Burpee Hills*

Repeated continental glaciation by the Cordilleran Ice Sheet in the Skagit Valley has created a dynamic landscape. The Puget Lobe of the Cordilleran Ice Sheet reached the mouth of the Skagit River at approximately 15,500 <sup>14</sup>C yr. BP and was totally retreated from the Puget Lowland at approximately 16,450 <sup>14</sup>C yr. BP (Porter and Swanson, 1998). The deposition of the advance and recessional sediment that forms the Burpee Hills landform occurred within this interval. The basal glaciolacustrine deposit (Qgl<sub>v</sub>) of the Burpee Hills formation was likely formed during pro-glacial melt waters prior to an advance of the Cordilleran ice sheet. Due to the unconformities between strata it is difficult to specify ages of the glacial deposits without absolute dating. The meter-scale cross bedding within the approximately 105-m thick package of advance outwash deposits suggests that this sediment was deposited in a glacio-fluvial setting. Advance outwash (Qga<sub>v</sub>) is thicker up valley and generally fines up valley (Jon Riedel, personal communication 2015). Within the advance outwash (Qga<sub>v</sub>) there are several channel deposits with drop-stones suggesting local variations of channel movement in a pro-glacial or interglacial environment. The retreat of the Puget Lobe deposited the recessional till (Qgt<sub>v</sub>) that caps the Burpee Hills overlying the advance outwash deposited during the Vashon Stade when the ice flowed south (Heller, 1980).

The post-glacial evolution of the Burpee Hills is complex and explains the current slope morphology. During the retreat of the Puget Lobe of the Cordilleran Ice Sheet to the north, pro-glacial lakes formed north of the Burpee Hills landform in the Baker River Valley. These lakes were formed by ice dams along the valley which eventually drained glacial melt waters to the southwest, from the North Cascades to the Puget Sound (Heller, 1978; Riedel, 2011). This drainage feature defined as Lake Tyee outlet by Riedel (2011) is apparent in the LiDAR where Grandy Creek now resides (Fig. 2). This drainage is also preferentially aligned with the Anderson Creek Fault bisecting the margin between Burpee Hills formation and the bedrock and glacial lake deposits to the north (Fig. 3). The marginal ice contact formed as the front of the Cordilleran Ice Sheet retreated from the lower Skagit Valley to the northwest.

### *Relationship between geology and slope morphology*

The geology of the Burpee Hills influences its slope morphology and stability, especially along the south-facing slopes. The comparison of geology to slope shows that the steepest slopes occur within the glacial till ( $Q_{gt_v}$ ) with an average slope of  $36^\circ$  (Fig. 7). Therefore the mapped landslides with a head scarp originating in the glacial till ( $Q_{gt_v}$ ) have a shallower slope, higher-elevation scarp and longer runout (Fig. 9b). The slope morphology of landslides originating in  $Q_{gt_v}$  indicates rotational features, based on the concavity of the normalized slope profile (Fig. 9b). Where the mapped landslides have head scarps originating in the advance outwash ( $Q_{ga_v}$ ) there is a shorter runout distance, steeper slope, and a lower head-scarp elevation. The morphology of the landslides with scarps in the advance outwash (Fig. 9b, LS\_1 to LS\_8) have a linear and less arcuate shape in profile than the landslides mapped with head scarp originating in  $Q_{gt_v}$ . This morphology shows a translational failure style in landslides with head-scarps in advance outwash sediment. There is a notable spatial variation among the mapped landslides, the slides along the western edge of south-facing slopes have head scarps that originate in the advance outwash sediment, and have a linear slope profile shape, indicative of translational failure. Along the eastern portion of the south-facing slopes, the head scarps originate in the glacial till ( $Q_{gt_v}$ ) and have a curvilinear slope profile shape, indicative of rotational failure.

The morphologic variation from west to east is related to the variation in thickness of the glacial sediments, depth to bedrock and location of the contacts between the geologic units (i.e. elevation above valley bottom). The depth to bedrock is estimated at  $>370$  m based on the DOE well log data. The depth to bedrock likely varies across the extent of the Burpee Hills but without more subsurface data, the exact values are unknown. The unconformities between the advance outwash and overlying glacial till (Appendix: AOBH 1a) suggest a change in density of sediments based on the weight of the overriding continental glacier during retreat. The spatial variation (W-E) of the stratigraphic position of the contacts between sediments likely affects the morphology of landslides along the Burpee Hills. Due to the thicker package of glacial sediments in the east (50-60 m thicker) than the western portion of the Burpee

Hills, there is a certain increase in landslide area and presence of rotational landslide features from the west to the east along the south-facing slopes of the Burpee Hills.

The glacial sediments affect the run out distance of the mapped landslides along the south facing slopes of the Burpee Hills. A large run out distance can have a severe effect on the people living in and around Concrete, Washington. The length of the run out distance increases from west to east across the landform (Table 4). The run out distances measured in the landslide deposits are likely eroded by the Skagit River, and may only represent the minimum run out distance. Therefore the values reported should be treated as minimum run out distances, thus minimum H: L ratios.

### *Landslide Occurrence*

The increase in landslide roughness from west to east along the Burpee Hills is also affected by the morphology of the Skagit River. The majority of the landslides occur along the southern facing slopes of the Burpee Hills landform (north wall of the Skagit River Valley). The Skagit River is very close to the toe of the mapped landslide deposits 16 through 19 (Fig. 8), indicating toe erosion prior to the construction of SR20, which is in between the south slopes of Burpee Hills and the Skagit River. The higher roughness values for the landslide deposits where the Skagit River is closest to the north valley wall [LS16, 17, 18] support the hypothesis that proximity to the river and toe erosion affects the stability of the slopes along the Burpee Hills. For example, basal erosion at the toe of landslide [LS16] is causing slumping along Challenger Road, evidenced by visible slumping and road closures beginning in February 2015. Some of the landslides with roughness ranges C and D [LS16, LS17 and LS18] occur at the central meander bend along the north edge of the Skagit floodplain (Fig. 11). This suggests that where the river is closer to the north valley wall, more downslope activity has occurred in recent past. However where the river is currently farther from the north valley wall, there are lower roughness values indicating older landslide deposits.

Within the Burpee Hills landform the majority (>50%) of landslides are initiated at or below the interface between the advance outwash ( $Q_{ga_v}$ ) and the overlying glacial till ( $Q_{gt_v}$ ) (Fig. 9a). The average slope ranges at the interface between these units vary from an average 27 degrees within the advance outwash ( $Q_{ga_v}$ ) to 36 degrees in the glacial till ( $Q_{gt_v}$ ). The upland glacial till ( $Q_{gt_u}$ ) has a low slope angle as it encompasses the terrace surface, which has little variation in slope (Fig. 9b). It is important to note that historically Vashon advance outwash ( $Q_{ga_v}$ ) in the Puget Lowland has been found to have a critical slope at the range between 30 – 35 degrees (Kathy Troost, personal communication, 2016). Although the average value reported for the advance outwash of the Burpee Hills is 27 degrees, the landslides with highest roughness values (most recent activity) have slope values between ranging between 30 – 50 degrees at the interface between glacial till and advance outwash. Therefore it is necessary to monitor the conditions where slopes are steepest and significant changes in slope and geology correspond. Combining this information with measured

H: L ratio and surface roughness can be a useful tool to screen for large run out events.

### *Comparison of Burpee Hills to Regional Landslides (SR530)*

#### Geology

Like the Burpee Hills, the Whitman Bench that failed in the SR 530 Landslide in the North Fork Stillaguamish Valley is a low relief terrace, underlain by unconsolidated glacial-fluvial outwash above thick deposits of glacial silts and clays. The Whitman Bench is a 200 m high hillslope comprised of unconsolidated glacial and colluvial deposits (Keaton et al., 2014). Burpee Hills is composed of unconsolidated glacial deposits and Quaternary alluvium with some surficial landslide deposits (colluvium). The glacial geology of the Whitman Bench contains Olympia non-glacial sediments at the base of the section, overlain by Vashon stade advance lacustrine and till deposits (Dragovich et al., 2003); with Everson interstade recessional lacustrine and outwash deposits forming the terrace surface of the Whitman Bench (Keaton et al., 2014). The Burpee Hills has slightly higher relief and local variation in glacial geology from Whitman Bench; however the general sequence of a thick glaciolacustrine deposit overlain by advance outwash and recessional till deposits is similar (Gerstel and Badger, 2014). This is the typical sequence found throughout the Puget Lowland (e.g. Booth, 1989).

#### Landslide Morphology

The North Fork Stillaguamish River valley, especially the north valley wall exhibits similar morphologic features to that of the Burpee Hills (north valley wall) of the Skagit River valley. The scalloped shape of the northern valley wall in the Skagit is comparable to the scalloped shape of the valley sides in the NFSR, and shares similar characteristics including the low relief upland terrace or bench like feature, and strip of steeper slopes. The steep and scalloped headscarp are interpreted to indicate rotational slope movement (Keaton et al., 2014). This rotational slope movement is described in the NFSR as involving the full height of the valley sides. A similar morphology can be seen on the south facing slopes of the Burpee Hills where slumping incorporates the entire height of the slopes and a flat terrace top with low relief has a steep strip of glacial till and coarse advance outwash at the highest elevations where arcuate head scarps form.

#### Roughness and relative mobility comparison

The surface roughness values reported in LaHusen et al., 2015 are used comparatively to show similarities and differences between the two neighboring river valleys. The observed standard deviation of slope values in this study range between 4.14 and 6.79 degrees within the Burpee Hills area, LaHusen et al., (2015) report SDS ranges from 4.04 to 8.02 degrees. They have used these values along radiocarbon dates from several landslides to estimate absolute ages for the NFSR. They find suggest the observed roughness values to correspond to landslide ages ranging 50 to 12,000 year before present (LaHusen et al., 2015). Although I cannot provide absolute age information for the Skagit Valley, based on the similar SDS ranges, topography and geology it is likely that landslides of the Burpee Hills fall within a similar age range.

Remobilizations of previous landslides affect the timeline of hillslope evolution within the Burpee Hills. The high roughness values of mapped remobilization of two landslides along the Burpee Hills landform (Fig. 12) suggest that these landslides have been reactivated more recently. This provides evidence to suggest landslides along the Burpee Hills develop at certain recurrence intervals and continue to fail under specific conditions.

Roughness values measured along the Burpee Hills are compared to the NFSR in order to determine the landslide history of the Skagit relative to another similar valley. In comparison, to LaHusen et al., (2015) they reported 30% of mapped landslides of the NFSR having H: L values  $\leq 0.20$ . Along the Burpee Hills landform, 33% of the mapped landslides have H: L values  $\leq 0.20$  (Table 4). There is a less than 10% difference in H: L ratio between the Skagit and NFSR suggesting the past landslides in both valleys have similar mobility. However none of the mapped landslides of the Burpee Hills have H: L ratio equal to that of the SR530 (Oso) landslide of 0.10 (Keaton et al., 2014; Iverson et al., 2015). This suggests that none of the mapped landslides of this study have as low height to run out length (high mobility) within the Skagit valley. It is important to note that landslide deposits are likely truncated or eroded by the Skagit River removing evidence of longer run out landslide features. This does not discount the similarity in morphology between the two valleys and suggests a similar history of landslide failure and landslide activity at varying intervals since the last glacial maximum.

To make this a more complete study of landslide probability and occurrence within the Skagit Valley, more information is necessary. That information includes higher resolution subsurface data, such as geotechnical borings or a higher volume of DOE well logs. This study could have been more robust if a 1:24,000 scale geology map were available for a more accurate interpretation of the subsurface geology of the landform. In order to present a complete analysis of the landslide types and explicit failure mechanisms a study of climate, precipitation and hydrologic data will be necessary. To absolute age the surface roughness according to methods presented in LaHusen et al., 2015, radiocarbon dates would be necessary within the extent of the landform to give precise estimates of landslide frequency of this landform. Without that information we can only discern the potential for remobilization without generating an actual timeline of landslide activity. This study is limited by the remote sensing data resources, i.e., resolution of LiDAR, subjectivity of delineating landslide features and artifacts within LiDAR DEM data sets. Landslides are complex features that may have been remobilized several times over the evolution of the Burpee Hills landform. The remotely mapped landslides may not be an actual representation of the distal edges of the landslide deposits of the Burpee Hills.

#### Potential impacts/implications

There is history of instability along Burpee Hills Road based on the observation of surface sloughing, tension cracks along the road, especially within the colluvial hollows, and evidence of seepage. In the past 20 years, several shallow landslides have been reported to the Skagit County Emergency Management leading to a compilation of a landslide awareness document (Skagit County, 2014). Similar

evidence has been found after investigations of the SR530 landslide in the North Fork Stillaguamish River (NFSR) and is comparable to the evidence presented for the Burpee Hills.

## Conclusions

The geology and landslides of the Burpee Hills were measured in the field and compared to remote measurements to better understand the geologic units involved in landslides, the slope morphology and the history of landslides along the landform. There are at least 30 landslides within the Burpee Hills with 85% occurring along the south-facing slopes on the north valley wall of the Skagit River valley. Based on the generalized geologic map all of the mapped landslides include the glaciolacustrine unit ( $Qgl_v$ ) and the overlying advance outwash ( $Qga_v$ ). Half of the mapped landslides have a headscarp originating in the overlying glacial till ( $Qgt_v$ ). The morphology of landslides initiated in advance outwash versus overlying glacial till varies from west to east across the landform. The landslides on the western side of the south facing slopes originate in the advance outwash and have a linear shape, a short run out distance and a distinct toe at the distal edge of the mapped deposits. The landslides mapped on the eastern side of the landform have headscarp originating in the overlying glacial till and have a curvilinear shape, longer run out distance and no notable toe at the distal edge of the profile.

The height to length ratio ( $H: L$ ) indicates the potential mobility for mapped landslides on the Burpee Hills. The lack of evidence of a landslide toe for many mapped deposits suggests the Skagit River likely truncates the landslide deposits after deposition. When run out distance ( $L$ ) is compared to height ( $H$ ) it can be a useful tool for identifying areas which may be overrun by landslides with an identified upslope area and low  $H: L$  ratio. The low  $H: L$  ratio (0.1) reported for the March 22, 2014 SR530 (Oso) Landslide indicates the high mobility (run out) that caused significant damage and loss of life. Although none of the mapped landslides in the Burpee Hills had an  $H: L$  ratio lower than 0.14,  $H: L$  ratios reported from the NFSR were within the range of values found in this study. Therefore there is similar potential for landslide mobility in both the NFSR and the Burpee Hills landform.

The surface roughness of mapped landslide deposits is also a useful metric in understanding historic landslide occurrence. The higher roughness values represent younger landslide features, where lower roughness values represent older deposits. The most recent landslide deposits according to the roughness analysis occurred along Challenger Road where the Skagit meanders closest to the south facing slopes of the Burpee Hills, along locations of remobilization features and where the Baker River actively cuts into the eastern edge of the Burpee Hills. Relative ages can be attributed to landslide deposits based on the surface roughness output, unfortunately no absolute ages are available for the Burpee Hills, no absolute ages are determined for the mapped landslides.



Therefore, I conclude that there have been several iterations of landslides predominantly along the south slopes of the Burpee Hills that have undergone downslope movement and remobilization since the retreat of the Cordilleran ice sheet at the last glacial maximum. The exact time frame of these landslides may fall within the reported interval of 50 to 12,000 years before present (LaHusen et al., 2015) but cannot be determined without further dating methods. Overall the Burpee Hills has similar stratigraphy, landslide extent, area, roughness and mobility. The similar depositional histories, the physical interconnectivity of the river valleys and the glacial dynamics likely contribute to the similarities in glacial sediments and morphology.

This investigation is intended as a screening tool for remotely identifying areas that have distinct landslide features and glacial stratigraphy. The H: L ratio and roughness analysis is useful for identifying locations that could be potentially overrun by landslides based on mobility and occurrence within a mapped area. This information can be useful for city or county planners to determine appropriate land use and how to minimize landslide hazards. Future work including absolute ages, hydrologic and climatic studies will contribute to a more predictive model of the landslides in the Skagit Valley and other regions. Continued remote, geomorphic investigations are necessary to better understand the effects of potential landslide hazards on the community and plan for future.

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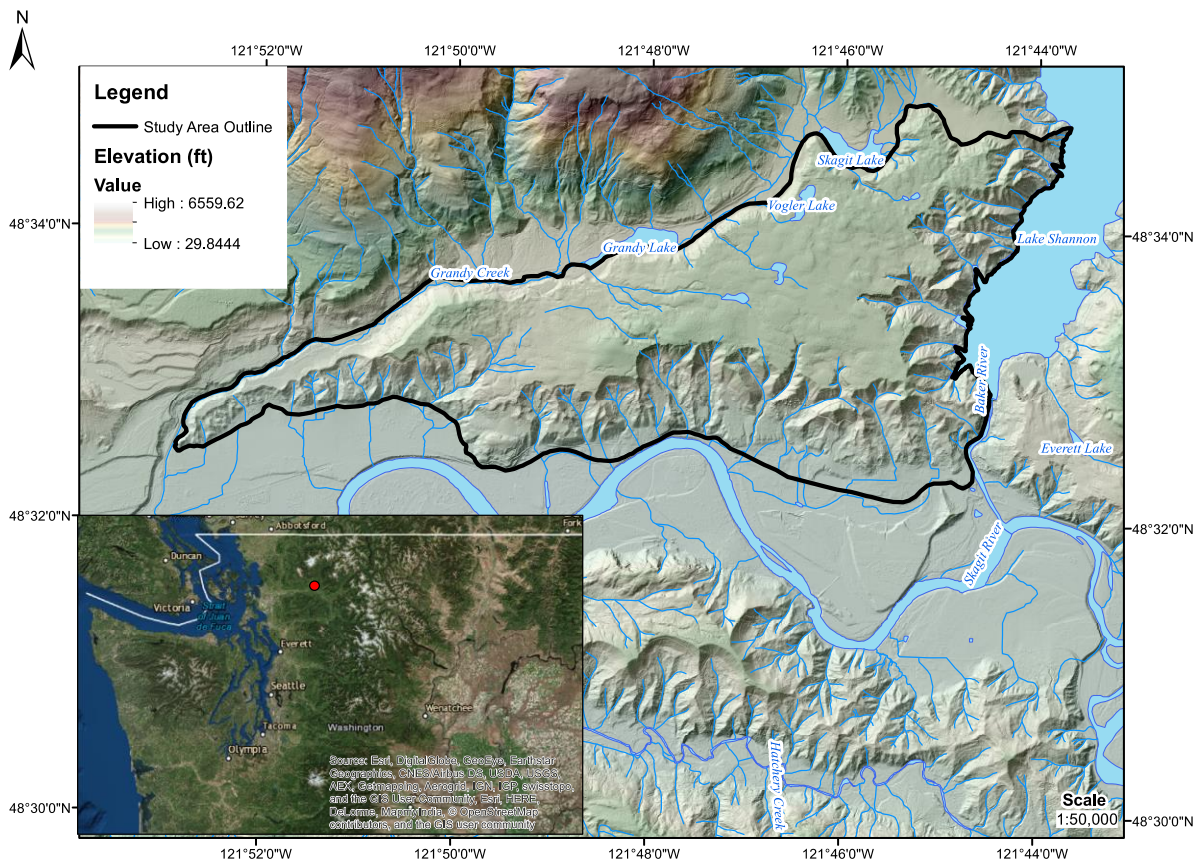


Figure 1. Location map of the study area, Burpee Hills (outlined in black) which lies at the confluence of the Baker and Skagit Rivers in Skagit County, Washington. The inset map shows the location of the study area (red dot) within Washington State.



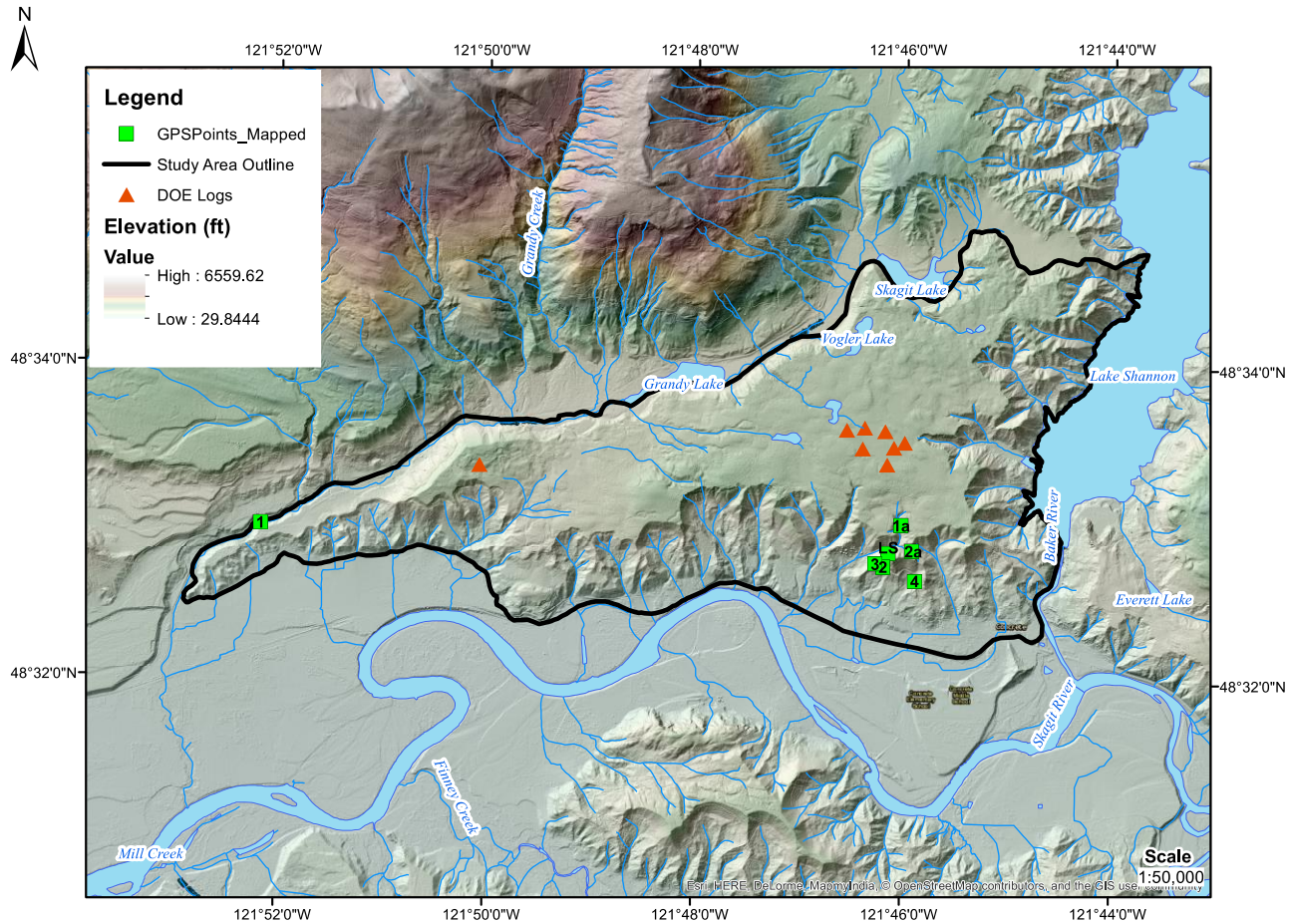


Figure 2. Location map with GPS points (green squares) representing each measured section observed during fieldwork. Measured sections are labeled to correspond to AOBH\_1a labels of stratigraphic columns in Appendix. The black triangles represent the Department of Ecology (DOE) well log locations that were used to estimate depth of regional geology. Two of Heller, 1980 measured sections 5 and 6 correspond to 1 and 2a.

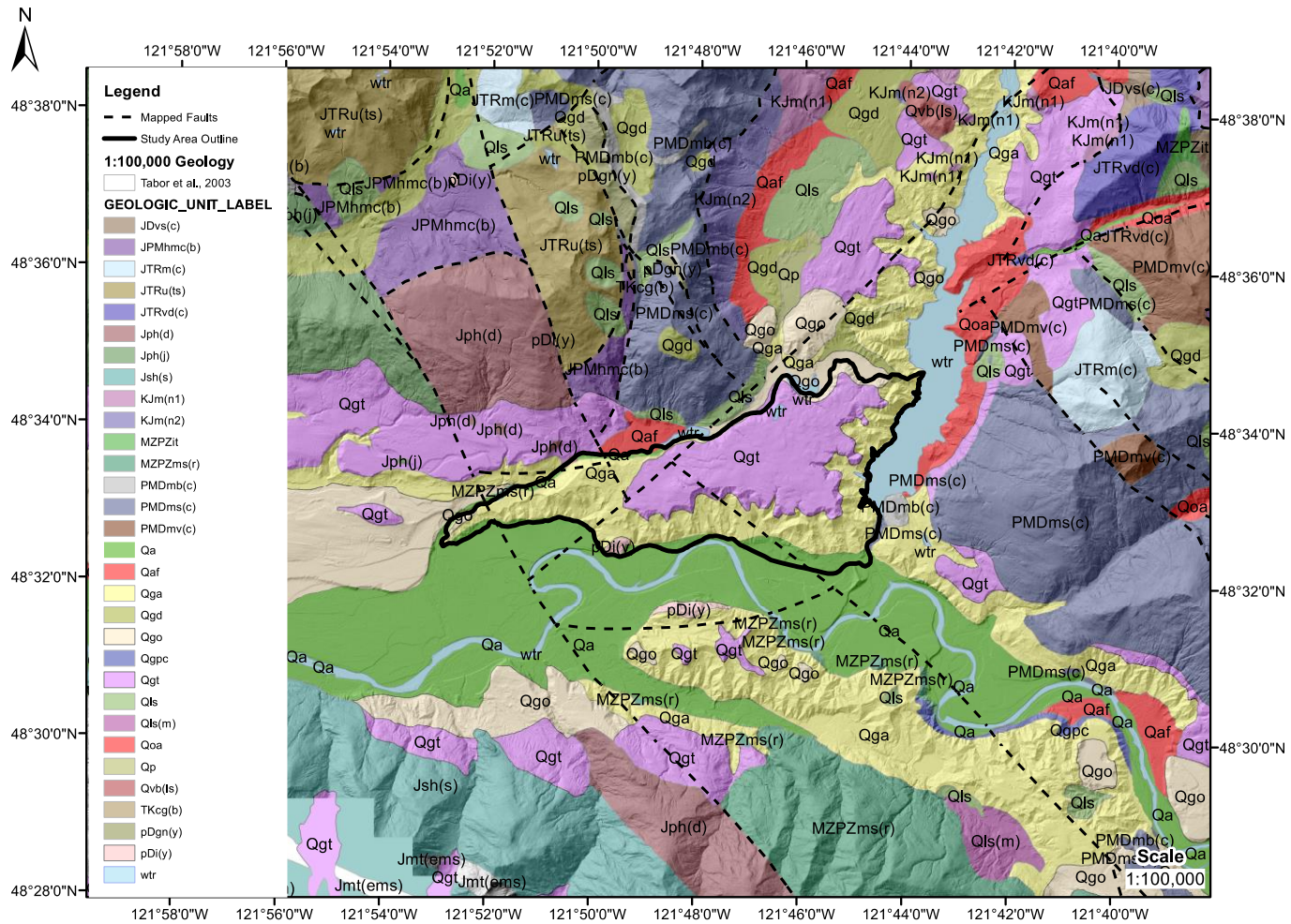


Figure 3. 1:100,000 scale geologic map of the study area. This map is adapted from Tabor et al., 2003.

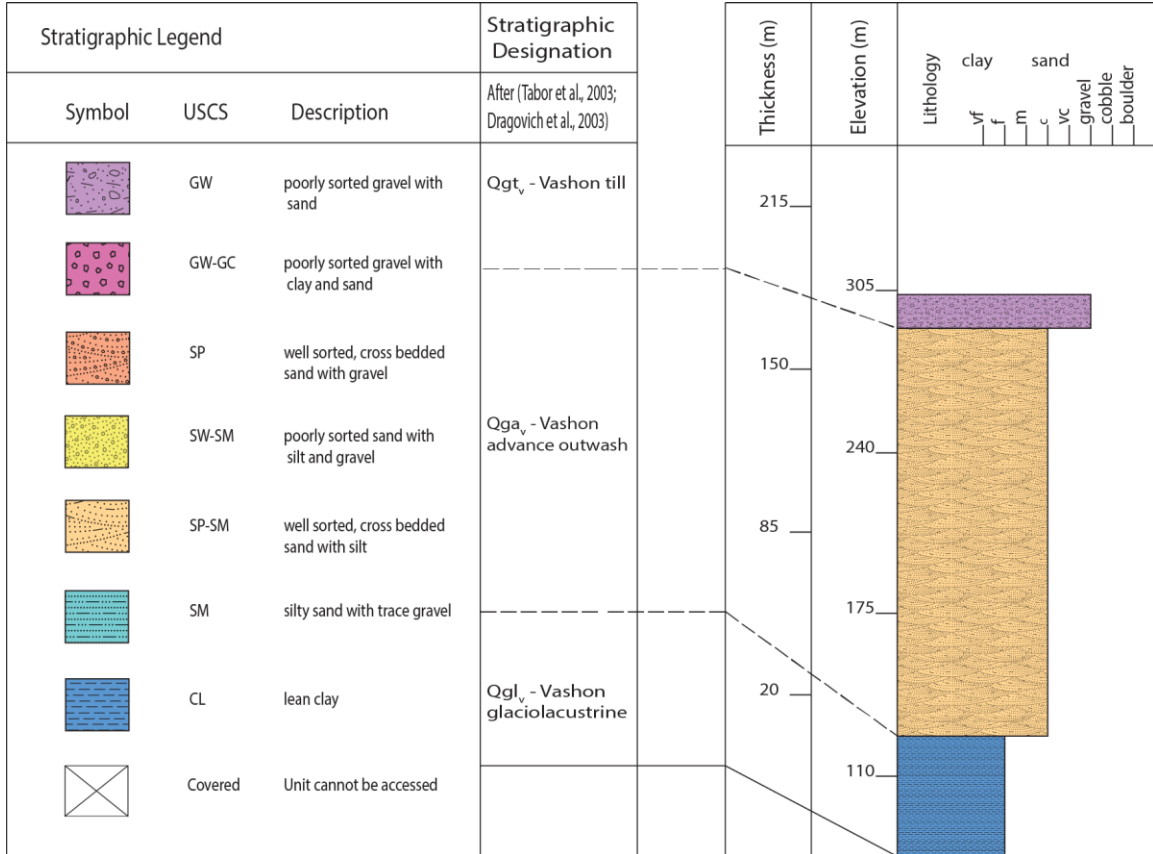


Figure 4. Key for measured sections (Appendix). Unit descriptions, USCS names and stratigraphic correlation are given with symbol from USGS. The units on the left compose the generalized stratigraphy on the right. The thickness of each unit varies across the landform but is generalized according to these measurements.

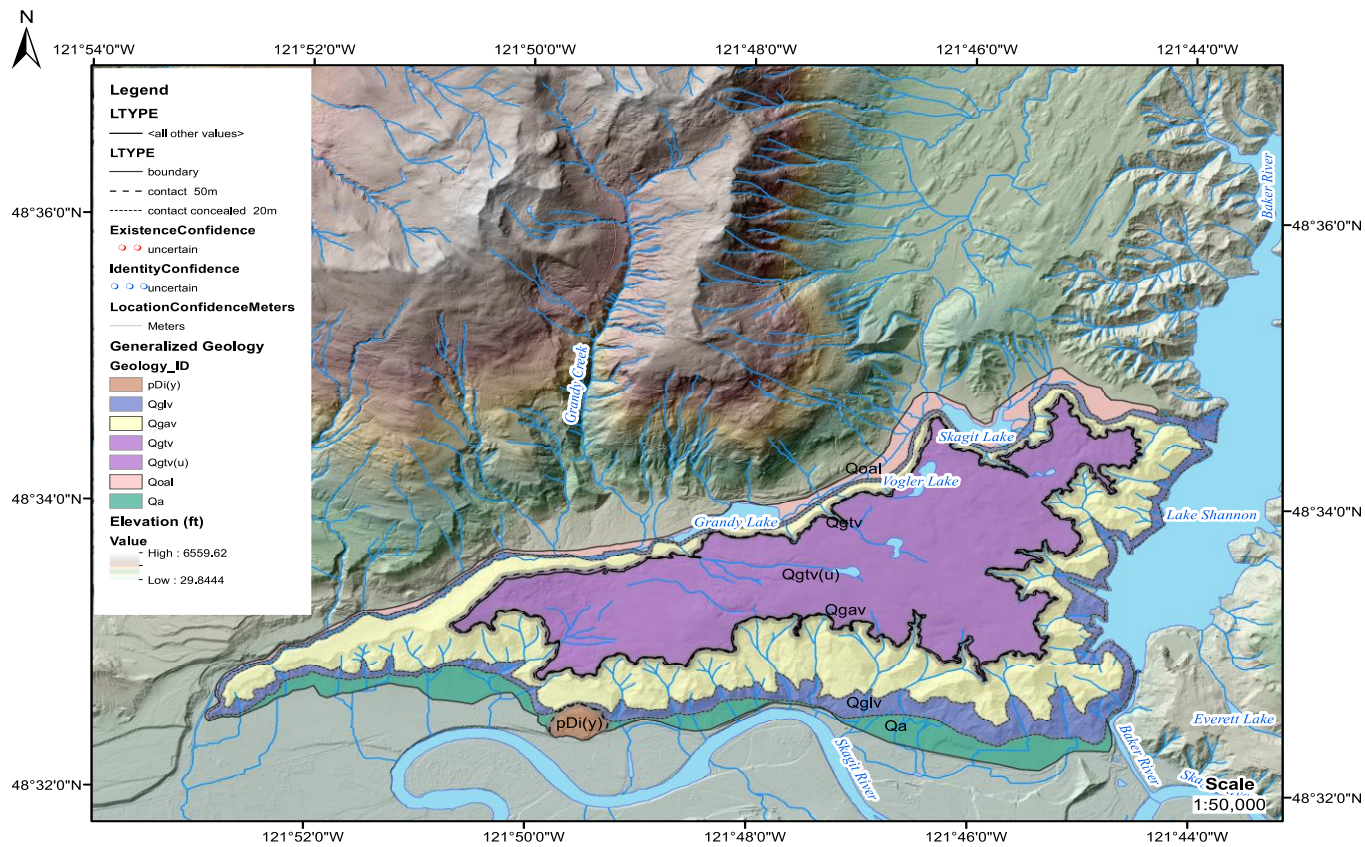


Figure 5. Generalized geologic map representing the hypothesized contacts between each generalized glacial unit within the Burpee Hills landform. The contacts are not certain but estimated based on Department of Ecology well log data, previous studies and new field observation. This is not meant to represent a scale finer than 1:50,000 and is useful in this investigation to compare unit lithology with slope characteristics.

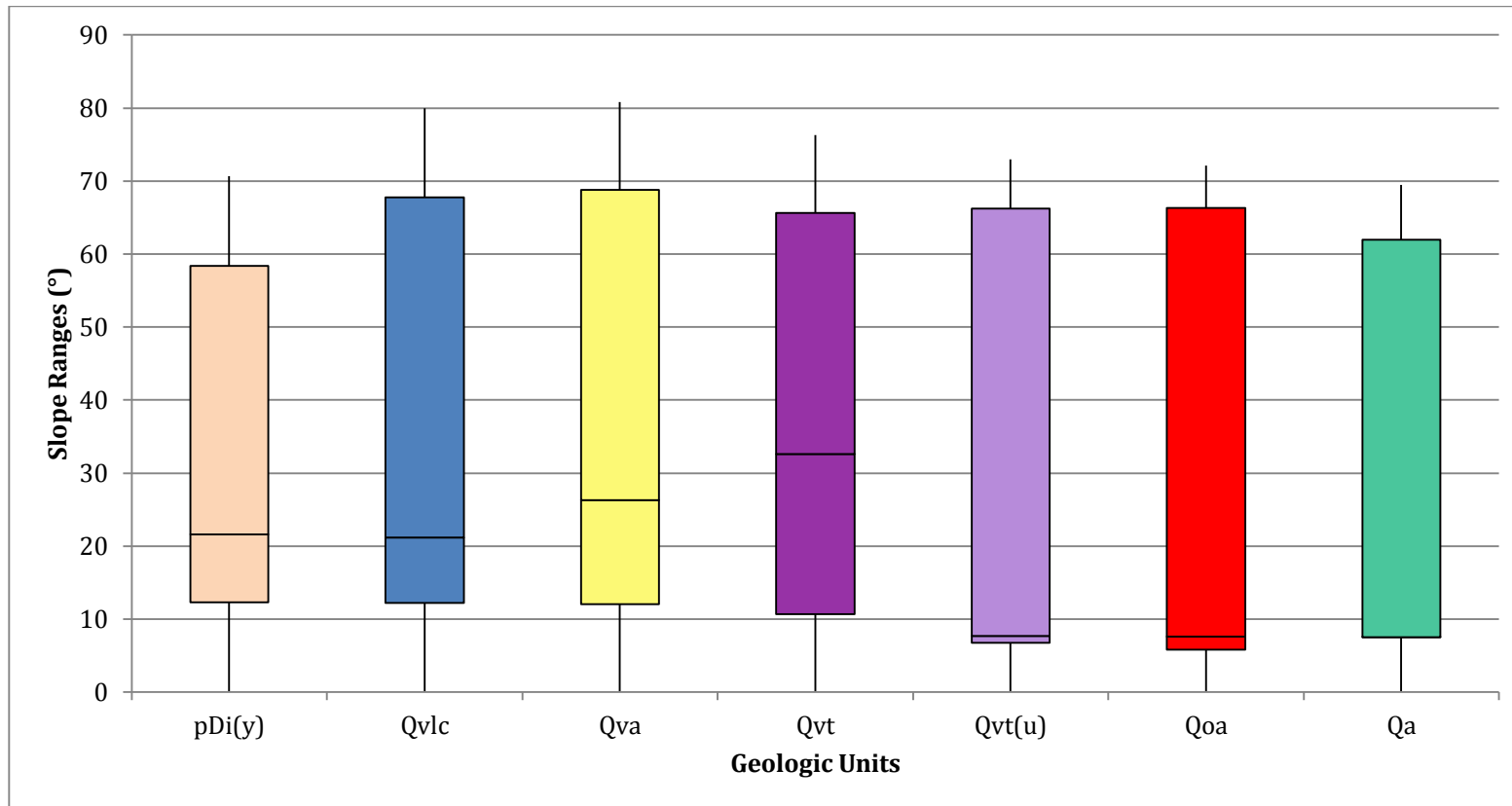


Figure 6. Box and Whisker Plot showing average slope (degrees) of each generalized geologic unit, compared to basal elevation of each mapped geologic unit. The glacial till has the highest average slope angle (33°) and the older alluvium has the lowest average slope angle (4°). Qgt<sub>v</sub>(u) represents the glaciated terrace upland that is composed of glacial till.

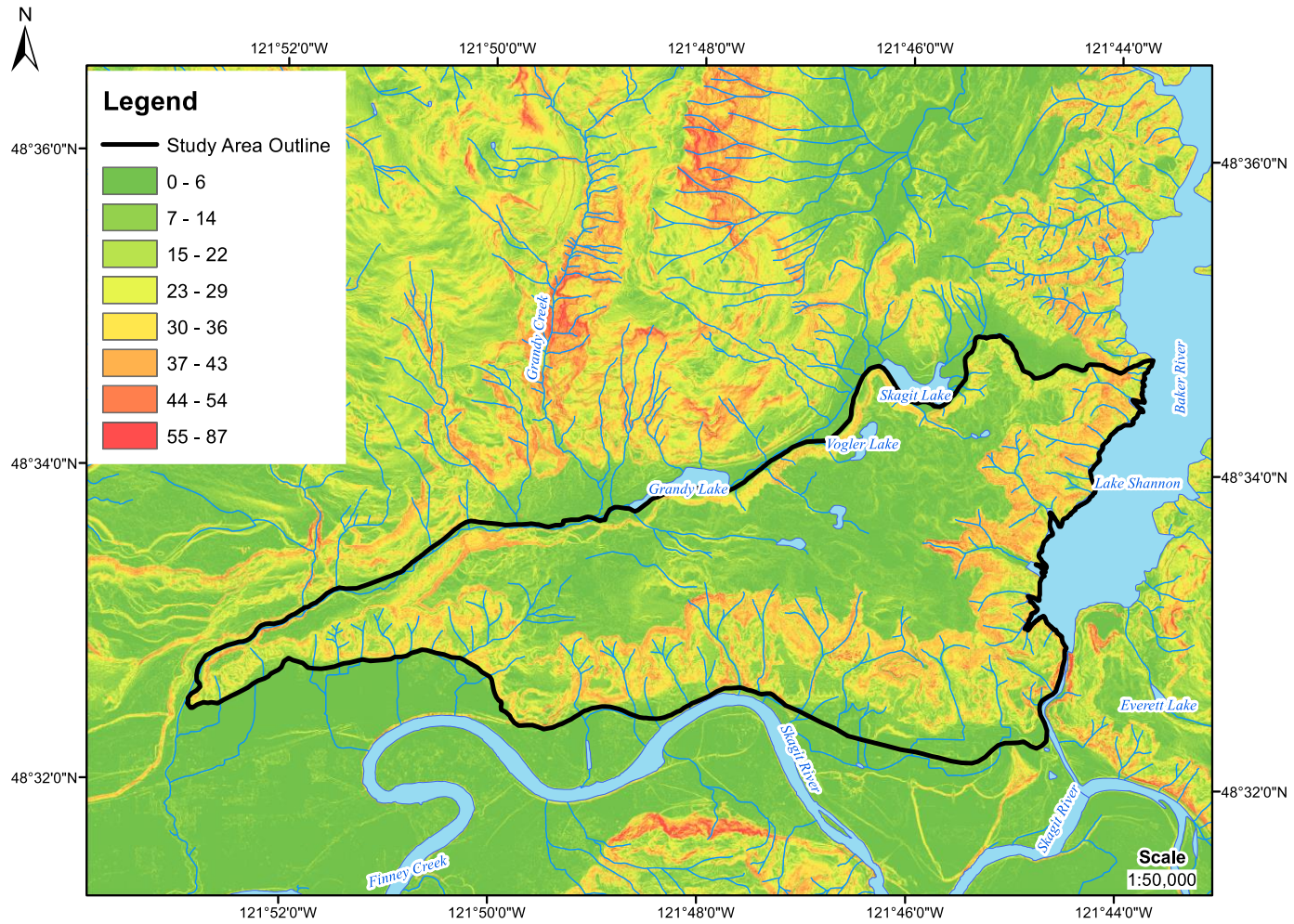


Figure 7. Slope map showing areas of high slope in red ( $> 37^\circ$ ), moderate slope in yellow ( $23^\circ$ - $30^\circ$ ) and lower slopes in green ( $< 22^\circ$ ).

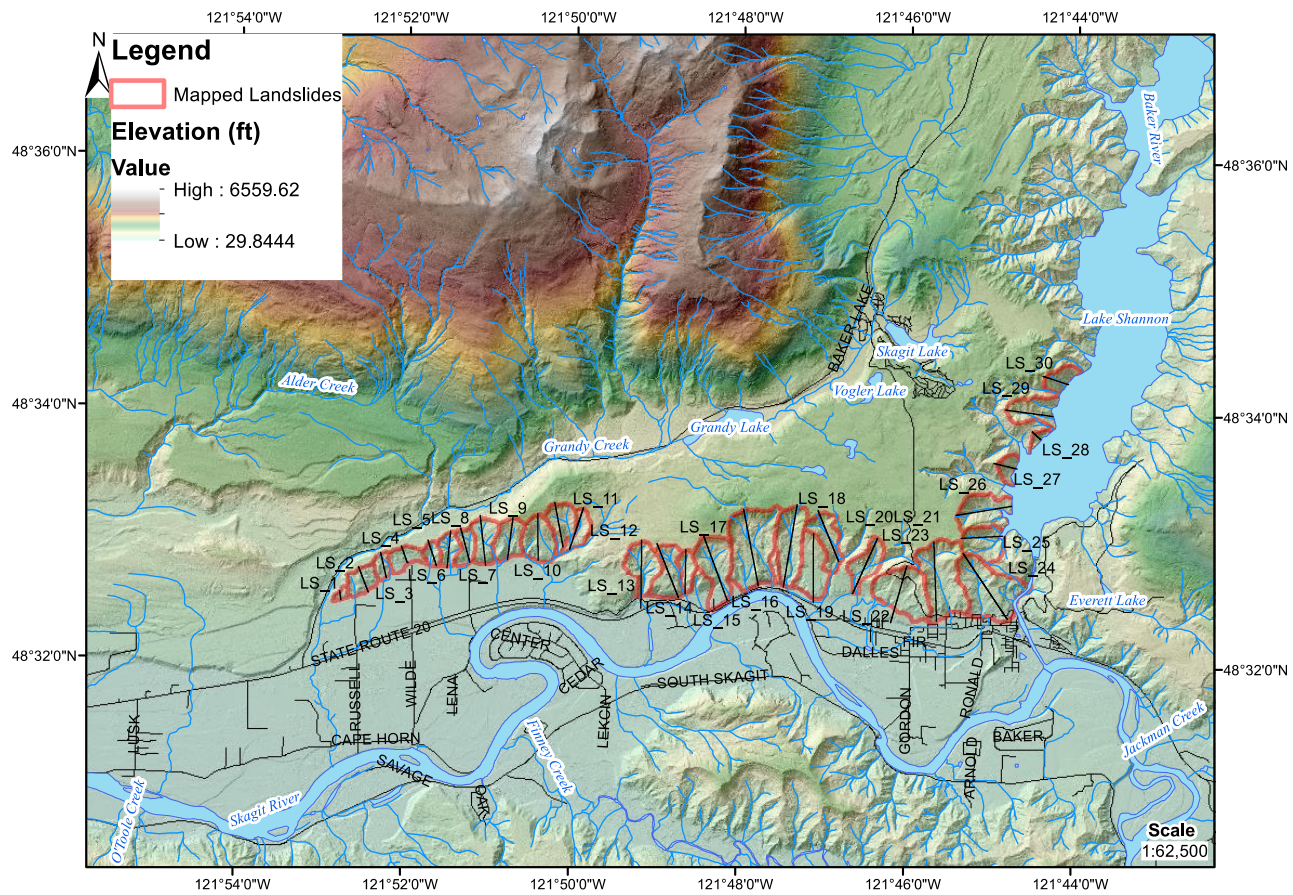


Figure 8. Numbered and mapped landslide features including scarps with slope profile transects drawn to correspond to landslide labels within Burpee Hills landform.

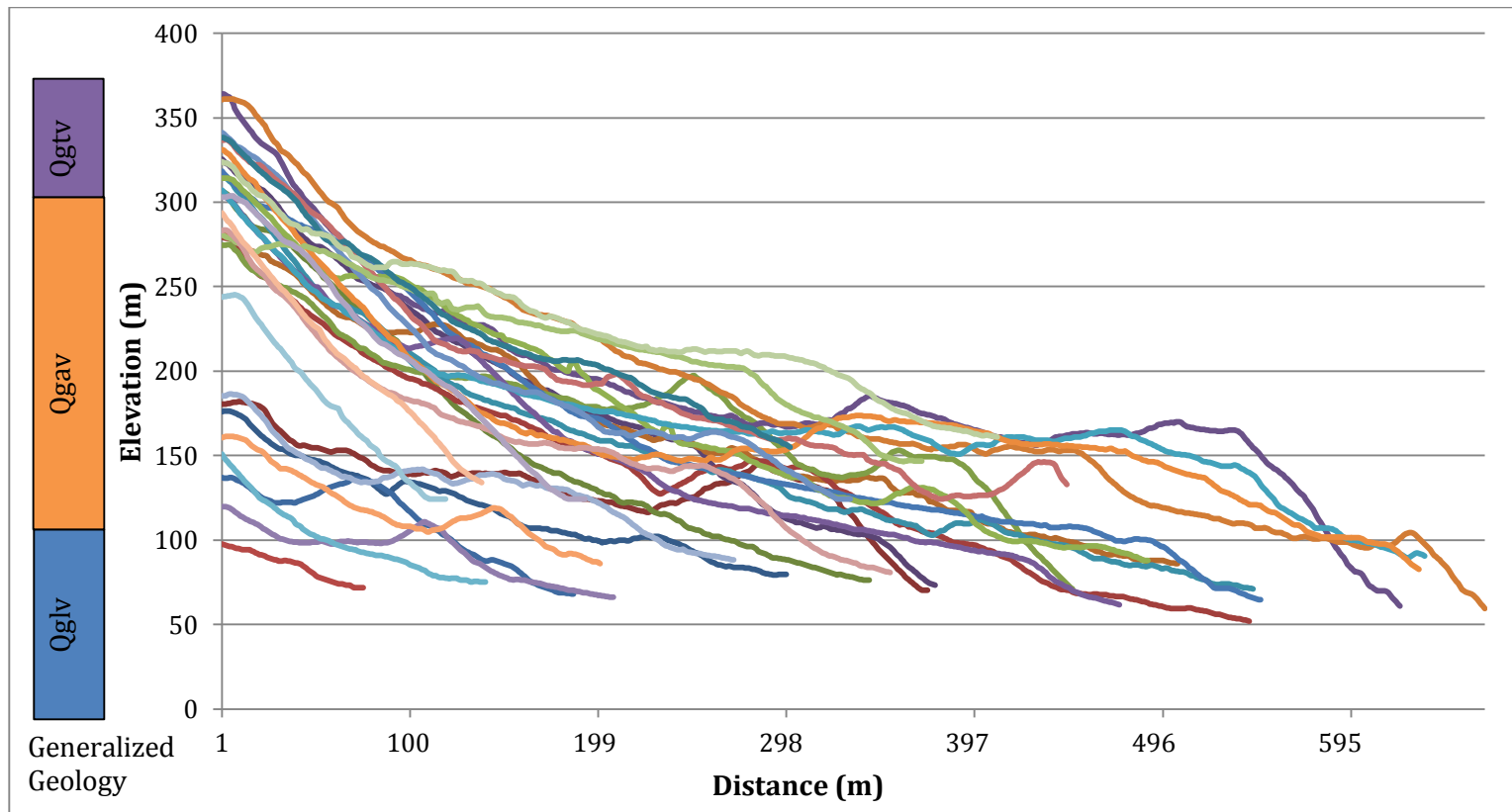


Figure 9a. Slope profiles of the mapped landslides from Figure 18. The slope profiles show variation in elevation and landslide morphology from the west side of the landform to the east side. The landslides mapped along the west side have the lowest head scarp elevation. Generalized geology is represented on the diagram to show the relative elevations of headscarp and their corresponding stratigraphic position.



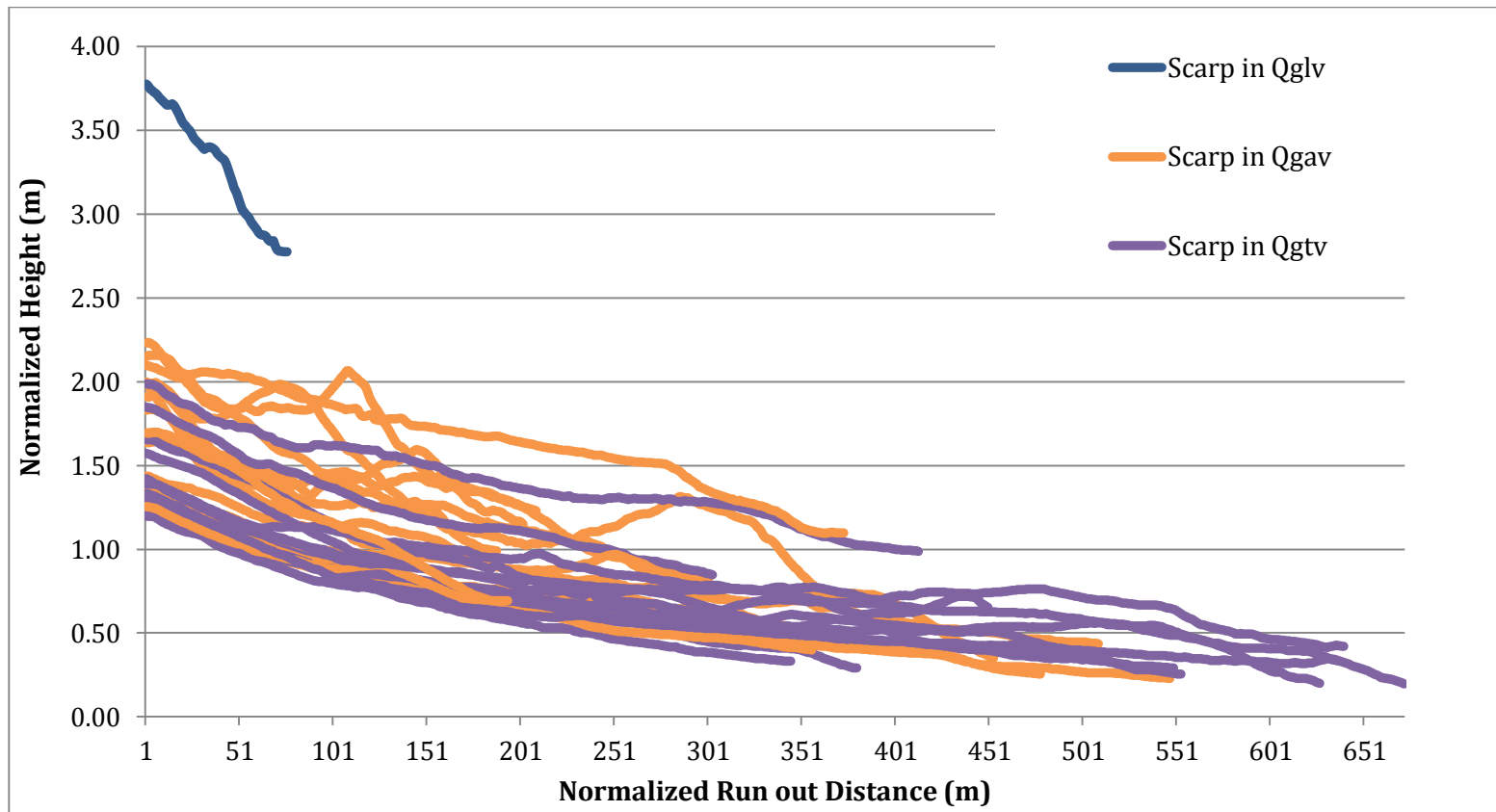


Figure 9b. Normalized slope profiles, show the variation of slope profile shape dependent upon headscarp origin sediment (Qglv – blue, Qgav – orange, Qgtv – purple).

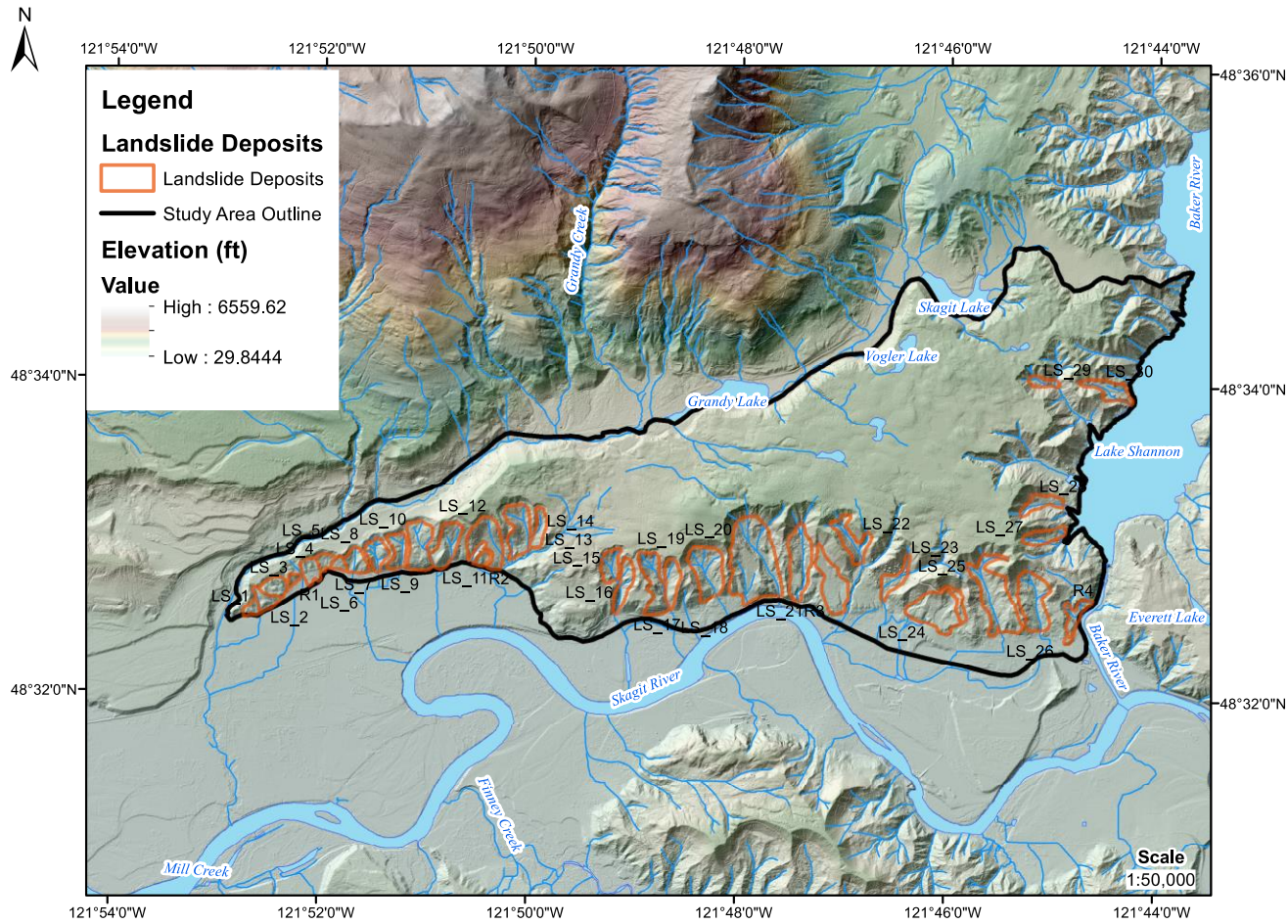


Figure 10. Mapped landslide deposits, excluding scarps. These mapped deposits are used to the roughness analysis.

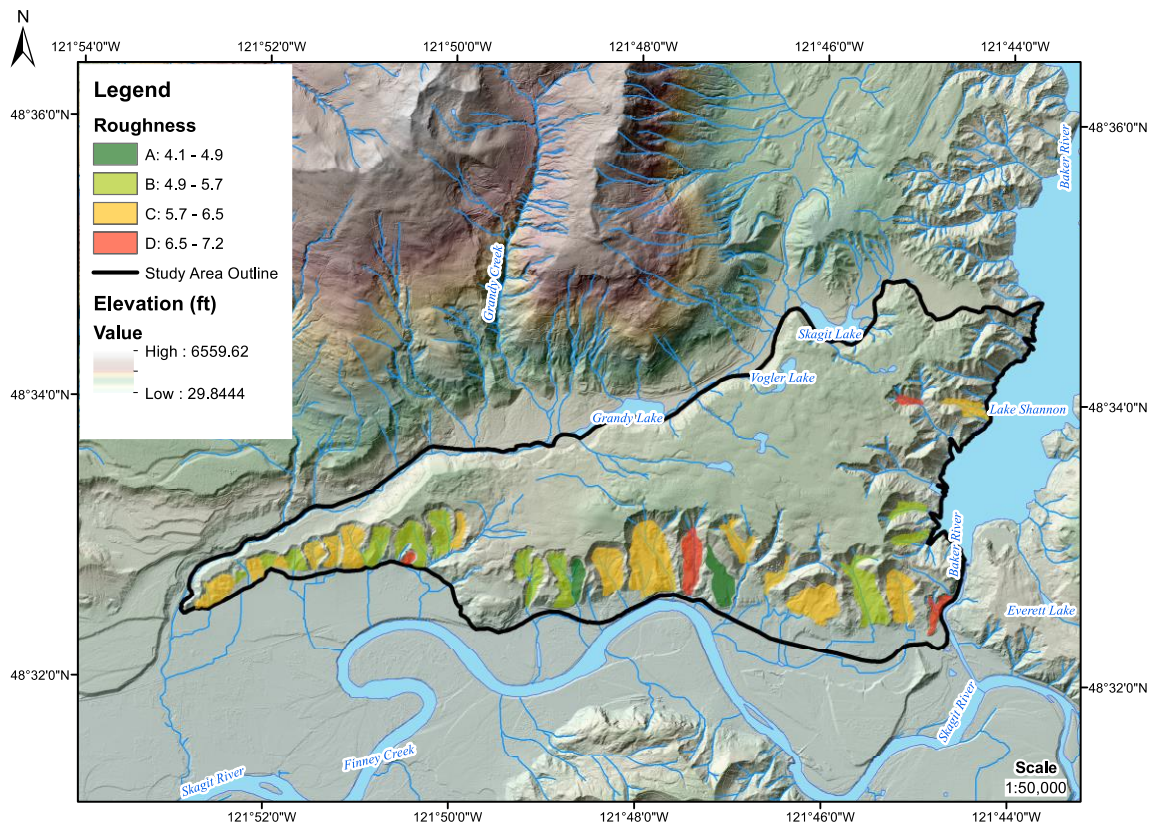


Figure 11. Relative roughness values based on standard deviation of slope and width of hummocks within landslide deposits. Values of high roughness (D) correspond to younger landslide deposits and low roughness (A) values correspond to older landslide deposits.

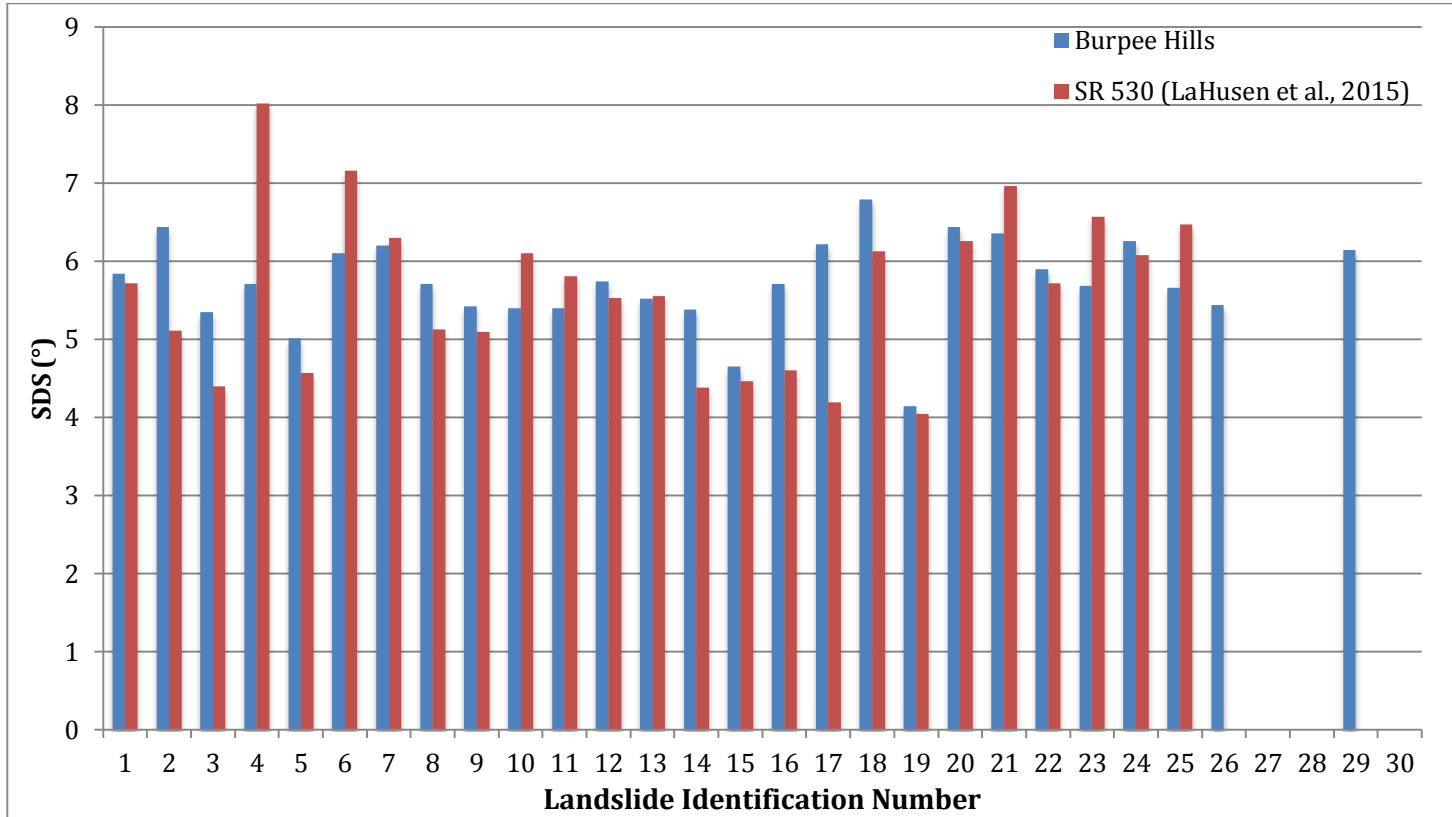


Figure 12. Histogram comparing the reported SDS values for the North Fork Stillaguamish River (NFSR) in red and the values calculated in this study in blue. The values fall within the same range with the exception of the LS4 reported in the NFSR which represents the value for the Oso landslide.

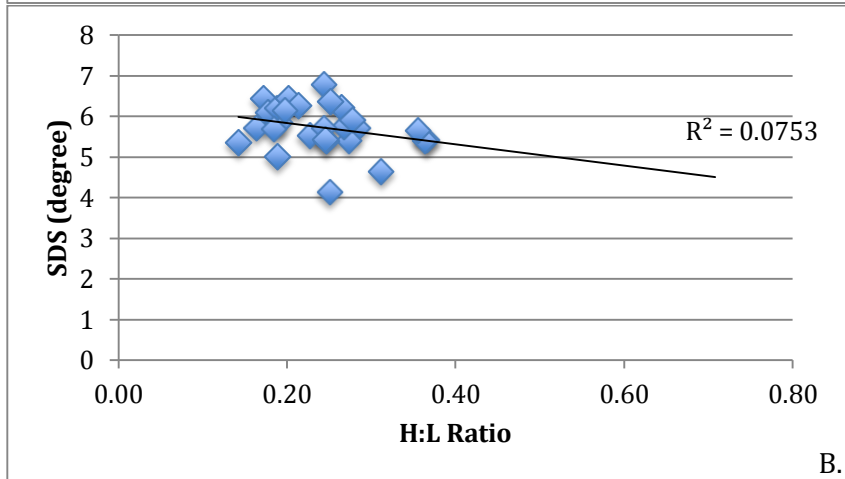
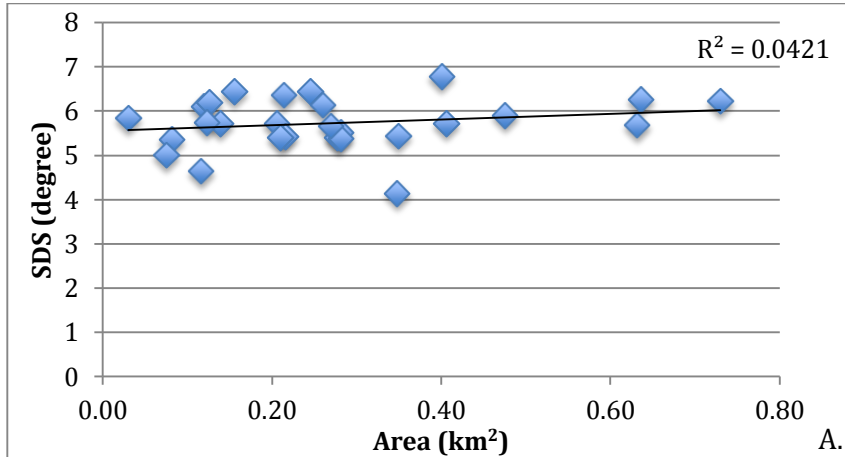


Figure 13. A. Standard deviation of slope plotted against the landslide area of each of the 30 measured slope profiles. There is no correlation ( $R^2$  value of 0.04).  
 Figure 13 B. Standard deviation of slope plotted against landslide H: L ratio for measured landslides in study area. There is no correlation ( $R^2$  value of 0.08).

Table 1. Measured elevation (m) values for each generalized unit represented in the Burpee Hills formation with average thicknesses of each unit per measured section. These are the values that were interpolated to create the generalized geologic map (Figure 5).

Unit ID	Geologic Description	Minimum Elevation (m)	Maximum Elevation (m)	Average Elevation (m)	Average Thickness (m)
Qgt <sub>v</sub>	Glacial Till	294.4	297.5	296.0	3.1
Qga <sub>v</sub>	Advance Outwash	226.7	239.8	233.3	13.1
Qgl <sub>v</sub>	Glaciolacustrine	108.8	116.7	112.8	7.9

Table 2. Data from the generalized geologic map, showing estimated area of each unit, and the range of elevations for each unit identified.

Unit ID	Geologic Description	Area (km <sup>2</sup> )	Minimum Elevation (m)	Maximum Elevation (m)	Average Elevation (m)	Standard Deviation
pDi(y)	Bedrock of the Yellow Aster Complex (Misch, 1966)	0.2	48.4	180.3	120.9	36.1
Qa	Quaternary Alluvium	1.9	49.1	173.4	73.7	10.4
Qgt <sub>v</sub>	Continental glacial till, Fraser-age, Vashon Stade	10.3	155.1	383.1	321.1	27.5
Qga <sub>v</sub>	Continental advance glacial outwash, Fraser-age, Vashon Stade	10.0	86.0	369.9	223.7	60.6
Qgl <sub>v</sub>	Continental glacial lacustrine, Fraser-age, Vashon Stade	3.4	57.5	313.9	145.7	55.5
Qoa	Quaternary older alluvium, paleo-channel	1.7	75.7	298.8	254.4	42.0
Total Area (km <sup>2</sup> )		27.6				

Table 3. Data derived from generalized geologic map, showing area of each unit, minimum and maximum slope (degree) compared to measured values from fieldwork.

Unit ID	Geologic Description	Area (km <sup>2</sup> )	Minimum Slope (Degree)	Maximum Slope (Degree)	Average Slope (Degree)	Standard Deviation	Measured Slope (Degree)
pDi(y)	Intrusive Bedrock of the Yellow Aster Complex (Misch, 1966)	0.2	0	70.7	21.6	12.3	Not Measured
Qa	Quaternary Alluvium	1.9	0	69.5	7.5	7.5	Valley Bottom
Qgt <sub>v</sub> (upland)	Continental glacial till, Fraser-age, Vashon Stade	10.2	0	73	7.7	6.8	Terrace Top
Qgt <sub>v</sub>	Continental glacial till, Fraser-age, Vashon Stade	0.69	0	76.3	32.6	10.7	32.7
Qga <sub>v</sub>	Continental advance glacial outwash, Fraser-age, Vashon Stade	10.0	0	80.8	26.7	12.1	64.5
Qgl <sub>v</sub>	Continental glacial lacustrine, Fraser-age, Vashon Stade	3.4	0	80.0	21.1	12.2	13.1
Qoa	Quaternary older alluvium, paleochannel	1.7	0	68.4	3.9	5.8	Not Measured



Table 4. Morphologic attributes of mapped landslides

LS ID	Area (km <sup>2</sup> )	Headscarp		Length (m)	H:L Ratio	SDS (°)	Remobilization SDS(°)
		Height (m)	Height (m)				
1	0.03	98	26	136	0.19	5.84	
2	0.16	137	69	402	0.17	6.44	
3	0.08	120	54	380	0.14	5.35	
4	0.14	151	76	268	0.28	5.71	
5	0.08	161	75	398	0.19	5	
6	0.12	176	97	548	0.18	6.1	
7	0.13	186	98	522	0.19	6.2	
8	0.21	182	112	685	0.16	5.71	
9	0.22	306	230	628	0.37	5.42	
10	0.28	326	252	692	0.36	5.4	7.22
11	0.21	338	183	668	0.27	5.4	
12	0.12	283	197	737	0.27	5.74	
13	0.28	279	227	998	0.23	5.52	
14	0.28	275	204	826	0.25	5.38	
15	0.12	283	202	649	0.31	4.65	
16	0.41	315	244	1000	0.24	5.71	
17	0.73	364	303	1144	0.26	6.22	
18	0.40	361	301	1233	0.24	6.79	
19	0.35	318	253	1009	0.25	4.14	
20	0.25	324	163	809	0.20	6.44	
21	0.21	314	226	898	0.25	6.36	
22	0.48	304	242	872	0.28	5.9	
23	0.63	307	216	1167	0.19	5.68	
24	0.64	331	248	1162	0.21	6.26	6.86
25	0.27	341	217	610	0.36	5.66	
26	0.35	337	204	830	0.25	5.44	
27	0.10	304	180	353	0.51	-	
28	0.06	245	121	171	0.71	-	
29	0.26	281	134	679	0.20	6.14	7.06
30	0.14	294	160	393	0.41	-	

## Appendix

### Field Observations

January 16, 2016

Measured Section 1 (AOBH 1a):

<b>Approximate Thickness (m)</b>	<b>Unit ID</b>	<b>Unit Description</b>
0 - 6.4	Unit 0	Covered - talus slope
6.4 – 10.8	Unit 1	Poorly graded sand with silt and gravel, SP-SM- about 50% fine to coarse, dark brown, angular to sub-angular sand; about 40% medium to coarse, dark grey, sub-rounded to rounded gravel; about 10% fines. Fine-grained sandy interbeds are approximately 10 cm; gravels within these sandy cross-beds were preferentially aligned and had a higher density than the rest of the unit. The cross-beds are approximately 2 m in width and undulate across the extent of the outcrop.
10.8 – 13.5	Unit 2	Silty sand with gravel, SM- about 50% fine to coarse, light tan to buff grey, angular to sub-angular sands; about 35% fines, and 15% medium to coarse, grey, sub-angular to sub-rounded gravel dropstones. The unit protrudes from the outcrop much further than Unit 1. There are pipes and seeps throughout with a consistent flow of water staining the surface of the unit, and vegetation growing around the seeps.
13.5 – 16.7	Unit 3	Well graded gravel with sand and minor cobbles, GW- about 50% coarse to very coarse, sub-angular to angular gravels; about 45% medium to very coarse, sub-angular to angular sands; 5% fines. There is a 0.5 m thick soil layer developing on top of this diamict, with root structures developing and overhanging the outcrop.

Measured Section 2 (AOBH 2a)

<b>Approximate Thickness (m)</b>	<b>Unit ID</b>	<b>Unit Description</b>
0 – 2.2	Unit 0	Well graded sand with silt and gravel, SW-SM- about 50% fine to coarse, sub-angular to angular sands; 40% medium to coarse, sub-angular to sub-rounded gravels; 10% fines with medium to high plasticity. A covered contact separates this unit from the overlying unit.
2.2 – 10.4	Unit 1	Poorly graded sand with gravel, SP- about 60% medium to coarse, sub-rounded to sub-angular clean sands; 35% coarse, sub-angular to angular gravels; 5% non-plastic fines. Massive unit with large cross-beds, some large boulder sized dropstones throughout. The unit coarsens up section. An angular unconformity marks the transition between Unit 1 and Unit 2
10.4 – 13.3	Unit 2	Well graded gravel with sand, GW- about 50% coarse to very coarse, sub-angular to angular gravels; about 40% coarse to very coarse, sub-angular to angular sands; 5% fines; 5% cobbles to boulder sized clasts. Very thin veneer of soil on top of diamict, does not overhang as much as AOBH_1

January 23, 2016

Measured Section 1 (AOBH 1)

<b>Approximate Thickness (m)</b>	<b>Unit ID</b>	<b>Unit Description</b>
0 – 7.9	Unit 1	Lean Clay, CL – about 100% fines with medium to high plasticity, very slow dilatency, and medium toughness; fully saturated in situ; blue gray color. Distinct unconformable contact with overlying layer.
7.9 - 26	Unit 2	Silty sand, SM – about 60% fine to coarse, sub-rounded to sub-angular sands; 35% very fine to fine particles, silts and clays with medium plasticity; less than 5% sub-angular gravels. Unit is a buff tan color and has minor laminations with 1-3 m thick cross beds of fine-grained sediment. Evidence of seepage within fine-grained interbeds.
26 - 30	Unit 3	Well graded sand with silt and gravel, SW-SM- about 50% fine to coarse, sub-angular to angular sands; 40% medium to coarse, sub-angular to sub-rounded gravels; 10% fines with medium to high plasticity. Gravels are preferentially aligned within greater matrix of sand. Distinct contact with overlying unit.
30 – 38.7	Unit 4	Well graded gravel with clay and sand, GW-GC - about 50% coarse to very coarse, sub-angular to angular gravels; about 30% coarse to very coarse, sub-angular to angular sands; 10% fines; 10% cobbles to boulder sized clasts. Very thin veneer of soil on top of diamict. Unit has near vertical slope.

Measured Section 2 (AOBH 2)

<b>Approximate Thickness (m)</b>	<b>Unit ID</b>	<b>Unit Description</b>
0 – 4.8	Unit 1	Well graded gravel with clay and sand, GW-GC - about 50% coarse to very coarse, sub-angular to angular gravels; about 30% coarse to very coarse, sub-angular to angular sands; 10% fines; 10% sporadically distributed cobbles to boulder sized clasts. Minor talus slope slumped from this layer accumulating behind guardrail.
4.8 – 9.4	Unit 2	Poorly graded sand with silt, SP-SM – about 60% fine to coarse, sub-angular to angular sands; about 30% fines with low to medium plasticity; about 10% sub-angular to angular, coarse gravels. This layer fines upward, and has small (< 0.5 m) fine grain cross-beds with visible seeps.
9.4 – 17	Unit 3	Well graded sand with silt and gravel, SW-SM- about 50% medium to very coarse, sub-angular to angular sands; 40% medium to coarse, sub-angular to sub-rounded gravels; 10% fines with medium to high plasticity. No clear upper boundary of this unit it is covered by vegetation.

Measured Section 3 (AOBH 3)

<b>Approximate Thickness (m)</b>	<b>Unit ID</b>	<b>Unit Description</b>
0 – 4	Unit 1	Silty sand, SM – about 60% fine to coarse, sub-rounded to sub-angular sands; 35% very fine to fine particles, silts and clays with medium plasticity; less than 5% sub-angular gravels. Unit is laminated and fines up section into Unit 2.
4 – 6	Unit 2	Lean Clay, CL – about 100% fines with medium to high plasticity, very slow dilatency, and medium toughness; fully saturated in situ; blue gray color. Covered basal contact. Water seeps from behind each layer scraped away. Layer is very dense, cannot be penetrated easily by fingernail.

6 – 15	Unit 3	Well graded sand with silt and gravel, SW-SM- about 50% medium to very coarse, sub-angular to angular sands; 40% medium to coarse, sub-angular to sub-rounded gravels; 10% fines with medium to high plasticity. Top of unit is not visible, grades into ground surface covered by vegetation approximately 4 m above.
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Measured Section 4 (AOBH 4)

<b>Approximate Thickness (m)</b>	<b>Unit ID</b>	<b>Unit Description</b>
0 – 6	Unit 1	Covered – talus slope
6 – 14	Unit 2	Silty sand, SM – about 60% fine to medium, sub-rounded to sub-angular sands; 35% very fine to fine particles, silts and clays with medium plasticity; less than 5% sub-angular gravels. Unit has minor laminations at base of fine-grained sediment. Seeps piping through this unit where silts are very dense.
14 – 20	Unit 3	Poorly graded sand with gravel, SP- about 60% medium to coarse, sub-rounded to sub-angular clean sands; 35% coarse, sub-angular to angular gravels; 5% non-plastic fines. Massive unit with large cross-beds. The unit coarsens up section. There is a distinct contact with overlying Unit 4.
20 – 22	Unit 4	Well graded sand with silt and gravel, SW-SM- about 60% fine to medium, sub-angular to angular sands; 30% medium to coarse, sub-angular to sub-rounded gravels; 10% fines with medium to high plasticity. The unit is a light buff tan color compared to the gray hues of underlying units. The top of the unit marks the ground surface covered with a thin veneer of soil, trees and low-lying vegetation.

## Field Notes

### **Day 1: January 16, 2016**

#### Measured Section 1 (AOBH 1a)

The outcrop is oriented SSW with an overall slope angle of 35 degrees, from the base of the outcrop to the ground surface at 16.7 meters. There are three distinct units on top of a talus slope that covers the basal 6.4 meters of the outcrop. (See Appendix for detailed description). The outcrop is 16.7 m tall. The contact between the basal talus slope (Unit 0) and Unit 1 is covered. Unit 1 is 4.4 m thick poorly graded sand with silt and gravel and fines upward into overlying Unit 2. Unit 1 contains ~2m wide cross-beds occurring within the middle of the outcrop and pinch out along the edges. Unit 1 was sampled in the field and returned to the lab to describe and classify. Unit 1 overhangs Unit 0 and appears to contribute sediment to the underlying talus slope. Unit 2 is a 2.7 m thick poorly graded fine sand with gravel. Unit 2 has fine laminations and minor cross bedding. There are obvious groundwater seeps and pipes developed in Unit 2. The unit has an undulating contact with overlying Unit 3. Unit 3 is 3.2 m thick well-graded gravel with sand. Unit 3 has a thin veneer of soil overhanging the entire outcrop (Figure 5) creating an undulating ground surface covered with small shrubs and trees. The outcrop represents the upper (~15 m) stratigraphy of the Burpee Hills deposit.

#### Measured Section 2 (AOBH 2a)

This outcrop is located southwest along Burpee Hill Road toward Concrete, Washington and is at a lower elevation than AOBH\_1. The outcrop is facing SSW and has a slope angle of 31 degrees. There are three units described at this outcrop. The outcrop is 13.3 m tall. The basal unit (Unit 0) at the road edge is approximately 2.2 m thick and is characterized as well-graded sand with silt and gravel. Unit 0 was sampled in the field and returned to the lab for description. There is a covered contact between Unit 0 and Unit 1 due to erosion of overlying sediment. Unit 1 is 8.2 m thick poorly graded sand with minor gravels. Unit 1 was sampled and described in the lab. The sands are bedded and stratified across the entire width of the outcrop. The cross-beds at this outcrop are 2-5 m in height and width. Unit 1 is not undercut by sloughing and does not protrude as far as units in AOBH\_1. Unit 1 contains minor cobble to boulder-sized clasts (Figure 6). Alternating fine and coarse cross-beds occur up to the unconformable contact with overlying Unit 2. Unit 2 is 2.9 m thick and is well-graded gravel with sand. Unit 2 is comparable to Unit 3 in AOBH\_1, as it has a thin veneer of soil overhanging the outcrop and creates an undulating ground surface above. Unit 3 pinches out along the eastern edge of the outcrop, where a

small access road opens to the Baker Valley to the east. Outcrop AOBH\_2 also represents the upper (~13 m) of the entire Burpee Hills deposit.

## **Field Day 2: January 23, 2016**

### Measured Section 1 (AOBH 1)

This outcrop is located along Baker Lake Road on the northeastern edge of the Burpee Hills formation. The outcrop is exposed on the left bank of Grandy Creek close to the 2-mile marker on Baker Lake Road. Due to the high levels of Grandy Creek, there was no safe access to sample the outcrop. The outcrop is facing NNW, has a slope angle of 36 degrees and is approximately 38.7 m tall. There are four units described at this outcrop. Unit 1 is characterized as massive, 7.9 m thick lean clay with fine laminations and seeps and pipes formed preferentially along laminations and varying beds. Unit 1 has surface staining and is capped by a 1 m buff tan layer (Figure 7). There is a distinct horizontal unconformity between Unit 1 and the overlying Unit 2, where minor vegetation is growing. Unit 2 is 18.1 m thick poorly graded cross-bedded sand with silt. Coarse and fine grain cross-beds (1-3m thick) alternate across the width of the outcrop but are covered to the west where recent surface erosion has occurred. The evidence of recent shallow landslide movement from surface is shown in Figure 7, where drunken trees have traveled upright downslope in a deposit of overlying sands and gravels. The sediment that has slumped includes deposits from Unit 2, 3 and 4. Unit 3 unconformably overlies Unit 2 and is described as well graded sand with silt and gravel. Unit 3 is approximately 4 m thick and coarsens upward into Unit 4. Unit 3 also contains preferential alignment of coarse gravel sediment indicating imbrication at the base of the unit. Unit 4 is 8.7 m thick well-graded gravel with sand. Unit 4 is covered with a thin veneer of soil overhanging the outcrop. The top of the outcrop is generally flat with less undulation on the ground surface as other outcrops measured in this investigation.

### Measured Section 2 (AOBH 2)

AOBH\_2 is stratigraphically lower than AO\_BH2a. It is approximately 17 m tall and includes three distinct units. The outcrop is facing SSW. This outcrop was particularly difficult to measure due to the guardrail on the side of Burpee Hill Road and tight corner of road (Figure 8). This outcrop represents the side of the terrace and does not capture the terrace top. Unit 1 is 4.8 m thick and is well-graded gravel with clay and sand. Unit 1 was sampled in the field and returned to the lab for analysis. Drunken trees and other overhanging vegetation cover part of the outcrop. The gravel in Unit 1 fines up section into Unit 2. Unit 2 is a 4.6 m thick, poorly graded cross-bedded sand with silt. This unit also fines upward into fine sands with minor silt beds with abundant seeps. Unit 3 is 7.6 m thick and is well-graded sand with silt and gravel. The matrix is coarse sand rather than fine-grained sands. The outcrop is exposed as it follows around the corner of Burpee Hills Road. The exposure pinches out as the road continues south toward the Town of Concrete.



### Measured Section 3 (AOBH\_3)

AOBH3 is stratigraphically above AOBH\_2. The outcrop wraps around a corner along Burpee Hills Road, with the outcrop facing west along the northern section of the outcrop and SSW on the southern section of the outcrop. The outcrop is approximately 15 m tall. There are three distinct units described at this outcrop. Unit 1 is 4 m thick, silty sand with trace gravels throughout. The fines have medium plasticity thus maybe be considered clay particles, although water content tests were not conducted on samples. Therefore it is classified as silt. Unit 1 fines upward and has an unconformable contact with overlying Unit 2. Unit 2 is 2 m thick and is classified as CL lean clay. This unit has medium plasticity and pinches out around the corner to the southeast. It is very stiff, blue gray, laminated and fractures vertically with water seeping from the fractures. Unit 2 was sampled in the field and described in the lab. Unit 3 unconformably overlies Unit 2 and is approximately 9 m thick. This unit is classified as well graded sand with silt and minor gravels. Above 13 m the unit is no longer exposed and is covered by vegetation. There is no visible bedding and it appears as though Unit 3 has been reworked, either by mass movement or alteration from road construction.

### Measured Section 4 (AOBH\_4)

This outcrop is stratigraphically below AOBH\_2 but is stratigraphically above AOBH\_1. The outcrop is approximately 22 m tall and faces due west along Burpee Hills Road. This outcrop is thickly bedded with laminations in the finer units and cross bedding throughout. There are three distinct units in this outcrop that overly a covered basal talus slope, containing the overlying sediment. Unit 0 is a covered talus slope and approximately 6 m thick. Unit 1 overlies the basal unit with no distinct contact and is approximately 8 m thick. Unit 1 is characterized as poorly graded sand with silt. This unit has <1 m thick laminations that alternate finer and coarser sands. Unit 1 was sampled in the field and described in the lab. Unit 2 is described as poorly graded sand with gravel and is approximately 8 m thick. This unit has local variation in each cross-bed, which is approximately 2 m wide, and coarsens up. Unit 2 was sampled in the field and described in the lab. However there is a great deal of variation in grain size within units due to cross bedding and variation in depositional environments (Figure 9). The overlying Unit 3 is approximately 2 m thick and described as well graded sand with silt and gravel. The sands in this unit are fine to medium sized and have a lighter tan color than the underlying units. Unit 3 is stratified with 0.5 m thick laminations.

### Observed Landslide (AOBH\_LS)

This landslide was observed at 261 m elevation (GPS point collected at this elevation). The feature occurs between AOBH\_2a and AOBH\_3. The scarp was measured at approximately 33 m above this point. Therefore the elevation of the scarp is 294 m. Vegetation has regrown on the landslide surface and visibly younger than vegetation on the sides of the landslide. The vegetation consists of sword ferns, small alder trees and minor grass. There is evidence the landslide has affected the road, where tension cracks along either shoulder are visible. There are large hummock features on the northern edge of the road that has failed downslope to the

NW. The sediment deposited across the road is an unconsolidated diamict with similar characteristics of SW-SM overlying SM or CL (Figure 4). The landslide is facing approximately N330W. The older trees along the edges of the landslide are drunken and bending in the downhill direction, evidence of deep-seated movement. Observed landslides occur within the advance outwash deposit and have a scarp elevation of approximately 33 m.

# Measured Sections

