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Sedimentologic changes in the deposits of an evolving lahar-flood in 2006, Hood
River Basin, Mount Hood, Oregon

by

Matthew Ray Poole

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geology

Thesis Committee:
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Portland State University
2016

Abstract

Over a span of six days from November 2nd – 7th, 2006 approximately 43 cm of precipitation fell over the Hood River Basin in Oregon. A lahar was initiated on the Eliot Branch of the Middle Fork Hood River by two or more landslides that occurred on the lateral moraines of the Eliot Glacier on the early part of November 7th, 2006. The Eliot Branch lahar was embedded within the larger regional flood that was occurring in the Hood River Basin and traveled a total of 48 km from the initiation points on the north flank of Mount Hood to the Hood Rivers confluence with the Columbia River.

The initiating landslides abruptly transformed into a debris flow upon mixing with flood waters of the Eliot Branch. The debris flow traveled a distance of ~28 km at which point it was transformed first to a hyperconcentrated flow and then to water flow via selective deposition of coarse sediment and progressive dilution by channel flow waters from the East and West Fork Hood Rivers. The transformation from debris flow to hyperconcentrated streamflow was recorded by a thickening wedge of hyperconcentrated streamflow sediments found above and below progressively fining debris flow sediments over a reach of 22 km. Finally, the hyperconcentrated-flow phase of the lahar transformed to water flow and then traveled an additional 20 km to the Hood River delta. Upon reaching the apex of the Hood River delta, depositing sediments led to an expansion of the delta. Debris-flow sediments were predominantly

gravel (36.0-69.7% by wt.) with sand (22.1-55.9% by wt.) and fines (4.7-7.8% by wt.).

Hyperconcentrated flow deposits contained a larger sand fraction of (66.8-99.2% by wt.) with few gravel clasts (0-26.0% by wt.) and fines (0-8.8% by wt.). Water flow deposits averaged 90.5% (wt.) sand with 6.0% (wt.) gravel and 3.0% (wt.) fines. Sorting was a key factor in flow identification and showed progressive improvement downstream from the initiation point. Sorting values for the flow types are as follows: debris flow deposits ranged from 3.3ϕ (very poorly sorted) to 1.8ϕ (poorly sorted), hyperconcentrated flow deposits ranged from 2.4ϕ (very poorly sorted) to 0.8ϕ (moderately sorted), and water flood deposits ranged between 1.4ϕ (poorly sorted) to 0.6ϕ (moderately sorted).

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Chapter 1

Introduction

During the first week of November, 2006, a large rain storm occurred across the Pacific Northwest region of the United States. The event caused widespread flooding and triggered multiple secondary lahars (high concentration, high discharge flow events) at volcanoes across the Cascade Mountain Range. The term *Lahar*, originally an Indonesian word, refers specifically to a mixture of pyroclastic debris, rock particles, and water flowing down the slopes of a volcano. As it pertains to this study, a lahar can be described as both debris flow and hyperconcentrated streamflow, whereas, the term flood refers to water flow (Vallance, 2000). Specific volcanoes known to have had lahar activity during the storm include Mount Hood, Mount Adams, Mount Jefferson, Mount St. Helens, and Mount Rainier (Copeland et al., 2008; Sobieszczyk et al., 2009; Burns et al., 2009; Olson, 2011; Williams, 2011). On Mount Hood, lahars occurred on 7 of the 11 major river drainages, including the Eliot Branch of the Hood River Basin which is the focus of this study (Pirrot, 2010).

The Hood River Basin drains the north and east sides of Mount Hood (Figure 1). It is comprised of three main tributaries - the West, Middle, and East Forks of the Hood River (5th order basins). Total basin area is approximately 878 km² and includes twelve 6th order basins. Elevations range from 24m at the mouth of the Hood River to over 3429 m at the top of Mount Hood.

The Eliot Branch lahar-flood initiated in the Upper Eliot Branch basin on the north flank of Mount Hood at an elevation of ~1835 m through landslides combining with heavy runoff along the lateral moraines of the Eliot Glacier (Figure 2). Along the path of the lahar, extensive damage to infrastructure was done. The Red Hill Road Bridge, a 20 m steel span, was ripped apart and buried by the debris, never

Figure 1. Hood River Basin vicinity map.

to be found. A water intake structure for the Hood River Irrigation District was damaged beyond repair. Approximately 1 km of the Laurance Lake Road (#2840) was inundated by debris, requiring it to be excavated and rebuilt. When flood waters entered the

Figure 2. Hood River Basin and lahar-flood path (yellow line) descending down the Eliot Branch, into the Middle Fork Hood River, to the main Hood River, and finally to the confluence with the Columbia River.

confluence with the Columbia River, much of the entrained sediment load was deposited at the river mouth, which greatly expanded the Hood River delta.

The purpose of this thesis is to enhance our understanding of the flow transformations between debris flow, hyperconcentrated stream flow, and flood. Few studies have been done that investigate the sedimentologic differences in deposits of lahars undergoing flow transformations. The Hood River Basin provided an opportunity to study the evolution of a lahar undergoing flow transformations over the length of the basin through downstream sedimentologic changes, as well as, through vertical transitions in stratigraphic sections at fixed points.

Aims and objectives

The objective of this study is to characterize the sedimentology of the Hood River lahar-flood of 2006 and compare this event to other volcano-related debris flows studies. By comparing the deposits emplaced by the flow types associated with lahar-floods, a greater understanding of volcanic related geomorphology and the hazards associated then can be achieved. To do this, this study aims to do the following:

- Characterize changes in the mass movement or flow type (debris flow, hyperconcentrated flow, and flood) from the initiation zone to the mouth of the Hood River based on deposit characteristics and grain size statistics.

- Characterize changes in the sedimentology as they are related to distance from the initiation zone.
- Create a spatial distribution map of the changes in flow type over the basin.
- Compare the sedimentologic changes in the Hood River Basin to those found in other studies done on lahars.
- Use the sedimentology to postulate the type of flow that is associated with each deposit and recreate the sequence of events.

Chapter 2

Background

Geologic History of Mount Hood

Mount Hood is an andesitic composite volcano in the Cascade Mountain Range with an elevation of 3,429 m. It is located 75 km east-southeast of Portland, Oregon and 35 km south of Hood River, Oregon on the Columbia River (Figure 1). Three main rivers coalesce from the mountain's 11 upper drainages and all flow eventually into the Columbia River; they are the Sandy, the White, and the Hood rivers. It is the tallest mountain in Oregon at 3,429 m. The mountain currently supports twelve glaciers which are drained by three river systems - the Sandy, White, and Hood rivers. The region has seen extensive volcanism since the late Miocene; however, the present cone is of late Pleistocene age (Cameron and Pringle, 1987). The mountain was carved by glaciers and mass wasting, primarily during the Fraser Glaciation between about 30,000 and 10,000 years BP. Alpine glaciers in the Pacific Northwest reached their maximum extents 20-21 ka (Licciardi et al., 2004). There have been three major eruptive periods since the last glacial maximum that have created large amounts of volcaniclastic debris, the last two of which produced a lava dome on the volcano's southwest flank (Crandell, 1980; Cameron and Pringle, 1987).

Mount Hood has been erupting and generating lahars for hundreds of thousands of years. The oldest known eruption occurred around 900,000 years ago and is found preserved in the Muddy Fork of the Sandy River (Scott et al., 1997). Another major event found in the geologic record occurred about 100,000 years ago when a massive debris avalanche collapsed from the north side of the mountain. The subsequent lahar traveled down the Hood River, into the Columbia River, and up the White Salmon River on the northern side of the Columbia for several kilometers. It is thought that this debris avalanche was large enough to have temporarily dammed the Columbia River (Scott et al., 1997).

The Polallie eruptive period is believed to have occurred between 15,000 to 12,000 years BP during the end of the Fraser Glaciation (Crandell, 1980). Deposits from the period occur primarily as pyroclastic flows and debris flows (lahars). They are found on all sides of the mountain. In the upper Hood River Valley lahar deposits, thin tephra, and pyroclastic flows are found interbedded with late Fraser-age glacial outwash (Crandell, 1980).

A gap of more than 10,000 years in the volcanic record exists between the Polallie eruptive period and the Timberline eruptive period which occurred between 1800 and 1400 years BP (Crandell, 1980; Cameron and Pringle, 1987). During this time, periodic pyroclastic flows flowed down the southwest side of Mount Hood from a vent below the summit. Lahars were produced that flowed into the Sandy and Zigzag River basins. Three major debris flows came down the Sandy River. Timberline deposits

cover much of the Sandy River delta in the Columbia River (Rapp, 2006). The current topography of the southwest side of the mountain including the main debris fan and Crater Rock, a dacitic composite dome, was created during this time period (Cameron and Pringle, 1986, Cameron and Pringle, 1987).

The most recent activity at Mount Hood occurred during the Old Maid eruptive period, the main part of which occurred between AD 1781 and 1793 (Pierson et al., 2011). Extensive inundation by primary eruption-triggered lahars and extreme volumes of volcano-fluvial sedimentation occurred in the White, Sandy, and Zigzag (Sandy River tributary) Rivers during this eruptive period, with most of the lahars extending a few tens of kilometers. Additionally, a lithic pyroclastic flow traveled at least 9 km down the White River from the dacite vent at Crater Rock. One lahar from this time period has been recorded at least as far downstream as Oxbow Park (70 km) on the Sandy River (Pierson et al., 2011), and it probably extends as far as the Sandy River delta apex, 80 km from Mount Hood. In the White River, Old Maid deposits extend as far as the Deschutes River, 75 km away. Along the Sandy River there was little attenuation of lahar stage height (Cameron and Pringle, 1987).

In more recent recorded history, Mount Hood has continued to have secondary lahars triggered by heavy rainfall but without accompanying volcanic activity. On December 25, 1980 heavy rainfall and saturated conditions combined to trigger a landslide at the head of Polallie Creek Canyon on the northeast flank of Mount Hood (Gallino and Pierson, 1985). The landslide transformed to a debris flow with flow

velocities of approximately 12 to 15 m/s. At the confluence of the East Fork Hood River the debris flow deposited over 90,000 m³ of poorly sorted debris with a maximum depth of 11 m. The debris created a temporary dam that, once breached, sent a flood wave down the East Fork Hood River. Ultimately, this event resulted in the loss of one life and over \$13 million in damage to infrastructure (Gallino and Pierson, 1985).

Prior to the 2006, a total of 26 debris flows had been documented on Mount Hood since 1907 (Pirot, 2010) (Table 1). Of all the drainages on Mount Hood, the White River Basin has shown the most debris flow activity in modern times. The steep slopes and unconsolidated deposits in the upper basin act as a potent initiation zone for debris flows (Pirot, 2010). The bridge over the White River on Highway 35 has been buried 20 times by debris flow or flood activity since 1907 (Anderson and DeRoo, 2006).

The rainstorm of November 2006 brought about the most extensive debris flow activity in the last few decades. Seven of the eleven main drainages received basin-impacting debris flows (Pirot, 2010). These included: the White River, Salmon River, Clark Creek, Newton Creek, Ladd Creek, Sandy River, and Eliot Branch. These events created widespread infrastructure damage with five of the seven flows damaging bridges or roads in the area (Pirot, 2010). Average initiation zone elevations were around 1,860 m and source materials consisted of unconsolidated glacial till and other volcanoclastic deposits. Out of the seven known debris flows at Mount Hood in 2006, four were initiated by landslides caused by undercutting of lateral moraines. The

remaining three were determined to be caused by a coalescence of many small debris flows into a large debris flow (Piriot, 2010).

Table 1. Recorded debris flow activity on Mount Hood since 1958 and prior to 2006 (Piriot, 2010).

Drainage	Year	Month	Initiation Elevation (m)
Coe	1958	November	unknown
Ladd	1961	September	2100
Newton	1978	August	unknown
Polallie	1980	December	2000
Newton	1991	November	unknown
Newton	1995	unknown	unknown
Ladd	1996	unknown	unknown
Polallie	1997	October	1900
Clark	1997	unknown	unknown
Newton	1998	July	2000
Clark	1999	November	2300
Eliot	1999	November	1900
Coe	2000	October	1800
Newton	2000	October	2200
Clark	2000	October	2400
Eliot	2000	January	1900
Eliot	2000	October	1900
Sandy	2000	October	2100
Muddy Fork	2000	October	1800
Muddy Fork	2002	June	1700
Newton	2003	October	2100
Clark	2003	October	2300
Sandy	2003	October	unknown
Clark	2005	September	unknown
Sandy	2005	September	unknown
Newton	2005	September	2300

The Fraser Glaciation maximum ice advance occurred on Mount Hood 20 to 21 thousand years ago, with minor advances at 17 ka and 12-13 ka (Licciardi et al., 2004).

Glacial till was measured at 17 locations around Mount Hood with a range of depth between 35 to 90 cm and an average of 63 cm (Crandell, 1980).

Meltwater from the Eliot Glacier feeds Eliot Branch, the site of initiation for the 2006 lahar. The Eliot Glacier is a small glacier on the northeast side of Mount Hood with an area of 1.6 km². Since 1901 the glacier has retreated 680 m, lost 19% of its area, and thinned by approximately 50 m at its terminus (Jackson and Fountain, 2007). At this point in time there is a large amount of ablation till and rockfall debris covering the stagnant toe of the glacier. Ice lacking in debris cover is currently located at an elevation of 2120 m. Approximately 27% of the lower portion of the Eliot Glacier is covered by debris that has been measured up to 1.5 m thick at the glacier's terminus (Jackson and Fountain, 2007). The retreat of the Eliot glacier since 1901 has been attributed to a changing climate on Mount Hood due to an increase in average summer temperatures from 5.6°C in 1902 to 8.8°C in 2002 (Jackson and Fountain, 2007).

Lahar-Flood Flow Types

There are three recognized types of sediment-water flows that can occur during high discharge flow events, which are defined by the amount of sediment carried in suspension. These flow types include debris flow, hyperconcentrated flow, and water flow, which can transform from one to another as the proportions of sediment and water change. Boundaries between each flow type are not sharp or always fixed at

particular sediment concentrations. Instead, boundaries vary according to grain-size distributions of the involved sediment-water mixtures, and the different types represent a continuum rather than entirely separate categories (Pierson, 2005a). Deposits of these flow types have characteristic sedimentary textures, structures, and grain size distributions, which can be identified by a combination of outcrop analysis in the field and laboratory analysis (Costa, 1988; Pierson, 2005a,b). Debris flows involving mixtures with the highest sediment concentrations typically have solids contents in excess of 80% by weight or 60% by volume (Pierson, 2005b).

Debris flow mechanics are influenced by both solid and fluid forces (Iverson et al., 1997). Debris flow mixtures were once thought of as having fixed rheologies, but the mechanics of flow can be better described as dependent on changing rheologies that derive from changes in shear rate, concentration, grain-size distribution, and composition (Iverson and Vallance, 2001). Initiation of debris flows can be caused by a number of processes, including pyroclastic flows entraining and melting snow or ice, surface runoff or flood waters eroding and incorporating a deposit of sediment, and mobilization from landslides (Iverson et al. 1997).

Geomorphic evidence for debris flows consists of steep, lobate deposit margins, commonly with a high concentration of large clasts. Lateral levies commonly develop and contain relatively coarse deposits. Flows typically occur in pulses or surges, and multiple debris flow lobe deposits can occur. Sedimentologic characteristics include a

relatively uniform distribution of sizes ranging from clay to boulders. Clasts in deposits are typically supported by a matrix of sand, silt, and clay, except where the matrix has been drained or washed away or where the proportion of clasts with respect to matrix material is high. A muddy matrix surrounding larger particles is common. Debris flows can vary in sorting values but are typically very or extremely poorly sorted. Values for debris flow deposits observed on Mount St Helens were in the range of 3.0ϕ to 5.0ϕ (Pierson and Scott, 1985). Debris flow deposits are commonly positively skewed or contain bimodal distributions.

There are two types of debris flows, cohesive and noncohesive (Scott, 1988). Cohesive debris flows contain a percentage of clay by weight greater than 3 to 5 percent. Grain interaction is affected by the adhering clay, which reduces particle interactions. Additionally, the differential movement and settling of coarse particles and the miscibility of the flow with streamflow is delayed. Noncohesive debris flows contain a percentage of clay by weight less than 3 to 5 percent. These debris flows are more granular than cohesive debris flows and are known to more readily transform between flow types upon mixing with channel flow (Scott et al., 1995).

Hyperconcentrated flows occur at sediment concentrations intermediate between those of debris flow and water flow. Suspended sediment in these flows is great enough to change the fluid properties and sediment transport mechanisms. They have been described by Pierson (2005b) as being, “turbulent, two-phase, gravity-driven

flows of water and sediment, intermediate in suspended-sediment concentration between normal sediment-laden streamflow and debris flow or mudflow”.

Differentiating hyperconcentrated flows from other flow types is based on sediment transport. Many different approaches have been used to make this definition.

Sediment concentration parameters were initially arbitrarily set between 20% by volume (40 wt%) and 60% by volume (80 wt%) (Beverage and Culbertson, 1964). Other defining criteria have been based on the bulk properties of the suspension and how much sand is suspended and deposited in the flow. As of yet, no single criteria for defining hyperconcentrated streamflow exists (Pierson, 2005b).

Hyperconcentrated flows are able to transport high concentrations of sand in suspension relative to the concentration of fines, once a minimum threshold of fines (3%-10%) has been reached (Pierson, 2005b). This has been explained through models that attribute the additional buoyancy to upwelling fluid created through displacement of water as a portion of the suspended load settles out of suspension (Druitt, 1995). Hyperconcentrated flows do not exclusively emplace stratified deposits. Once the concentrations of clasts reaches a sufficient level, selective settling ceases due to grain-to-grain frictional and collisional forces. The effect of this process on deposition is that the deposits can become unsorted and unstratified. Graphic sorting values will typically fall in the range between 1.1-1.6 ϕ (Costa, 1988).

Hyperconcentrated flows deposit their load as turbulence decreases and the flow no longer has enough energy to entrain large particles. The deposits generally exhibit a finer and more sorted character than debris flows. Faint horizontal stratification with gravel lenses is commonly present, but distinct stratification can occur as well. Water-flow deposits have more distinctly bedded strata than hyperconcentrated flow deposits. Additionally, hyperconcentrated flow deposits do not exhibit cross-bedding, whereas water-flow deposits do (Pierson, 2005b).

During a water flood, sediment moves by suspension and through rolling and saltating along the channel bottom by turbulent water flow. Clay-sized sediments remain in suspension in part through electrostatic charges. Grains larger than clay are supported in part by turbulent flow. The settling velocity of the particle will be proportional to the amount of turbulence applied. During water floods, these sediment-support mechanisms allow sediment transport at concentrations as high as 20% by volume (~40% by weight) (Costa, 1988), but on volcanoes the upper limit is more typically 11-12% by volume (Pierson, 2005a).

Sedimentologic evidence for water floods consist of primary sedimentary structures and deposition on bars. Primary sedimentary structures found associated with water floods include horizontal and inclined stratification, cross bedding, cut and fill structures, and imbrication. In channels with mobile beds and high sediment loads,

water floods typically form wide shallow channels. Deposits on point bars and inside meanders are common (Costa, 1988).

The rheology of a sediment-water suspension can be described as either Newtonian or non-Newtonian. Water is an example of a Newtonian fluid. A Newtonian fluid is defined as a mixture having a linear relationship between applied stress and strain with no yield strength. Water can exhibit these characteristics with a sediment load of very well-sorted sand and/or gravel up to about 35% by volume. However, measureable yield strengths may result when fines (silt and clay) are added to the suspension (Pierson, 2005b). With sufficient fines the mixture becomes a non-Newtonian fluid, which is defined by a non-linear relationship between applied stress and strain rate or by having a yield strength (Figure 3).

Figure 3. Definitions of flow type based on an idealized yield-strength curve of a poorly sorted sediment-water mixture (Pierson, 2005a). The relationship between yield strength and sediment concentration is defined as a non-Newtonian fluid for hyperconcentrated streamflow and debris flows.

Toutle River Lahar, 1982, Mount St. Helens, USA

In 1982 a dome building eruption released two lake-outbreak meltwater floods totaling 10^7 m^3 in volume down the north side of Mount St. Helens. The flow surged for nearly 100 km down the Toutle River transforming from water flow to debris flow, then to hyperconcentrated flow, and finally back to water flow (Pierson and Scott, 1985; Dinehart, 1999). The flood surges eroded and entrained large volumes of volcanic debris from the crater breach. Debris flow surges were generated 2 km downstream of the initiation point by rapid entrainment of sediment, and they flowed 27 km down the North Fork Toutle River. Beyond 27 km, the flow started incorporating enough river water to begin a flow transformation to hyperconcentrated flow. This transition occurred progressively over a reach of 27 and 43 km downstream of the crater. The lahar then flowed as a hyperconcentrated flow to the confluence with the Cowlitz River, 83 km from the crater. Mixing of the lahar with the Cowlitz River transformed the hyperconcentrated flow to water flow, and the lahar became a muddy water flood (Pierson and Scott, 1985).

Along this 1982 lahar flow path, the flow deposits initially exhibited characteristics of debris-flow deposits, but gradually transitioned downstream to a different deposit type. Deposits close to the volcano were very poorly sorted to extremely poorly sorted ($3.0\text{-}5.0\phi$) and had no stratification. The matrix was clast supported with inverse grading near the bottom and normal grading near the top

(Pierson and Scott, 1985; Dinehart, 1999). The transitional zone from 27 to 43 km downstream of the crater, began to show a unique facies type that differed from debris flow deposits and from typical fluvial deposits; this facies type was fully developed in the hyperconcentrated flow reach (Pierson and Scott, 1985). This new facies type for hyperconcentrated flow, not previously described in detail, was characterized by a coarse sandy texture with less fines than the debris flow deposits, poor sorting ($1.1-1.6\phi$), faint horizontal stratification with an overall massive appearance, thin lenses of gravel at varying levels, a clast-supported open texture, and a surface layer of woody debris and pumice clasts. Stratigraphically in the transition zone, the sandy hyperconcentrated flow deposits occurred below the debris flow deposits (Figure 4), suggesting that sequential deposition required the transformation of debris flow to hyperconcentrated flow to be occurring at the lahar flow front due to dilution from mixing with overtaken river water. This transitional sequence was found over a distance of 16 km for the first surge and 6 km for the second. The flow-front mixing hypothesis required the lahar to be moving faster than the streamflow in the river, for vigorous turbulent mixing and dilution to be occurring at the mixing interface, and for subsequent deposition to be occurring as coarser size fractions could no longer be supported in suspension.

Figure 4. Diagram depicting deposits as flow type transformations from debris flow to hyperconcentrated flow. Note the decrease in grain size, increase in sorting, and presence of stratification (Pierson and Scott, 1985).

Whangaehu River Lahars, 1995, Ruapehu Volcano, New Zealand

In 1995 multiple lahars occurred in the Whangaehu River during a series of eruptions from Ruapehu Volcano in New Zealand and exhibited flow transformations (Cronin et al., 1997; Cronin et al., 1999; Cronin et al., 2000). During the phreatomagmatic eruptions lahars were created by flood waters leaving Ruapehu's Crater Lake until it emptied and, thereafter, lahars were generated through seasonal

snowpack melt mixed with tephra. Four different types of lahars were generated through this eruptive sequence: snow-slurry lahars composed of granular snow and ice with 2.5%-20% sediment; dilute lahars from expelled water from the crater lake, which formed hyperconcentrated flows for up to 84 km from the initiation point; concentrated lahars with high sediment concentrations between 46%-52% by volume; and remobilized tephra lahars, which were generated from melted snowpack (Cronin et al., 1997; Cronin et al., 1999; Cronin et al., 2000).

Deposits from the Ruapehu Volcano eruption sequence ranged from debris-flow deposits to water-flow deposits. Included in this range was the transitional stratigraphic sequence showing hyperconcentrated-flow sediment transitioning stratigraphically upward into debris-flow sediment, as was observed by Pierson and Scott from the 1982 eruption on Mount St. Helens. Debris flow deposits from the 1995 lahars contained common features including: matrix supported texture, lack of internal stratification, and extremely poor sorting with grain sizes ranging from clay to boulders.

Hyperconcentrated streamflow deposits exhibited faint to strong planar fabric, weak bedding, and contained local concentrations of clasts up to small cobble size, which occurred in planar strings (Cronin et al., 1997; Cronin et al., 1999; Cronin et al., 2000).

Additional lahar deposits from the 1995 event exhibited the transformation between debris flow and hyperconcentrated flow. They were described by Cronin et al. (1997) as

being comprised of a massive matrix-supported coarse gravel bearing unit overlying a massive or weakly planar bedded gravelly sand.

Study Area Climate

The climate of the Hood River Basin is characteristic of the Western Cascades physiographic province. Summers are warm and dry. Winters are cool and receive the bulk of the yearly precipitation (Peterson et al., 2002). Although the basin ranges in elevation from 22 m to 3429 m above sea level, the climatic effects on Mount Hood have the greatest influence. The Cascade Range forms a barrier to the eastward movement of air from the Pacific Ocean which causes an orographic effect to produce large amounts of precipitation on the western flanks of the range. Low elevation air masses are forced to rise due to the change in elevation created by the Cascade Mountain Range. As the air rises it cools adiabatically causing the relative humidity to rise. This relative rise in humidity and subsequent rainfall induces a mean annual precipitation range from 300 cm in the western Cascades to 100 cm on the eastern slopes as the air mass loses moisture content across the range (Peterson et al., 2002). Higher elevations receive the bulk of this as snow, allowing a deep snowpack to form. Lower elevations receive mostly rain. The Parkdale weather station at an elevation of 506 m, receives an average annual rainfall precipitation of 87 cm with an average annual snowfall of 140 cm (U.S. Climate Data, 2015).

The 2006 lahar-flood that started in Eliot Branch of the Middle Fork Hood River was caused by an extreme precipitation event generated by what is known as an atmospheric river or, colloquially, as a “Pineapple Express” storm. Atmospheric rivers are a manifestation of the Madden-Julian oscillation (MJO), which is an intra-seasonal fluctuation in the tropics that propagates eastward over a 30-60 day cycle (Madden and Julian, 1971). The MJO impacts patterns of precipitation, atmospheric circulation, and surface temperatures in the tropics and subtropics. Evidence indicates that the MJO affects the El Nino Southern Oscillation (ENSO). The generalized pattern of the MJO begins when heavy tropical air masses in the eastern Indian Ocean migrate east to the western Pacific Ocean. The air mass continues to move northeast across the Pacific, until a convergence with a strong high pressure zone in the Gulf of Alaska (NOAA-NWS, 2002). Divergence of the circulation pattern into the Pacific Northwest is further enhanced by a deep, low pressure zone over the area. The final outcome can create up to a week of intense precipitation, as was observed in November of 2006.

2006 Lahar-flood Precipitation and Streamflow

The 2006 Pineapple Express storm dumped over 50 cm of rain onto the Cascade Mountain Range of Oregon and Washington. The most intense rainfall occurred over a 36 hour period between November 6th and 7th, 2006 (Burns et al., 2009).

Two SNOTEL weather stations are located near or within the study area. The Red Hill station is located within the Hood River Basin near Laurance Lake (45.46 N, - 121.70 W) at an elevation of 1344 m while Greenpoint station is located west of the confluence of the East and West Fork Hood River's at an elevation of 1009 m (45.62 N, - 121.70 W) (Figure 2). Red Hill station recorded a cumulative total of 42.7 cm of rainfall between November 2nd-7th. Greenpoint station recorded lower cumulative precipitation amounts of 32.3 cm over the same time period. November 6th saw the highest daily rainfall totals of 13.0 cm at Red Hill and 9.1 cm at Greenpoint (Figure 5).

Hood River water flow data was obtained from the USGS National Water Information System (USGS NWIS). The gaging station for the Hood River is located 25 ft downstream of Tucker Bridge on the main stem Hood River at river mile 6.1. The discharge is computed from gage height recorded at the station using a discharge rating curve. The pre-flood baseline average discharge was 297 ft³/s for the 2006 water year between October 1st and November 2nd (10:30pm). After 10:30pm on November 2nd a noticeable rise in gage height begins. This was followed by a steady increase until November 5th, where a subtle dip in discharge is noted, but still exceeds baseline values. Between November 5th and the 7th the discharge rose rapidly to a plateau between 10,000 to 11,000 ft³/s with a narrow spike occurring on November 7th at approximately 8:00am. Peak discharge at this time was estimated to be 18,700 ft³/s This peak would have been caused by the lahar-flood surging downstream and mixing with flood waters

from the other main tributaries. The lahar would have created the sharp peak due to the pulse of water with a relatively high sediment concentration compared to the non-lahar flood waters. After the peak, a steady drop was recorded until a return to about 2000 ft³/s on the 9th of November (Figure 6). Estimation of the gage height and discharge for the peak flow was necessary due to erroneous data recorded at the station on November 7th. Corrections were applied based upon visits by USGS personnel, pictures supplied by Hood River News, and information from kayakers (Parham, 2015).

Figure 5. SNOTEL weather station data for Red Hill and Greenpoint stations. Data were recorded at 0:00 on the date shown and is therefore the previous day's cumulative rainfall.

Figure 6. Flood hydrograph displaying discharge (ft^3/s) for the USGS Tucker Bridge gage station (#14120000) with 24-hour rainfall from Figure 5 superposed. Date range covers the entire multi-day rainstorm. Peak discharge was estimated to be 18,700 CCF on the morning of 11/7/2006 at 8:00 am, and this sharp peak likely records the brief lahar-flood of this study. Bar chart represents Red Hill SNOTEL weather station data. Largest daily accumulation of 13.0 cm of rainfall occurred over November 6th. Date marks are at 00:00 at beginning of days shown; SNOTEL record reflects accumulated 24-hr rainfall from previous day.

Hood River Delta Prior to 2006

In order to understand the expansion of the Hood River delta caused by the 2006 lahar-flood a look at the historical changes to the delta needs to be observed. The Hood River Delta has evolved significantly due to engineered structures. Construction of Bonneville Dam on the Columbia River and an engineered channel at the confluence of the Hood River with the Columbia River has altered the historical characteristics of the Hood River delta. Flow velocities have decreased and fluctuating river levels have been

diminished. Prior to dam construction the Hood River entered the Columbia as a series of braided distributary channels through a sandy delta. As the Hood River deposited its load of sediment on the delta, the Columbia River's current and probably also easterly winds (at low water levels) caused most of the deposition to occur west and downstream of the mouth (Figure 7). Prior to the completion of the Bonneville Dam by

Figure 7. Hood River Delta circa 1935. Prior to Bonneville Dam and the Nichols boat basin construction the Hood River entered the Columbia through a series of channels. The delta evolved over time and was influenced by the current of the Columbia River (USACE, 2010).

the United States Army Corp of Engineers (USACE) in 1937 (USACE, 2001), the average water surface elevation of the Columbia River at Hood River varied between 18 m to 22

m above mean sea level (ft ASL). Upon dam completion, the operating range for the Bonneville Pool was narrowed to 22 m to 23 m ASL (USACE, 2010). In addition, the river mouth was confined to a single engineered channel under authorization by the Rivers and Harbors Act of 1945, and the Nichols Boat Basin and west breakwater were constructed in the early 1960's (Figure 8).

Figure 8. Hood River Port construction circa early 1960s . Nichols Boat Basin and the west breakwater were constructed during this timeframe. The Hood River waterfront, seen in the center of the photograph, can be seen being actively filled from dredged sand of the Columbia Channel (courtesy of the History Museum of Hood River County).

The breakwater jetties created a single channel for the river and extended the river mouth 600 m to the north. This acted to limit the lateral variation in the Hood

River and shift deposition north towards the Columbia navigation channel (McElwee, 2010) (Figure 9). The Columbia River Dam system upstream of the Bonneville Dam has reduced the average magnitude of the annual freshet, or spring floods, from 700,000 to 1,000,000 ft³/s before dam construction to 300,000 to 400,000 ft³/s after. This, in conjunction with the steady high stage of the Bonneville Pool, creates a backwater condition at the mouth of the Hood River. Velocities in the mouth of the Hood River have decreased, and the fan shaped delta has formed in response (USACE, 2010).

Figure 9. Aerial view of the Hood River delta in 2005 at the confluence with the Columbia River (McElwee, 2010).

Chapter 3

Methods

Field work

The effects of the lahar-flood were determined through field examination of deposits and real-time and post-event observation by area residents, specifically those located in the City of Hood River and the unincorporated area of Parkdale, Oregon. The initiation zone of the event was first described by Portland State University graduate student Rachel Pirot (2010) as arising from landslides from lateral moraines of the Eliot Glacier on Mount Hood's northeast flank. These determinations were used as the initial outline for the study area.

Field work for my study was conducted under the guidance of Dr. Thomas Pierson of the USGS Cascades Volcano Observatory. The Hood River Basin was visited a total of eight days between June and November 2012. Sample and observation sites were selected based on a combination of accessibility, known deposition, and suspected deposition related to the 2006 lahar-flood. Field sites were selected from remote sensing information and topographic maps. Accessibility throughout the Hood River Basin is limited by topography and the barriers of private land ownership.

Major deposits from the 2006 lahar-flood are located in two primary locations. One of these occurs where Forest Service Road 2840 (Laurance Lake Drive) crosses Eliot Branch, just upstream of the confluence of Eliot Branch and Middle Fork Hood River. Here is where much of the debris-flow phase of the lahar was deposited as a large bouldery, debris field. The second major deposit is found at the Hood River delta in the Columbia River. Selecting previously unknown sites for observation and sampling was done using Google Earth imagery, GIS, and topographic maps. Four USGS 7.5' quadrangles were obtained to outline the entirety of the study area: Mount Hood North, Parkdale, Hood River, and Dee. Aerial photos and satellite images were studied to identify any areas along the path of the debris flow that appeared disturbed. This information was combined with road access to define feasibility. A total of seven primary locations were visited for field study and sample collection, with multiple samples collected at each location.

Sample sites were chosen based on field evidence that strongly indicated a relationship to the 2006 event. Field observations were conducted approximately six years after the debris flow occurred. Recognition of the 2006 deposits was based on position (highest deposits since the flood of 1996), color (light brown to light gray), lack of weathering, and a lack of significant vegetation growth on bench surfaces. Some incision into and reworking of 2006 deposits has occurred, particularly where Eliot Branch has incised into the large debris field in the Laurance Lake Road area, and where

deltaic sands have been reworked into waveforms by wind waves and currents of the Hood and Columbia Rivers.

Ideal sample sites were located along cut banks where the vertical profile could be observed because textural and structural changes in the vertical profile were used to identify flow type. Sample sites were located spatially using GPS datum NAD27 CONUS. When required, sample sites located mid-channel were reached by wading across low water access points. A sampling protocol was followed at each site and involved the following steps, in no particular order. The three principal axes of five largest boulders in the immediate vicinity of each sampling site were measured. Where deposition was sufficiently expansive, lateral extent was surveyed and samples were taken near the surface. The following vertical profile characteristics were noted: color, stratification, texture, grading, thickness, lateral extent of lithofacies, and representative samples of all distinct lithofacies were collected. All samples were obtained to fulfill laboratory requirements for grain size distribution.

Laboratory Analysis

Particle size analysis was conducted following the ASTM D422 Standard Test Method for Particle-Size Analysis of Soils (ASTM, 2007). Samples were air dried, weighed and dry sieved in a stack on a mechanical shaking table. The range of sieves used included the following Phi scale sizes: -5 (32mm), -4 (16mm), -3 (8mm), -2 (4mm),

-1 (2mm), 0 (1mm), 1 (0.5mm), 2 (0.25mm), 3 (0.125mm), and 4 (0.063mm). A minimum 100g of soil was used from each sample. For samples containing gravel larger than sieve -5 phi (31.5mm), the three principal axes of the largest single gravel clast were measured and recorded.

If, after the initial shake, fines remained adhering to the sand and gravel component, the samples were recombined and wet sieved. Wet sieving allows all of the fines to be measured and is important with debris flow deposits. Each sample was then rinsed through a 4 phi sieve to separate out the fines fraction. Care was taken not to exceed 1000 ml of water since that was the volume of the graduated cylinder used for the analysis of fines.

Pipette analysis to determine the weight percentage of silt and clay was conducted for any sample where a minimum of 10% of the overall sample weight was fines, as well as for all samples that underwent wet sieving (Gee and Bauder, 1986). This fraction was placed into a 1000 ml graduated cylinder for sedimentation analysis using pipette withdrawal. Due to the cohesiveness and electrostatic charges of certain clay minerals, sieve analysis does not adequately measure particles smaller than 4 phi (0.063 mm). Pipette analysis relies on the settling velocity of particles within a fluid. A particle falling freely through a fluid will cease to accelerate as the frictional force exerted on the particle by the fluid balances the force of gravity on the particle. This action, known as Stokes Law, is the basis for pipette analysis and the fall velocity of

small particles (<0.1 mm diameter). Stokes Law predicts the relationship between particle size and settling velocity through a fluid medium. One assumption of note for this approach is that each particle within the fluid is assumed to be spherical.

The following outlines the methods taken to accomplish the pipette method of determining the weight percent of fines within each debris flow sample. Approximately 125 g of the bulk sample was segregated, weighed, and recorded for the initial wet sieving through a 4 phi sieve. To ensure that the fines do not flocculate, 50 mL of the dispersing agent sodium hexametaphosphate, was added at a concentration of 50 g/L to the dry sample. This was then mixed into a slurry. Once the slurry had been established the mixture was then wet sieved through the 4-phi sieve until the water through the sieve ran clear. The remainder larger than 4 phi was then oven dried for dry sieving. The silt, clay, dispersant, and water mixture was then added to a 1000 ml graduated cylinder and filled to 1000 ml. This mixture was then left in a temperature controlled laboratory room for sufficient time for the water temperature to equilibrate to the room's air temperature of 21°C. The importance of this step and as well as keeping accurate time is critical as pipette analysis is a time and temperature dependent procedure. Once the temperature reached a constant 21°C, pipette withdrawal was ready to begin. First, the mixture within the graduated cylinder was mechanically mixed for five minutes. A digital timer was used to record the subsequent time of pipette withdrawal. For each withdrawal a volume of 25 ml was withdrawn at set time

intervals. These time intervals correspond to the settling velocities of each particle size diameter range (Table 2). Each withdrawal, therefore, represents the remaining particles with diameters smaller than that interval.

Pipette withdrawals were collected in 50ml plastic beakers and oven dried. The remaining dry sample was weighed to the nearest decigram. Each beaker was given a unique identifier and weighed to the nearest decigram. This weight and the weight of the dispersant was then subtracted from the total weight of the combination of sample/beaker/dispersant to achieve the weight of the fine grained sediment.

Table 2. Sedimentation time for pipette withdrawal of fine sediments (Gee and Bauder, 1986).

	Diameter (μm)	Diameter (ϕ)	Withdrawal	Withdrawal Time @ 21°C		
	Less than	Less Than	Depth (cm)	hr	m	s
Silt	62.5	4	20	-	-	20
	31.2	5	10	-	1	51
	15.6	6	10	-	7	25
	7.8	7	10	-	29	41
	3.9	8	5	-	59	23
Clay	1.95	9	5	3	58	0

Grain size statistics were calculated using the statistical procedures described by Folk and Ward (1957). The Mode is defined as the most frequently-occurring particle

diameter by weight. The Median occurs where half of the particles by weight are coarser and half are finer and occurs at the 50% point on the cumulative distribution curve. The Graphic Mean is the center of the distribution and found using three points at 16, 50, and 84 percent coarser on the cumulative frequency curve (Eq. 1). The Graphic Standard Deviation can be used to measure sorting and is defined as a measure of the uniformity of the grain size distribution (Eq. 2). The Inclusive Standard Deviation takes into account 90% of the distribution and for brevity the Inclusive Graphic Standard Deviation is termed the “sorting value” in this study. The Inclusive Graphic Skewness is a measure of the asymmetry of the particle size distribution and includes 90% of the distribution curve (Eq.3). Finally, Graphic Kurtosis is a measure of the peakedness of the particle size distribution curve (Eq. 4). There are three descriptors of Graphic Kurtosis: leptokurtic, mesokurtic, and platykurtic. Leptokurtic occurs when the curve is excessively peaked indicating that the center is better sorted than the tails of the distribution. Mesokurtic describes a normal distribution where the center and tails have more equal sorting. Platykurtic describes a particle size distribution curve where the tails are better sorted than the center of the distribution. Except for the mode, values for the calculations were taken directly from grain size plots using Dplot software.

$$M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \quad (\text{Eq. 1})$$

$$\sigma = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \quad (\text{Eq. 2})$$

$$Sk_I = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)} \quad (\text{Eq. 3})$$

$$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})} \quad (\text{Eq. 4})$$

Chapter 4

Results

A total of seven sites were visited in the Hood River Basin for data and sample collection. For clarity, sites are described here sequentially starting with the Eliot Branch located in the upper Hood River Basin and ending at the confluence with the Columbia River. Locations within the sequence were visited over varying times between June and November 2012. Samples for laboratory sieve analysis were collected from all locations except the initiation zone. Observations were made at each site pertaining to the following: general site description and location, GPS coordinates, photographs, surrounding vegetation, deposition or erosional characteristics, outcrop description, and sediment facies characteristics. Samples were obtained from variable depths of outcrop layers or soil pits depending on the local depositional characteristics.

Initiation Zone

The initiation zone of the 2006 Hood River debris flow event was visited on 9/16/2012. The Eliot Branch basin, located on the northeast flank of Mount Hood, contains the Eliot Glacier, one of five glaciers that discharge into the Hood River Basin (Figure 10). The drainage basin has a total area of approximately 3.3 km² and is primarily composed of unconsolidated ablation till on steep exposed slopes. The Eliot Glacier is an alpine glacier with an area of approximately 1.6 km² (Jackson and Fountain,

2007). Since measurements began in 1901 the glacier has retreated 680m and lost 19% of its area. The ablation zone of the glacier is now largely stagnant ice covered by till and rocky debris (Figure 11). This stagnant ice marks the Little Ice Age maximum (Jackson and Fountain, 2007).

Figure 10. A view looking southwest from Cooper Spur of Mount Hood and the Eliot Glacier. Note the recession of the glacier has exposed the terminal moraine in the foreground. Down valley of this point in the side of an older lateral moraine is the initiation zone for the Hood River debris flow of 2006.

The lahar-flood was initiated in the Eliot Branch of the Hood River basin through two or more landslides from the lateral moraines of the Eliot Glacier between on the morning of November 7th, 2006 (Hood River News, 2006). The slides originated in the sidewalls of the moraines where apparent head scarps were visible (Figure 12). Using GIS, the area of the landslides was estimated to be approximately $16,000 \text{ m}^2$, with a minimum estimated volume of $32,000 \text{ m}^3$. The characteristics of the head scarps were

that of exposed till with saturated spots in the middle of each scarp. These spots are interpreted to reflect melting of interstitial ice buried by morainal material (Piriot, 2010).

Figure 11. Northeast view looking down valley of the Eliot Glacier moraine complex. The location of the western initiation zone is just beyond the extent of the photograph on the left (north) lateral moraine (see Figure 12).

The maximum elevation for the Eliot branch basin is 3,417 m above the headwall of the Eliot Glacier down to a low of 792 m at the confluence with the Middle Fork Hood River. Stranahan Falls, a 60 meter waterfall, separates the Eliot Branch into distinct upper and lower areas (Northwest Waterfall Survey, 2011). The channel gradient between the initiation zone to the first known deposits at the Laurance Lake Road debris field is 142 m/km. Particle size analysis of the initiation zone was determined by

Pirot (2010). Six samples were taken from the lateral moraines for an average of 40.5% gravel, 56.3% sand, and 2.9% fines.

Figure 12. View looking north of the initiation zone for the Hood River debris flow of 2006 located on the lateral moraine of the Eliot Glacier, Mount Hood. The initiation zone for the lahar-flood was determined to be caused by two or more landslides triggered from heavy rains during November of 2006 (Pirot, 2010). Note the visible head scarp surrounding the wet sediment in the middle of the image. The damp soil is believed to be caused by melting of interstitial ice, a relic of the Eliot Glacier before the last century of recession.

Laurance Lake Road Site (6 km from Initiation)

After the landslides initiated in the Eliot Branch, entrainment of debris and erosion by high flow in Eliot Branch commenced. The excavated channel upstream of the Laurance Lake debris field indicates that erosion of the channel bed and sides by the lahar-flood waters occurred for ~6.2 km downstream from the initiation zone to the Laurance Lake Road debris field (Figure 13). The zone of erosion changes to a zone of

deposition where the valley transitions from a constricted and narrow canyon reach to a wide and broad depositional reach (Figure 13, Figure 14). Channel gradient decreases from 142 m/km upstream of the depositional reach to 73 m/km in the debris field. The debris field ends downstream near the confluence with the Middle Fork Hood River, where it ran into the Parkdale Lava Flow. At this point the valley transitions from the broad depositional reach to a narrow canyon as the Middle Fork Hood River flows to the west of the Parkdale Lava Flow. Access to the site was provided by Laurance Lake Road (Forest Road 2840) and was visited on two occasions, June 12 and July 28, 2012. The June 12th samples were taken along a 170 m transit across the large debris field.

The Laurance Lake Road debris field, 2 km long and up to 0.9 km wide (Figure 15, 17), was the primary site of deposition for the lahar. Based on the deposits and debris field characteristics at the site, the flow was primarily a fully developed debris flow when deposition occurred. Deposition was induced by the decrease in channel gradient, by valley widening, and by hydraulic damming due to abrupt channel narrowing caused by the Parkdale Lava Flow. The deposit fills this entire wide valley reach (up to 0.9 km wide), and it buried 0.62 km of Laurance Lake Road (FR 2840) (Figure 16). The deposit surface is characterized by multiple debris-flow lobes that cover a total area of $\sim 0.8 \text{ km}^2$. Each lobe represents a point at which a flow surge reached an impasse and local deposition occurred, forcing succeeding surges to take

other lower-elevation flow paths and eventually causing the entire valley cross-section to be aggraded.

Sediments deposited by the 2006 lahar in the debris field are primarily debris-flow deposits that range between 1 and 3 m in thickness. Post-event incision by Eliot Branch created terraces that reveal the 2006 deposits overlying older debris flow deposits (Figure 18), indicating that this has been a depositional site for previous lahars. Boulders up to 6 m in diameter were moved and deposited by the debris flow (Figure 19). A complete survey of the deposit thickness was not conducted, but unconfined deposition of debris flows on low-gradient fans commonly produces deposits averaging 1 to 2 m thick (Pierson, 1980; Pierson et al., 1990). Assuming that average thickness here is similar, which was supported by observed sample outcrops thicknesses, the debris-flow deposit volume would range between $0.8 \times 10^6 \text{ m}^3$ and $2.4 \times 10^6 \text{ m}^3$.

Flow depth and erosive strength can be inferred from the damage profile on the remaining stands of trees. Mud coatings and stripped bark on the upstream side of trees as high as 3 m above the pre-lahar ground surface were observed (Figure 20). In most cases, greater damage occurred near the base of the trees. Log jams and splintered tree stumps were visible throughout the debris field (Figure 21). Splintered tree stumps relate to the erosive strength and velocity of the debris flow, while log jams mark ends to flow progress and redirection of flow.

Figure 13. A view looking southwest and upstream along the Eliot Branch near where the Laurance Lake Rd crosses the Eliot Branch. The beginning of valley widening seen here marks the transition area between erosion and deposition by the lahar. The north flank of Mount Hood is visible in the distance.

Figure 14. Upper debris field section. The Eliot Branch has incised into older debris-flow deposits having the light yellowish-tan color. View is looking upstream.

Figure 15. View (looking upstream) of large debris field near river mile 24.8 in the Eliot Branch valley. The debris field was determined to be ~0.9 km at its widest point and up to 2 km long with a total area of ~0.8 km².

Figure 16. View of large debris field looking down-valley and northeast near river mile 25.5. Mount Adams is visible in the distance.

Figure 17. View looking east along the regraded portion of Laurance Lake Road 2840 at river mile 24.5. During the 2006 lahar-flood, Road 2840 was buried by debris flow deposits for 0.62 km.

Figure 18. Older debris-flow deposits (light yellowish tan in color) along Eliot Branch channel at river mile 25.

Figure 19. Boulder up to 6 m in diameter deposited by the 2006 debris flow near Laurance Lake Rd.

Figure 20. Tree damage and mud coating up to 3 m above pre-lahar ground surface near Laurance Lake Rd. Damage indicates peak lahar-flood height at this point.

Figure 21. Log jam deposit from the 2006 lahar-flood located near the middle of the 2-km-long debris field.

Deposit Characteristics

The flow that emplaced deposits at the Laurance Lake Road debris field site was identified as a debris flow based on the following characteristics. Samples were taken from three of the five locations visited in the debris field (Figure 22). Deposits are classified as massive diamictons with extremely poor sorting and depositional units as being nonstratified (Figure 23). The exposed units had a friable to slightly firm texture and contained vesicles within the matrix. The average largest boulder size from all sample locations was 0.6 m (intermediate axis).

Deposits on the western edge of the debris field within an incised channel displayed characteristics associated with a transformation between debris flow and

hyperconcentrated streamflow. The outcrop at this location differed from the others in that it possessed lamination, normal grading, and contained lithic sands and fines (Figure 24). Stratigraphically, the hyperconcentrated flow deposit is above the debris flow deposits in this section, which indicates that the transformation to hyperconcentrated streamflow occurred at the tail end of the debris flow.

Samples having the field characteristics of debris flows contained on average 69.7% by weight gravel, 22.1% by weight sand, and 7.8% by weight silt and clay. The hyperconcentrated streamflow samples contained on average 26.0% by weight gravel, 66.8% by weight sand, and 6.9% by weight silt and clay (Table 3). For both flow types the percentage of clay alone was negligible at less than 1% by weight.

The field identified hyperconcentrated streamflow deposit has a mode of -3ϕ , a median of 0.7ϕ , a graphic mean of 0.6ϕ , with a sorting value of 2.4ϕ which is indicative of very poor sorting (Boggs, 1987). The skewness is nearly symmetrical at 0, while the sample is mesokurtic with a kurtosis value of 0.9 (Table 4).

Table 3. Eliot Branch deposits. Particle size fraction of gravel, sand, and silt/clay in weight percent. Note: no standard deviation for the hyperconcentrated sample since the percentages are from one sample.

	% Gravel	% Sand	% Silt/Clay
Debris Flow	69.7	22.1	7.8
Debris Flow (Standard Deviation)	5.9	4.1	3.2
Hyperconcentrated Flow	26.0	66.8	6.9

Figure 22. Laurance Lake Road Site (6 km downstream of initiation) (Oregon Spatial Data Library).

Figure 23. Laurance Lake Road debris flow deposit stratigraphic section.

Figure 24. Laurance Lake Road stratigraphic section showing transformation from debris flow to hyperconcentrated flow.

Table 4. Statistical Parameters for samples in the Eliot Branch debris field located along the Laurance Lake Road (values in ϕ).

	Mode	Median	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis
Debris Flow Average	-5	-4.5	-2.5	3.3	0.9	0.8
Hyperconcentrated streamflow	-3	0.7	0.6	2.4	0.0	0.9

Figure 25. Particle size distribution of the lahar-flood deposits from the Eliot Branch debris field near Laurance Lake Road.

Between the two flow types a distinctive shift in grain size and sorting can be seen. The average of the debris flow samples have a mean grain size of -2.5ϕ , a mode of -5ϕ , a median of -4.5ϕ , and a sorting value of 3.3ϕ which indicates very poor sorting. The data are nearly symmetrical with a skewness of 0.9 and is platykurtic with a kurtosis of 0.8.

Flow Interpretation

Shortly after initiation of the lahar by the landslides in the initiation zone, a debris flow eroded the upper 6.2 km of the Eliot Branch above the debris field near Laurance Lake Road. The debris flow entered the low-gradient valley in the previous

stream channel and began depositing the entrained sediment. Deposition within the active channel obstructed flow, causing the lahar to avulse and follow a new path of least resistance to flow. This process repeated itself throughout the debris field many times as multiple lobe deposits were observed. Log jams and large boulder deposits contributed to the depositional sequence. Numerous log jams in the area indicate an impasse to flow, including a large log jam near the downstream side of the debris field near the Parkdale Lava Flow. The combination of relatively low gradient, downstream constriction near the lava flow and log jams contributed to the forced deposition of the debris flow. The flow through this section was dominated by debris flow. However, deposits of hyperconcentrated flow on the flow margins indicates a flow transformation was taking place at the tail of the debris flow. Sorting of these deposits was poorer (2.4ϕ) than is typical for normal streamflow; and faint horizontal lamination indicates that the deposit was not emplaced by debris flow (Smith, 1986). The normal grading of the deposit indicates that the energy of the hyperconcentrated flow was most likely dissipating at the tail of the lahar as it was transitioning into a less dense flow.

Red Hill Road Site (16 km from initiation)

Downstream of the Eliot Branch debris flow deposits is the Red Hill Road Bridge which crosses the Middle Fork Hood River at river mile 19.3 (Figure 26). At this location flood deposits have become recolonized by 2012 with red alder and a few small firs.

Figure 26. Red Hill Road site 16 km from initiation

Woody debris was abundant at the surface, but the Middle Fork Hood River has reworked the entire section leaving little unadulterated from the initial flood. During the flood, the Red Hill Road bridge was destroyed. The original section, a 18 m steel structure, has since been replaced by a 96 m concrete span that is designed to handle large flood events (Hood River News, 2011). The replacement was finished in June of 2011 at the expense of \$1.3 million (Figure 27).

Figure 27. 16 km from initiation at Red Hill Road bridge. The bridge was completed on June 1, 2011 and replaced a 18 m steel bridge that was destroyed by the flood of 2006.

Samples were taken from the east side of the Middle Fork Hood River and consisted of debris flow slurry that was deposited outside of the main levies. At this

site, newer flood deposited sands were found stratigraphically above older more consolidated sands. The older more consolidated sand was sampled and interpreted to be from the 2006 flood. Below the lahar-flood deposit of 2006, the contact with the previous surface was observed and found to contain organics, darker colors, and woody debris (Figure 28).

Figure 28. Stratigraphic section for debris flow deposits at the Red Hill Road site.

Deposits at the Red Hill Road site contained evidence for both debris flow and hyperconcentrated flow. The debris flow deposits were characterized as having clay coatings on rounded gravels indicative of escaping pore water. The consistence was very firm and consolidated and was interpreted as being composed of flow-entrained stream bed material due to the roundness of the grains. Hyperconcentrated flow deposits in this area contain sub-rounded coarse sand with fines. They can be characterized as being loose, friable, with normal grading, and containing large amounts of woody debris (Figure 29).

Figure 29. Stratigraphic section of hyperconcentrated flow deposits at the Red Hill Road site.

Deposit Characteristics

The majority of this area has been reworked by the Middle Fork Hood River since the 2006 flood. The main channel of the river sits at a higher elevation than the side channel to the east. A lobe of hyperconcentrated flood deposits is blocking the current stream flow from entering the lower elevation channel. Of the four samples taken from this location, two were field identified as debris flow deposits and two as hyperconcentrated streamflow deposits. The particle size distribution verifies field identification. Distribution curves can be seen shifted to the right with greater sorting and less fines present (Figure 30).

The debris flow samples contained 61.3% by weight gravel, 33.6% by weight sand, and 4.7% by weight silt and clay. The hyperconcentrated streamflow contained 4.6% by weight gravel, 86.2% by weight sand, and 8.8% by weight silt and clay (Table 3). For both flow types the percentage of clay alone was negligible at less than 1% by weight.

Grain size statistics for the debris flow samples taken at Red Hill Road Bridge indicate that the highly concentrated phase of the lahar-flood was more finely grained here than at the upstream Laurance Lake Road site. The sieve results contained the following range of values: a mode of -4ϕ and -5ϕ , graphic median of -1.0ϕ and -4.1ϕ , and a graphic mean of -1.0ϕ and -2.5ϕ . The samples are very poorly sorted with a

Figure 30. Particle size distribution from deposits located near Red Hill Road Bridge.

Table 5. Red Hill Road bridge particle size fraction of gravel, sand, and silt/clay in weight percent.

	% Gravel	% Sand	% Silt/Clay
Debris flow Average	61.3	33.6	4.7
Debris Flow STD	16.5	18.2	1.5
Hyperconcentrated Average	4.6	86.2	8.8
Hyperconcentrated STD	2.8	3.5	0.3

sorting value of 2.7ϕ . Sample (120625-6A) has a graphic skewness value of 0.1, which indicates positive skewness. The distribution is very platykurtic with a kurtosis value of 0.6. This contrasts with the other debris flow sample (120625-6B), which has a strong coarsely skewed distribution with a skewness of 0.8 and a mesokurtic distribution of 0.9 (Table 6).

Of the two hyperconcentrated samples taken, sample 120625-7 has a mode of 2ϕ , a graphic median of 1.6ϕ , and a graphic mean of 1.8ϕ . Whereas, sample 120625-8 has a mode of 1ϕ , a graphic median of 1.1ϕ , and a graphic mean of 1.3ϕ . Both samples are very poorly sorted with graphic standard deviations of 1.6ϕ and 1.8ϕ , respectively. The samples are positively skewed towards coarse distributions with values of 0.1 and 0.2. Kurtosis values are 1.0 which indicates mesokurtic distributions.

Table 6. Statistical parameters for samples near Red Hill Road bridge. DF = debris flow, HF = hyperconcentrated streamflow

Sample	Mode	Median	Graphic Mean	Inclusive Graphic	Inclusive Graphic Skewness	Graphic Kurtosis
				Standard Deviation (sorting)		
DF 120625-6A	-4	-1.0	-1.0	2.7	0.1	0.6
DF 120625-6B	-5	-4.1	-2.5	3.1	0.8	0.9
HS 120625-7	2	1.6	1.8	1.6	0.1	1.0
HS 120625-8	1	1.1	1.3	1.8	0.2	1.0

Flow Interpretation

Downstream of the Laurance Lake Road the lahar-flood was hemmed into the channel by the steep stream bank to the west and the Parkdale lava flow to the east.

Little deposition would have been likely in this stretch. The majority of the deposition would have occurred north of this point, where the valley begins to open up again. The flow types observed at this location are debris flow and, most likely, hyperconcentrated flow, similar to the Laurance Lake Road debris field. The debris flow is beginning to show a decrease in average grain size from -2.5ϕ to -1.0ϕ . Sorting values have improved from upstream, but overall the flow is still very poorly sorted. Graphic skewness in the debris flow deposits has dropped from being very positively skewed to positively skewed, which indicates a decrease in fines. Evidence for hyperconcentrated flow deposits at this location includes better sorting compared to similarly placed debris flow deposits but less than typical streamflow deposits ($1.6-1.8\phi$), firm consolidated sands with little observable lamination and no cross-bedding, and an overall massive appearance (Pierson and Scott, 1985).

Average grain size for the hyperconcentrated flow has decreased from 0.6ϕ to a maximum of 1.8ϕ . Sorting values have improved from being very poorly sorted upstream to poorly sorted at the Red Hill bridge. Graphic skewness for the hyperconcentrated flow changes from being nearly symmetrical upstream to positively skewed, indicating a shift to more fines being present.

Based on the depositional record, the lahar-flood front is a debris flow with a transformation to hyperconcentrated flow towards the tail end of the flow. The volume of the debris flow deposits has decreased from the Laurance Lake Road site.

The gravel fraction dropped from the highest observed fraction of 69.7% by weight at Laurance Lake Road to 61.3% by weight. A drop in fines was observed, as well, from 7.8% to 4.7% by weight. The shift between the two depositional areas is seen in the sand fraction which has increased from 22.1% to 33.6% by weight. This shift coincides with an increase in observed hyperconcentrated flow deposits as sediment is dropping out of suspension; and water from the river channel dilutes the flow. The change in flow types occurs from a combination of energy dissipation by the gradient change and the addition of water from tributaries and the river channel. The basin broadens north of the lava flow allowing flows to spread out and velocity to decrease. Up to six tributaries enter the Middle Fork Hood River between Laurance Lake Road and the Red Hill Road Bridge: Squeegee Creek, Boomer Creek, Bear Creek, Little Creek, and two unnamed creeks. The addition of these water sources and the water from the river channel would dilute the lahar and inhibit the grain support mechanisms, allowing increasingly larger diameter grain sizes to drop out of suspension (Iverson et al., 1997).

East Fork Hood River Site Upriver of Dee Lumber Mill (24 km from initiation)

Flood deposits were found and sampled 5 km downriver of Red Hill Road and approximately 1 km upstream of the Dee Lumber Mill (Figure 31). At this site the East Fork Hood River widens on the west side and a flood plain emerges marked by a raised

Figure 31. Dee Lumber Mill Sample Site (24 km from initiation). Dee Lumber Mill is located just north of the map's extent.

river terrace (Figure 32). Evidence that the lahar-flood still had a debris flow component at this site was found in the form of small willow trees sheared off at the level of the channel bed when peak flow arrived (Figure 32) and mud coatings and sediment plugs left on and between tree trunks (Pierson, 2005b) (Figure 33). The limited re-colonization by the flora on the river bench and similarities in elevation as the splintered trees were indications that this bench was deposited during the 2006 lahar. A total of 27 samples from two outcrops were taken for sieve analysis.

Figure 32. View looking west approximately 24 km from the initiation zone in Eliot Branch. Evidence of debris flow activity includes splintered trees and mud coatings between trunks, indicating that these trees had been buried in sediment up to the shear-off level prior to abrasion and removal of the trees. The height of the stumps is approximately 2.3 m above the post-flood main channel of the East Fork Hood River, which is approximately equal to the top of the outcrop shown in Figure 34.

Figure 33. Somewhat cohesive mud caked between splintered trees indicates that debris flow was involved in the deposition that partially buried the trees .

Deposit Characteristics

Outcrop 1 was deposited approximately 2.33 m above the low water level in the channel measured on June 26, 2012. Distinct stratigraphic layers were present in the outcrop with grain sizes ranging from gravel to clay. Sand, however, comprised the bulk of the deposition (Figure 34). Dark brown fine to medium sand is present at the base. This progresses to medium brown to gray, fine to medium sand that lacks bedding. The thickest deposit is in the middle of the outcrop and is composed of fine to very coarse sand with poorly sorted gravel clasts up to 3 cm. Above this layer there is a transition to a normally graded, well-sorted fine to medium sand with coarse laminations. Finally,

the top of the outcrop has slight lamination, is poorly-sorted with fine to very coarse sand, and is inversely graded (Figure 35).

Particle size diameters vary with vertical position in the outcrop and correspond with the observable layers (Figure 36). The greatest variation can be observed through the distribution of the mode in the samples. Particle sizes range at the base of the outcrop from 2ϕ to a maximum grain size of -1ϕ near the middle of the outcrop. The trend then reverses towards the top of the outcrop with a grain size of 3ϕ . From the graphic mean, the grain size is medium grained to coarse grained at the base and middle of the outcrop with a transition to fine grained at the top (Figure 36).

Particle size sorting varies with depth and generally follows an inverse of the trend seen in particle size diameter. The poorly sorted base of the outcrop transitions into a very poorly sorted middle section with sorting values of 1.4ϕ and 2.2ϕ , respectively. The trend reverses and becomes poorly sorted with some subtle variations back and forth towards the top with a sorting value of 1.4ϕ (Figure 37).

The results of the sieve analysis are shown based on vertical position in the outcrop (Table 7). The weight percent fraction of the samples reiterates the pattern of particle size discussed previously. The bottom of outcrop 1 is predominately sand with no gravel. The middle of the outcrop shows normal grading with a weight percent change for the gravel fraction from 36.0% to 6.2%. A fining up occurs above the middle section with one gravel rich layer present near the top of the outcrop.

Figure 34. Dee Outcrop 1 vertical section of the sediments deposited by the 2006 lahar. Section thickness is 1.23 m from top of terrace to contact with pre-flood surface (red line).

Figure 35. Dee Lumber Mill outcrop 1. Diagram of laharc-flood deposits (Figure 34). Samples were taken from each identifiable layer. The overall trend is a coarsening of the middle of the deposits followed by a fining upwards to the top of the river bench.

Figure 36. Dee Lumber Mill outcrop 1 particle size variations with depth. The mode, median, and graphic mean follow similar patterns within the outcrop. Lines between points are given to infer an overall trend but are not indicative of a relationship between points. Depth to major unit boundaries are shown (light gray); (see Figure 35 for comparison).

The second outcrop is located on the west side of the East Fork Hood River, approximately 100m downstream of the first outcrop and sits ~3.4 m above the water level measured on June 26, 2012. The outcrop resides in a minor channel approximately 70 m from the middle of the main channel of East Fork Hood River. Notable secondary sedimentary depositional features of outcrop 2 include flame structures, dish structures, and sand blows (Figure 38, Figure 39, Figure 40). The base of the outcrop is composed

Figure 37. Dee Lumber Mill outcrop 1 sorting statistics. Note that the kurtosis and graphic skewness are not in ϕ units, but are shown for comparison to the inclusive graphic standard deviation. Lines between points are given to infer an overall trend but are not indicative of a relationship between points. Depth to major unit boundaries are shown (light gray); (see Figure 35 for comparison).

of bedded layers of light gray to light brown, well sorted, fine to coarse sand from 137 cm to 277 cm. This transitions into a medium brown diamicton that is poorly sorted and contains coarse to very coarse sand up to 89 cm below the ground surface. Convolute bedded layers of light brown to light gray, friable, fine to coarse sand blends into subtly bedded layers of coarse to very coarse sand that again becomes convolute bedding up to 76 cm. Between 71 cm and 41 cm below ground surface, soft sediment

Table 7. Dee lumber mill, Outcrop 1 particle size fraction of gravel, sand, and silt/clay in weight percent.

Sample	Depth (cm)	% Gravel	% Sand	% Silt/Clay
120626-1L	2	0.5	89.4	6.8
120626-1K	10	12.3	82.2	5.1
120626-1J	15	9.2	83.8	6.7
120626-1I	22	0.7	92.2	6.9
120626-1H	28	0.5	92.7	6.2
120626-1G	32	0	89.0	9.4
120626-1F	34	0	95.6	3.9
120626-1E	37	6.2	91.0	2.8
120626-1D	52	20.0	74.0	5.4
120626-1C	82	36.0	55.9	7.4
120626-1B	101	0	91.2	8.1
120626-1A	110	0	90.8	4.6

Figure 38. Dee Lumber Mill outcrop 2. Flame structures, up to 10 cm high, visible in lower center of image. Overhang of the upper unit is defined by a contact, with the upper unit being slightly more cohesive than the unit below.

deformation features occur in two separate sections. The first contains light gray to medium brown coarse to very coarse sand with no bedding, is slightly firm, and is poorly sorted. This contrasts with the above section of fine to medium sand that is well sorted, light brown to light gray, and friable. Extending above to 23 cm below ground surface, soft sediment deformation occurs in the form of dish structures, but the depositional layering is still present with faintly bedded layers of light gray to light brown medium to very coarse sand with moderate sorting (Figure 41).

Figure 39. Dee Lumber Mill outcrop 2 Sample Site. Additional image of flame structures present in the 2006 flood deposits. Close up view of Figure 38.

Figure 40. Dee Lumber Mill outcrop 2. Cross-section of sand blow, where undrained loading of saturated sand at the bottom of the photo caused a water-sand mixture to be expelled upward through the overlying units.

Figure 41. Dee Lumber Mill outcrop 2. Diagram of flood deposits (Figure 34). Samples were taken from each identifiable layer. The overall trend is a coarsening up in the middle of the deposits followed by a fining upwards to the top of the river bench. Sand blows, flame structures, and dish structures are found in the upper portion of the outcrop.

Particle size diameters vary with depth and correspond with the observable layers (Figure 42). The greatest variation can be observed through the distribution of the sample mode. The mode of the particle sizes ranges at the base of the outcrop from 3ϕ to a maximum grain size of 0ϕ near the middle of the outcrop. The trend then reverses towards the top of the outcrop to a maximum mode of 4ϕ . From the graphic mean, grain size is very fine grained at the base to medium grained near the middle of the outcrop with a transition to very fine grained at the top (Figure 36).

Figure 42. Dee Lumber Mill outcrop 2 particle size variations with depth. The mode, median, and graphic mean follow similar patterns within the outcrop. Lines between points are given to infer an overall trend but are not indicative of a relationship. Depth to major unit boundaries are shown (light gray), see (Figure 41) for comparison.

Particle size sorting varies with depth and generally follows an inverse of the trend seen in particle size diameter. Overall, the sediment in the outcrop is poorly sorted. Sorting values range from 1.0ϕ to 1.8ϕ . The bottom and top of the outcrop show better sorting relative to the more poorly sorted middle section (Figure 43).

Figure 43. Dee Lumber Mill outcrop 2 sorting statistics as a variance with depth within the outcrop. Note that the kurtosis and inclusive graphic skewness are not in ϕ units but are shown for comparison to the graphic standard deviation. Lines between points are given to infer an overall trend but are not indicative of a relationship between points. Depth to major unit boundaries are shown (light gray); (see Figure 41 for comparison).

The results of the sieve analysis are shown based on depth in the outcrop (Table 8). The weight percent fraction of the samples reiterates the pattern of particle size discussed previously and has a similar pattern as outcrop 1. The bottom of outcrop 2 is predominately sand with no gravel and up to 16.2% by weight silt and clay. The middle of the outcrop shows normal grading with a weight percent change for the gravel fraction moving upward in the deposit from 10.2% to 2.1%. From there, a fining upwards occurs above the middle section. In contrast to outcrop 1, no gravel section appears towards the top of outcrop 2. The top of the Outcrop 2 contains the largest fraction of fines present at 18.5% by weight.

Table 8. Dee lumber mill, Outcrop 2 particle size fraction of gravel, sand, and silt/clay in weight percent.

Sample	Depth (cm)	% Gravel	% Sand	% Silt/Clay
120626-2O	2	0	88.2	7.8
120626-2N	4	0	77.8	18.5
120626-2M	14	0	92.8	6.1
120626-2L	30	1.0	92.3	6.1
120626-2K	45	0	89.5	10.4
120626-2J	57	3.2	89.7	6.8
120626-2I	67	0	91.3	6.1
120626-2H	72	0	93.9	2.9
120626-2G	79	0	91.0	8.9
120626-2F	97	2.1	90.1	7.1
120626-2E	112	8.7	83.9	6.8
120626-2D	127	10.2	84.0	5.3
120626-2C	170	0	91.7	4.1
120626-2B	210	0	93.6	3.2
120626-2A	250	0	80.4	16.2

Flow Interpretation

Between the Red Hill Road site and the confluence with the East Fork Hood River the lahar-flood would have continued to deposit its sediment and continue a gradual flow transformation. With the influx of water from the East Fork Hood River, a rapid transformation from debris flow to hyperconcentrated flow began to occur. The depositional sequence 24 km from the initiation zone records a passage of the flood wave over time as sediment is deposited at the bed progressively during bed aggradation. The deposits of the Eliot Branch lahar-flood at this point are at the highest levels relative to the simultaneous Hood River flood event. This is an indication that the lahar had the largest peak discharge compared to that of the flood. The two observed outcrops show variations laterally in the flow. Subtle variations between outcrops are indicative of a dynamic flow where different flow types move in different parts of the flow cross-section. Water influx from the East Fork Hood River would have caused the lahar-flood flow front to transform from debris flow into hyperconcentrated flow, which is what is observed in the two outcrops at the Dee Lumber Mill site.

Outcrop 1 recorded the entire spectrum of flow transformations from water flood to hyperconcentrated flow to debris flow and back as the lahar moved through this area during the high discharge flood event. The boundary with the preexisting terrace surface is located at 123 cm. Between 115 cm to 123 cm the pre-lahar flood deposited the layer of fine, well sorted sand. Between 106 cm to 115 cm the deposits

become poorly sorted (1.3ϕ) and massive in appearance. These sands contain no bedding but lack the sorting to imply debris flow. These layers most likely represent the initial deposits by the lahar in the form of hyperconcentrated flow. Between 44 cm to 106 cm the deposits appear massive and become very poorly sorted with sorting values up to 2.2ϕ . Although this value is below the typical sorting value for debris flow deposits, the presence of muddy deposits found between the sheared off trees (Figure 33) indicates that these deposits are most likely debris flow. Above the debris flow deposits, a layer of well sorted, normally graded sand with zones of coarse laminated sand is found between ~39 cm to 44 cm. These are most likely deposited by the high intensity water flood and are not distinctly deposited from the lahar. Above the water flood deposits, a diamicton of poorly sorted fine to very coarse sand with inverse grading and slight lamination was deposited between 3 cm to 39 cm. Sorting values between 1.6 to 1.7ϕ and the presence of the subtle lamination suggest that these deposits are from hyperconcentrated flow. The top 3 cm of the section consists of a layer of loose unconsolidated well sorted sand of fluvial origin that indicates the lahar has passed through the area.

Although Outcrop 2 is only ~100 m away from Outcrop 1 the deposits vary. These variations reflect the differences that can occur in lahar deposits within close proximity to one another. Deposits can be laid down with non-uniformity as flow characteristics adapt to the differences in stream channel morphology. No boundary

with the previous terrace surface was revealed. Between 137 cm to 277 cm the poorly sorted sands with layers of fine to coarse sand (1-5 cm) indicate that they were deposited by hyperconcentrated flow. Above this layer, between 89 cm to 137 cm sorting deteriorates to 1.8ϕ , lamination disappears and the layers appear massive. This is most likely close to a transformation to debris flow, but due to the lower sorting values ($<2.5\phi$) the flow is attributed to hyperconcentrated flow. Above this, hyperconcentrated flow continues to dominate the outcrop to the ground surface. Within this section there appears to be three depositional units. Between 71 cm to 89 cm the poor sorting and convolute bedding reflect hyperconcentrated flow that has undergone soft sediment deformation. This was most likely a result of the above unit between 57 cm to 71 cm. In this layer bedding disappears but the deposit remains poorly sorted, again, reflecting hyperconcentrated flow. Flame structures are present and are a result of the weight of the rapid deposition of the above layer between 7 cm and 41 cm. Poor sorting, faint bedding, and the presence of dish structures are the result of hyperconcentrated flow that has deposited these layers in several different pulses of deposition. Above this layer, between 0 to 7 cm, sorting remains poor and faint bedding fades to a more massive appearance.

From the Red Hill Road site to the Dee Lumber Mill site sorting has improved throughout the observed deposits. The base of the outcrop has changed from being very poorly sorted to being poorly sorted. This combined with the subtle bedding and

friable texture indicates that the flow front is now a hyperconcentrated flow. The middle of the outcrop coarsens and becomes very poorly sorted. The massive appearance with subtle normal grading towards the top are signs that the middle of the flow was still a debris flow through this section. Near the tail of the flow a transformation back to hyperconcentrated flow occurs which is based on improved sorting, a decrease in mean grain size, bedding, and a friable texture. Deposits at the top of the outcrop suggest that the tail of the lahar-flood has transformed into a water flood. Deposits consist of loose, friable, moderately sorted sand.

Soft sediment deformation features (flame structures, dish structures, and convolute bedding) indicate excess pore-fluid pressure was high at the time of deposition. Pore-fluid pressure diminishes the frictional strength of sedimentary deposits causing them to liquefy and form soft sediment deformation features (Collinson and Thompson, 1989). The downward flux of buoyant sediment from layers above those with high pore-fluid pressure created the soft sediment deformation features and in itself indicates a transformation in flow types (Major, 2000).

East Fork and West Fork Hood River Confluence Site (28 km from initiation)

The confluence of the East Fork Hood River and the West Fork Hood River was visited on July 7, 2012 and September 27, 2012 (Figure 44). At this location the environment is not as conducive to deposition as previous sites. As the rivers come

together, they enter a constricted ravine that acts to increase river velocity and limits bank deposits (Figure 45). Suitable sites of deposition were found along the western bank of the main body of the Hood River just downstream of the confluence.

Figure 44. Confluence of East Fork and West Fork Hood Rivers (28 km from initiation). Sample site is on west bank of Hood River downstream of confluence.

Deposit Characteristics

Deposits from the 2006 lahar-flood were found along the western bank of the Hood River just downstream of the confluence (Figure 46). Each layer is approximately 11 cm in depth. The lower layer is in contact with the old surface and contains larger clasts than the top layer, with the largest measuring 26cm (a) x 18cm (b) x 8cm (c) along the particle axes. The lower layer consists primarily of sand and gravel with few fines present. The top layer is primarily composed of sand with horizontal laminations (Figure 47). A sample was taken from each layer for sieve analysis.

Figure 45. Confluence of the East Fork and West Fork Hood River. View looking south and upriver. The East Fork can be seen as the white water in the left-center of the photograph, while the West Fork is visible in front of the large gravel bar in the right of the photograph.

Figure 46. Outcrop of deposit from the 2006 at the confluence of the East Fork and West Fork Hood Rivers. Unit boundaries between flood deposits (yellow) with previous surface (Red).

Figure 47. Stratigraphic cross-section of deposits at the confluence of the East Fork and West Fork Hood Rivers

Particle size distributions reflect a consistent shift in characteristics between the bottom and top layers (Figure 48). From the bottom of the outcrop to the top, the mode changes from 0ϕ to 2ϕ . The graphic median shifts from -0.8ϕ to 1.1ϕ . The graphic mean shifts from -1.4ϕ to 1.1ϕ . This shift correlates with the graphic standard deviations, which change from 1.8ϕ to 0.8ϕ . Skewness values indicate a coarse-tailed distribution at the base of outcrop downstream of the confluence. This shifts back to a nearly symmetrical grain size distribution at the top. Kurtosis values range from 0.8 to

0.9, indicating a shift from platykurtic to mesokurtic distributions as deposits become progressively more sorted (Table 9).

Figure 48. Particle size distribution of deposits at the confluence of the East Fork Hood River and West Fork Hood River. Samples 120927-1A (upper layer) and 120927-1B (lower layer) were taken from the outcrop on the west side of the Hood River just downstream from the confluence.

The results of the sieve analysis are displayed in order of deposition (Table 10).

The lower layer in the outcrop on the Hood River downstream of the confluence has a gravel fraction of 44.1% by weight, a sand fraction of 24.6% by weight, and a silt and

Table 9. Grain-size statistics for samples from the confluence of the East Fork and West Fork Hood Rivers. Samples 120927-1A (upper layer) and 120927-1B (lower layer) were taken from the outcrop on the west side of the Hood River just downstream from the confluence (values in ϕ).

Sample	Mode	Median	Graphic Mean	Inclusive Graphic Standard Deviation (sorting)	Inclusive Graphic Skewness	Graphic Kurtosis
120927-1B	0	-0.8	-1.4	1.8	-0.4	0.8
120927-1A	2	1.1	1.1	0.8	0.0	0.9

clay fraction of 0.1% by weight. The upper layer of the outcrop is primarily sand at 99.2% by weight. No gravel is present in the sample and a negligible percentage of fines.

Table 10. Middle Fork Hood River and West Fork Hood River confluence particle size fraction of gravel, sand, and silt/clay in weight percent.

Sample	% Gravel	% Sand	% Silt/clay
120927-1B	44.1	55.7	0.1
120927-1A	0	99.2	0

Flow Interpretation

When the lahar-flood traveling down the East Fork Hood River converged with the West Fork Hood River; the influx of water created an immediate flow transformation. The lahar-flood that was composed of hyperconcentrated and debris flows is being transformed into a water flood at this point. Sorting has improved from the upstream Dee Lumber Mill site and is now poorly sorted to moderately sorted. The

textures of the deposits are loose. The fines have dropped out of the deposit, and the matrix is now entirely composed of sand. Based on the higher sorting values (1.8ϕ) of the lower unit at this site it is possible that the deposit was laid down by hyperconcentrated flow. Additionally, the lower unit appeared massive with little to no bedding. Between 0 to ~11 cm the deposit was moderately sorted (0.8ϕ) and contained extensive horizontal lamination. The sorting in the upper layer has improved out of the range typical of hyperconcentrated flow and into that of water flood flow. The thickening of the upper most fluvial layer at this point when compared to the thicknesses upstream at the Dee Lumber Mill site indicates that the lahar has lost much of its energy, and a total transformation to water flood is occurring. Both units at this location were very loose. This suggests that there were less fines binding the sand grains together which could indicate that an entirely fluvial source of deposition occurred at this location.

Mount Hood Railroad Bridge (46 km from initiation)

Upstream of the Hood River Railroad bridge at river mile 1.2, assumed-to-be peak-flow deposits from the lahar-flood were found on a longitudinal mid-channel bar (Figure 49). The top surface of the sand bar is approximately 3.2 m above the thalweg channel bed and east of the main Hood River channel.

A sample pit was dug on June 27, 2012 into the bar surface that exposed the entirety of the 2006 lahar-flood deposits down to the previous surface (Figure 50). The total pit depth was 1.2 m. There were three visually identifiable layers. Samples were collected at intervals and sieved for analysis.

Deposit Characteristics

The upper and lower layers were separated by a lens of light brown fine sand ~3 cm thick (Figure 51). Throughout the outcrop, the color ranged from light gray to light brown; and the consistency was friable to slightly firm. The upper sand deposit was composed of fine to medium coarse sand, was bedded, with some cross-bedding, and was well sorted. The lower layer was nearly identical to the upper layer but had less visible bedding.

The results of the grain size statistics are displayed as function of depth (Figure 52). The lower layer had a graphic mean and median of 1.9ϕ . The middle layer which contained the lens of light brown fine sand, contained a greater amount of fines and had a graphic mean and median of 3.3ϕ . The top layer of the soil pit had a graphic mean between 1.8ϕ and 2.3ϕ and a median between 1.7ϕ and 2.4ϕ .

Figure 49. Sample sites near the Mount Hood Railroad bridge (~46 km from initiation).

Figure 50. Soil pit located at river mile 1.2 on a mid-channel bar east of the Hood River's main channel. Upper most layer visible in photograph.

The sample pit ranged from being moderately sorted to poorly sorted. The lower layer is moderately sorted near the bottom to poorly sorted at the top with sorting values of 0.9ϕ to 1.0ϕ . The middle layer is poorly sorted with a sorting value of 1.0ϕ . The upper layer is moderately sorted with a sorting value of 0.8ϕ .

The results of the sieve analysis are displayed as a function of depth for the outcrop upstream of the railroad bridge (Table 11). There is no gravel fraction in the outcrop. The samples are almost entirely composed of sand except for a finer layer in the middle of the outcrop, which has a silt fraction of 18.5% by weight.

Figure 51. Stratigraphic cross-section of the site upstream of the Mount Hood Railroad bridge at river mile 1.2

Figure 52. Particle size distribution of the gravel bar located upstream of the Mount Hood Railroad at river mile 1.2. Depth to major unit boundaries are shown (light gray); (see Figure 51 and Figure 41 for comparison).

Table 11. Site upstream of the Mt Hood Railroad bridge at river mile 1.2. Particle size fraction of gravel, sand, and silt in weight percent.

Sample	Depth (cm)	% Sand	% Silt
120627-1G	15	96.1	3.7
120627-1F	40	96.2	2.6
120627-1E	65	97.3	2.4
120627-1D	70	80.0	18.5
120627-1C	75	91.6	8.5
120627-1B	90	97.1	2.6
120627-1A	115	97.4	2.1

Mount Hood Railroad Bridge (river mile 0.8)

Downstream of the Hood River Railroad bridge at river mile 0.8, deposits from the lahar-flood were found on a point bar along the west bank of the Hood River (Figure 49). The point bar reached up to 3.5 m above the water level measured on June 27, 2012 (Figure 53, Figure 54). Sheared off trunks of trees were found at the same height as the deposit tops (Figure 55) and, also, within the deposits buried to a depth of 1.7 m (Figure 56). Two outcrops were observed, and samples were taken at distinct transitions. Both outcrops are located along the same point bar. Outcrop 1 is located upstream of Outcrop 2 by approximately 200 m.

Figure 53. 2006 lahar-flood deposits near river mile 0.8 (Outcrop 1). Thickness of deposit was 3.5 m and contained bedding.

Figure 54. 2006 lahar-flood deposit at river mile 0.8 (Outcrop 2). Deposit thickness is 3.5m. Note the extensive lamination with some areas of cross bedding.

Figure 55. 2006 lahar-flood deposit at river mile 0.8. Sheared off tree stumps are approximately the same height as the top of the sand deposit.

Figure 56. 2006 lahar-flood deposit at river mile 0.8. Sheared off tree stumps were found buried within the flood deposit.

Deposit Characteristics

Outcrop 1 is 2.7 m thick, and it is approximately 3.1 m to the top of the outcrop from the water line (measured on June 27, 2012, Figure 57). The base layer is between

212 cm and 270 cm below ground surface and is slightly bedded, dark gray to brown very coarse sand with medium pebble float. The middle section is between 28 cm and 212 cm below ground surface and consists of light gray to light brown, finely bedded, fine to medium sand which transitions from being well sorted to moderately sorted. The upper layer is 28 cm thick and consists of dark gray to brown, poorly sorted, coarse to very coarse sand with extensive cross bedding.

The particle size distributions for outcrop 1 indicate that the base is comparatively coarser than the middle which then transitions into coarser layers up to the ground surface. The graphic mean over this depth ranges from 1.9ϕ at the base to a minimum grain size of 3.3ϕ in the middle to the coarsest grain size of 0.6ϕ at the top (Figure 58). Sorting statistics are relatively consistent over this range. Sorting values range from 0.8ϕ to 1.1ϕ . Skewness values range from 0.0 to 0.2. Kurtosis ranges from 1.0 to 1.3.

The results of the sieve analysis are displayed as a function of depth for the outcrop 1 downstream of the railroad bridge (Table 12). Although the outcrop is predominately composed of sand, there is some gravel fraction in the lowest and upper most layers sampled at 3.0% and 16.1 % by weight, respectively. As was seen upstream of the railroad bridge there are some fines present in the middle of the outcrop with a high of 10.1% by weight.

Figure 57. Stratigraphic cross-section of outcrop 1 downstream of the Mount Hood Railroad Bridge at river mile 0.8.

Figure 58. Particle size distribution of outcrop 1 downstream of the Mount Hood Railroad bridge at river mile 0.8. Note: graphic median is not shown because it mirrors the graphic mean. Depth to major unit boundaries are shown (light gray), see (Figure 57) for comparison.

Table 12. Particle size distribution for outcrop 1, downstream of Mt Hood Railroad bridge near river mile 0.8. Particle size fraction of gravel, sand, and silt in weight percent.

Sample	Depth (cm)	% Gravel	% Sand	% Silt
120627-3F	20	16.1	83.9	0
120627-3E	48	0	96.1	3.7
120627-3D	113	0	98.7	1.0
120627-3C	153	0	89.1	10.1
120627-3B	193	0	94.4	5.3
120627-3A	251	3.0	96.5	0

Outcrop 2 is approximately 1.95 m thick, and it is approximately 3.5 m to the top of the outcrop from the water line on June 27, 2012 (Figure 59). The exposure at outcrop 2 is similar to outcrop 1 with one notable exception; outcrop 2 lacks the coarse base layer. The base layer at outcrop 2 is between 130 cm to 195 cm below the ground surface and contains light gray to light brown, fine to very fine sand. Fine bedding exists throughout this section. The section is friable and well sorted. The middle layer is between 40 cm to 130 cm below ground surface and is slightly bedded, contains light brown to dark brown to light gray coarse to very coarse sand, is poorly sorted, and loose. The top layer is 40 cm thick and consists of dark gray to brown coarse sand with gravels and cobbles up to 8 cm, is poorly sorted, and loose.

Particle size distributions for the outcrop furthest from the Mount Hood Railroad Bridge follow similar trends between mode, mean, and median. The outcrop shows a pattern of inverse grading up with a graphic mean of 4.0ϕ at the base to a maximum grain size of -1.4ϕ (Figure 60). Sorting statistics vary with depth in response to the inversely graded relationship. From the base of the outcrop to the ground surface sorting values range from 0.9ϕ to 2.0ϕ , skewness values range from 0.1 to -0.1, and kurtosis values range from 1.2 to 0.8.

The results of the sieve analysis are displayed as a function of depth for the outcrop furthest downstream of the railroad bridge (Table 12). Overall, the sediment coarsens upwards through the outcrop. The outcrop at this location is

Figure 59. Stratigraphic cross-section of outcrop 2 downstream of the Mount Hood Railroad Bridge at river mile 0.8. See Figure 57 for reference.

Figure 60. Particle size diagram outcrop 2 downstream of the Mount Hood Railroad bridge at river mile 0.8. Median is not shown because it mirrors the graphic mean. Note that below 195 cm is the previous surface. The values here are not considered a part of the overall depositional trend. Depth to major unit boundaries are shown (light gray); (see Figure 59 for comparison).

Table 13. Particle size distribution for outcrop 2, downstream of Mt Hood Railroad bridge near river mile 0.8. Particle size fraction of gravel, sand, and silt in weight percent.

Sample	Depth (cm)	% Gravel	% Sand	% Silt
120627-4E	20	52.8	47.0	0
120627-4D	50	2.4	96.9	0.7
120627-4C	80	0	98.3	1.4
120627-4B	110	0	91.2	8.4
120627-4A	180	0	55.5	42.1

composed primarily of sand with some exceptions. The base of the outcrop has a fines percentage of 42.1% by weight, and the top layer of the outcrop was analyzed to contain a gravel fraction of 52.8% by weight.

Flow Interpretation (RM 1.2 and RM 0.8)

With the additional water flow from the West Fork Hood River, the lahar from Eliot Branch transformed into a water flood and merged with the larger flood in the Hood River; transporting the remainder of its sediment load to the Columbia River. At the Mt Hood Railroad bridge, between river mile 1.2 and 0.8, flood waters crested the deck of the bridge on the morning of November 7, 2006, indicating a peak flow depth exceeding 3 - 4 m (Figure 61). Despite the assault on the structure, the lower density flood waters (compared to the debris flow and hyperconcentrated flows that removed the Red Hill Road bridge) created no permanent damage to the structure (Figure 62). Additionally, peak flow depth was sufficient to submerge all channel bars in the river (Figure 63).

Sorting values continued to improve in the downstream direction from sample sites upstream at the confluence of the West and East Fork Hood Rivers to the delta. Average grain size has decreased as the flood has progressed downstream. Deposits at the Mt Hood Railroad site are poorly sorted to moderately sorted. In addition to the

Figure 61. Mt Hood Railroad Bridge on the morning of November 7, 2006. Flood waters can be seen breaching the deck of the railroad bridge. Brown color of water indicates a relatively high concentration of suspended sediment. (Courtesy of Darryl Lloyd)

Figure 62. Hood River Bridge on June 27, 2012 during normal seasonal low water flow. The bridge suffered no permanent damage from the 2006 event and is still in use.

Figure 63. Photo taken during flood stage on the morning of November 7, 2006 looking north along the Hood River near the East State Street bridge (background). Lower sampling location is located just downstream of the grouping of trees visible in the left-center of the photograph (Courtesy of Darryl Lloyd).

photo record, parallel laminations in the deposits in this area may be an indication that upper flow regime was present. Paola (1989) found that parallel lamination with flat-bed conditions can be formed under two conditions. Initial grain motion is known to create parallel lamination under lower flow regime, however, when there is abundant sediment in suspension, parallel lamination can be formed under upper flow regime. Based on the discharge spike and photographs of the flow (Figure 61 and Figure 63) a large sediment load is believed to be moving through this location during the flood. Therefore, upper flow regime is believed to have created these depositional features.

Additionally, the cross-bedding observed in outcrop 1, downstream of the railroad bridge, are interpreted as the product of antidunes during upper flow regime (Fielding, 2006). Through this section, the presence of the sheared off trees are interpreted to have been created through the abrasive action found during supercritical flow. The characteristics of the depositional units indicate that only flood waters deposited these units. It is interpreted that the trees were sheared off by a bed load of gravels that were deposited further downstream at the apex of the delta. These depositional features support the interpretation that abundant sediment was held in suspension by the water flood during supercritical flow.

Hood River Delta (48 km from initiation)

Figure 64. Aerial view of the Hood River delta at the confluence with the Columbia River in 2007 after the 2006 flood event (Google Earth).

The November 7, 2006 lahar-flood extended the Hood River delta front approximately 700 m out from the delta apex into the Columbia River (Bonneville Pool) and increased the above-water area of the delta by about 50 ha (120 acres) with deposits as much as 2.5 to 2.7 m thick (Figure 64). The United States Army Corp of

Engineers determined the new delta deposit to be approximately 0.7 million cubic meters of sediment and indicated that the deposition occurred over a span of 5 to 6 hours (USACE, 2010). Using the time of peak flow recorded at the Tucker Bridge gaging station and digital photo time stamps taken by an eye witness the flood peak arrived at the delta on the morning of November 7, 2006 between 8 and 9 am. Large standing antidune waves demonstrated supercritical turbulent (upper regime) flow (Figure 65). Additionally, large amounts of woody debris, mobilized by the lahar-flood, entered the delta (Figure 66). Since 2006, some reworking of the delta surface by the Columbia and Hood rivers has occurred. Sampling and measurement of the Hood River delta was carried out on November 2, 2012. A total of 21 samples were collected from 14 sample pits, which were dug to a maximum of 60 cm or to the levels at which the water table was encountered.

Figure 65. Lahar-flood waters on November 7, 2006 at approximately 9:00 AM at the Hood River Pedestrian Footbridge, about 570 m upstream of the river mouth and delta apex. Note large standing waves, which are indicative of upper regime flow (Courtesy of Darryl Lloyd).

Figure 66. Lahar-flood the apex of the Hood River delta on November 7, 2006 at approximately 9:00 AM. Note the woody debris floating in the delta and the plume of turbid, sediment-laden floodwater that is pushing out into the Columbia River. Both the east and west marginal channel levees (vegetated) are visible.

Deposit Characteristics

Based on observations in the Hood River delta sample pits, dug to a maximum depth of 60 cm, two texturally distinct layers were noted. The lower layer varies in composition from gravels near the mouth of the Hood River to more coarse grained sand farther out onto the delta. The lower layer has a range of graphic means between -1.0ϕ to 0.6ϕ and a range of medians between -0.2ϕ to 0.59ϕ . Sorting values range from 0.6ϕ (moderately sorted) to 2.3ϕ (very poorly sorted). Kurtosis ranges from 0.9 (mesokurtic) to 1.3 (leptokurtic) and skewness ranges from -0.3 (negatively skewed) to

0.1 (positively skewed). The upper layer consists of sand with a graphic mean range between 0.4ϕ to 1.5ϕ . The median ranges between 0.3ϕ to 1.49ϕ . Sorting values ranges from 0.6ϕ (moderately sorted) to 1.4ϕ (poorly sorted). Kurtosis ranges from 0.7 (platykurtic) to 1.4 (leptokurtic) and skewness ranges from -0.1 (negatively skewed) to 0.4 (very positively skewed). Other than the occurrence of the gravels around the mouth of the Hood River, there was no trend in grain size statistics in relation to depth for either layer. The contact between the two layers is diffuse. Depths of the contact varies throughout the delta between 15 cm – 20 cm from the surface. Within a radius of about 100 m near the delta apex, isolated gravel clasts were found on the surface. The average intermediate (b) axis for large clasts found on the delta surface within range of the sample pits nearest the delta apex is 8.4 cm with a standard deviation of 5.0 (Figure 67).

The results of the sieve analysis are displayed as averages of the two identified layers in the delta (Table 14). Overall, the finer upper section has an average gravel fraction of 3.1% by weight, a sand fraction of 96.0% by weight, and a fines fraction of 0.5% by weight. The coarser lower section has an average gravel fraction of 11.7% by weight, a sand fraction of 87.9% by weight, with no detectable fine fraction.

Arbitrary survey lines were established to measure distances between sample sites (Figure 67). To determine whether there was a relationship between grain size and sorting with distance in the delta a regression line analysis was done. The samples were

separated into upper and lower layers. Regression lines were applied to each layer's grain size diameters graphic means as a function of distance north of the survey line (Figure 68) and west from the survey line (Figure 69). Additionally, regression lines were applied to each layer's sorting values as a function of distance north of the survey line (Figure 70) and west of the survey line (Figure 71). To determine significance a two-tailed T-test was applied to the slope of the regression line (Table 15). The null hypothesis defines no relationship between the slope of the regression line and the data points. Rejection of the null hypothesis signifies a significant relationship with 95% certainty. For the most part, the overall trend was that there was no significant relationship with grain size or sorting with distance north or west along the delta. The only exception to this was found in the upper layer where sorting was found to improve with distance north of the survey line.

Table 14. Particle size fraction averages of gravel, sand, and silt in weight percent for Hood River delta sample sites. Samples are separated based on field evidence and grain size analysis into two distinct layers a coarse lower layer and a fine upper layer.

	# of Samples	% Gravel	% Sand	% Silt/Clay
Upper Layer	13	3.1	96.0	0.5
Upper Layer Standard Deviation		3.9	3.9	1.3
Lower Layer	8	11.7	87.9	0
Lower Layer Standard Deviation		11.7	11.8

Figure 67. Aerial view of the Hood River Delta in 2013. Green circles represent sample locations. Relative size indicates mean grain size. Yellow lines represent the arbitrarily positioned survey lines used as references to locate sample sites (Oregon Geospatial Data Clearinghouse).

Figure 68. Grain size distribution for graphic mean as it varies across delta distance to the north of the survey line (see Figure 66). Samples were separated into two depositional layers (Upper and Lower) based on field observations.

Figure 69. Grain size distribution of graphic mean as it varies across delta distance west of the survey line. Samples were separated into two depositional layers (Upper and Lower) based on field observations.

Figure 70. Sorting values of the grain size distribution as it varies across delta distance to the north of the survey line. Samples were separated into two depositional layers (Upper and Lower) based on field observations.

Figure 71. Sorting values for grain size distribution as it varies across delta distance west of the survey line. Samples were separated into two depositional layers (Upper and Lower) based on field observations.

Table 15. Regression line T-test for particle size diameter (sorting and mean) as a function of distance west and north of the survey lines (Figure 67). Null hypothesis defines no relationship between regression line slope and data points. Rejection of null hypothesis signifies significant relationship with 95% certainty. Note that sorting with distance north in the upper layer is the only significant relationship. Fines samples 12 df, coarse samples 7 df.

Two-tailed test. $H_0: \beta_1 = 0$ vs. $H_1: \beta_1 \neq 0$ at $\alpha = 0.05$			
	t table 0.05		t table 0.05
Upper Layer	± 2.179	Lower Layer	± 2.365
Mean with distance N	-0.508	Mean with distance N	0.734
Mean with distance W	-0.563	Mean with distance W	0.304
Sorting with distance N	-2.640	Sorting with distance N	-1.974
Sorting with distance W	-0.951	Sorting with distance W	-0.584

Flow Interpretation

The Eliot Branch lahar-flood of 2006 entered the apex of the Hood River delta as a highly concentrated flood surge, embedded within a larger regional flood. The flow type was water flow, highly charged with suspended sediment, moving as upper regime flow during the flood peak (Figure 72). Much of the high sediment load carried as bed load was deposited as the flood reached the low energy environment of the Bonneville Pool. Grain size and sorting of the deposits remained relatively similar to those at the Mt Hood Railroad site, but less lamination was present. This is attributed to a drop in flow velocity and a change to lower regime flow with distance from the apex of the delta and outside of the main channel of the Hood River.

Figure 72. Lahar-flood waters near the apex of the Hood River delta on the morning of November 8, 2006. Note the presence of antidune waves

Chapter 5

Discussion

The sedimentology of the deposits from the Hood River lahar-flood of 2006 supports previous research that a spectrum of flow types can occur in a single lahar-flood event, with transformations involving at least three distinct flow types. From the initiation of the lahar in the upper Eliot Branch as landslides in the lateral moraines of the Eliot Glacier, the lahar-flood transformed from landslide to debris flow to hyperconcentrated flow to water flood over 48 km to the Hood River delta.

The debris flow deposits emplaced in the debris field around Laurance Lake Road exhibited characteristics similar to debris flow deposits at other volcanoes. A large range of grain sizes was found from clay to large boulders (Costa 1984; Pierson and Scott, 1985; Coussot and Meunier, 1996) with no noticeable grading or internal sedimentary structures (Friedman et al., 1992). However, grading has been observed in many debris flow deposits. One such example was observed on Mount St. Helens after the 1982 eruption and lahar, where the deposit exhibited inverse grading near the bottom and normal grading near the top (Pierson and Scott, 1985). The debris-flow deposits in the debris field at the Laurance Lake site are massive diamictons throughout the observed depth of the deposit. The debris flow deposits in the Laurance Lake road area were most likely deposited by multiple surging debris flow lobes. This has been noted in other debris flows, such as, those from Jiangjia Gully, China which appeared

homogeneous and massive and had been deposited by separate surges of one debris flow (Major, 1997).

The clasts of the debris flow deposits are largely matrix-supported and are within the sorting range calculated by Pierson and Scott (1985) after the 1982 eruption and lahar on Mount St. Helens. The average sorting value for the debris flow deposits at the Laurance Lake Road site is 3.3ϕ . This falls within their identified sorting range of 3.0ϕ to 5.0ϕ for debris flow deposits. In the downstream direction, sorting of the debris flow deposits improves and falls below this range with values of 2.9ϕ at 16.3 km from initiation, and between the range of 1.7ϕ to 2.2ϕ at 24.3 km from initiation (Figure 73). Debris flow deposits downstream of the Laurance Lake debris field are beginning to fall out of the typical range for debris flows (Pierson and Scott, 1985) and are showing signs of transforming into hyperconcentrated flow. This progressive loss of the coarsest fraction with distance downstream is due to selective deposition. It has been observed that downstream fining of gravels occur through a combination of abrasion and sorting with sorting considered the dominant factor. The geomorphological control of this fining with distance downstream occurs through slope reduction (Ferguson et al., 1996).

The negligible percentage of clay sized particles throughout the debris flow deposits is characteristic of a noncohesive debris flow (less than 3 to 5% clay-size sediment), which readily transform to other flow types (Scott et al., 1995). The granularity of the noncohesive flow increases the rate of mixing with overtaken

Figure 73. Sorting over distance from the initiation point of the lahar-flood.

streamflow and the influx of the main tributaries. This explains the observed transformations at the East Fork and West Fork Hood Rivers. As the flow becomes diluted, it loses strength. The fluid phase begins to outpace the sediment phase, where upon the sediment is deposited.

The first evidence of the transformation from debris flow to hyperconcentrated flow occurs at the Laurance Lake Road site (6 km from initiation) where a layer of laminated sands with normal grading was found above the debris flow deposits in the incised channel along the periphery of the main debris field. Pierson and Scott (1985)

hypothesized three ways in which a debris flow transformed into hyperconcentrated flow through the downstream alteration of the sediment concentration: the lahar overtaking existing flow in the channel, erosion and incorporation of the saturated streambed material, and by progressive settling out of the coarsest particles in the granular phase. At the Laurance Lake Road debris field, the expansive debris flow deposits were caused by the relative decrease in slope, broadening of the reach, and constriction downstream caused by the Parkdale Lava Flow. In this area, settling out of the coarsest particles in the granular phase becomes the primary mode of deposition.

Deposit characteristics from the 2006 lahar-flood progressively change with distance from the initiation point. At the Red Hill Road site, 16.3 km downstream of the initiation point, the hyperconcentrated flow facies has become equal in scale to the debris flow deposits due primarily to mixing with the Middle Fork Hood River. The sediment concentration has dropped to a point to allow for more widespread primary sedimentary structures to appear such as soft sediment deformation, lamination, and cross bedding. Greater occurrence of faint lamination is visible, but overall the deposits appear massive. When the lahar-flood reached the site at Dee Lumber Mill (24.3 km from initiation), the greatest evidence of hyperconcentrated flow emplaced deposits is present. Sorting has improved beyond what has been observed from debris flow deposits. The range of $1.0-1.8\phi$ covers both the Red Hill Road and Dee Lumber Mill sites. These values compare favorably with those observed from the 1982 lahar on

Mount St. Helens , which had sorting values between 1.1-1.6 ϕ (Pierson and Scott, 1985) and from the 2008-2009 sedimentation response to the eruption of Chaiten volcano in Chile where sorting values between 1.3 ϕ to 1.8 ϕ were noted (Pierson et al., 2013).

In addition to the grain size statistics, the deposits at the Dee Lumber Mill site contain secondary sedimentary structures that have been commonly associated with hyperconcentrated flow deposits. Dish structures, sand blows, and flame structures were noted in the layers above the massive debris flow slurries in the outcrop 2. These secondary sedimentary structures have been associated with dewatering of sediment-gravity flows intermediate between debris flow and water flood (Scott et al., 1995). The deposits at the Dee Lumber Mill site support the notion that flow transformations during a lahar-flood cover a spectrum as the flow becomes more dilute. The hyperconcentrated flow distinction appears valid for these deposits, but the defining lines between debris flow and water flood are gradational rather than sharp and discrete (Pierson et al, 2013).

Each major flow transformation began to occur at the confluences with the major tributaries and were associated with large influxes of water. This indicates that for the Hood River Basin 2006 lahar-flood, dilution was most likely a major factor in creating the abrupt flow transformations. There is evidence that supports a gradual transformation as the debris flow loses energy due to selective settling created by the geomorphology of the reach (i.e. Laurance Lake Road and Red Hill Road sites), but the

greatest flow transformations are related to the confluence points. However, these transformations are not immediate and occur over distance with the primary transformation initiation occurring at each confluence. Using basin area as a proxy for proportional water flow and assuming that rainfall and water input was consistent across the entire Hood River Basin, the East Fork Hood River would have contributed 2.5 times more water flow to the flood than the Middle Fork Hood River. Similarly, downstream the West Fork Hood River would have contributed 2.3 times more water than the Middle Fork Hood River. This transformation over distance downstream of each major confluence indicates that added water volume alone is not enough to create immediate flow transformation, rather, water mixing with the flow was needed. This would have occurred over time and ultimately distance until the water was sufficiently mixed with the ever evolving flow.

No direct observation of the flow in the upper reaches where debris flow and hyperconcentrated flow occurred was made, but comparing the depositional sequence to findings from other researchers, it is believed that the Eliot Branch lahar-flood of 2006 started as a water flood that transformed into a debris flow due to the influx of sediment from landslides in the lateral moraines of the Eliot Glacier. This debris flow subsequently transformed to hyperconcentrated flow and ultimately back to a water flood. Selective deposition, incorporating overtaken channel flow, and tributary dilution caused the fronts and tails of the debris flow to transform. The transformation was

occurring at the front and tail of the debris flow. This is recorded in the deposits as hyperconcentrated-flow deposits are found below and above the debris flow deposits. The progressive thinning of the debris flow with distance downstream indicates that the hyperconcentrated flow was gradually replacing debris flow as the primary flow type. This observation and finding has been supported in other studies where the vertical progression through an outcrop shows debris flow deposits sandwiched between hyperconcentrated flow deposits (Pierson, 1986; Vallance, 2000). The vertical progression through an outcrop reflects a temporal passing of the flow and, assuming a continuous flow front, records the transformations from front to back.

Downstream of the confluence with the West Fork Hood River, the debris flow and hyperconcentrated flows had fully transformed into water flood. However, the identity of the Eliot Branch lahar is preserved within the deposits of the larger regional flood downstream. The peak discharge recorded at the Tucker Bridge gaging station gives an indication that the flow spiked in response to the passing of the lahar-mixed flood waters. The sheared off trees observed downstream of the Mount Hood Railroad bridge give an indication that they may have been created by flood waters with a relatively high concentration of sediment which would have been responsible for the abrasion. This extra sediment would have been from the Eliot Branch lahar. Although dilution would have occurred at the confluence with the West Fork Hood River followed by gradual flow transformation downstream, the sediment load would have been

carried, potentially in one large pulse, downstream to the delta. It is believed that the deposits found above the sheared-off trees are the sediments derived from the lahar, as well as the majority of the sand deposited at the delta. The extent to which the deltaic sands are derived from the lahar or related to the regional flood is not known. The regional flood would have contributed sediment to the system, as well. A comparison can be made to the widespread floods of 1996. During this event, no lahars were known to have occurred within the Hood River Basin and subsequently no major expansion to the delta occurred. Therefore, it is reasonable to assume that the majority of the sediment carried by the regional flood to the Hood River delta was derived from the Eliot Branch lahar.

The intensity, duration, and type of precipitation has shown to have a significant influence on lahar initiation and flow development. For lahars on Mount Semeru, Indonesia, 90% of the debris flows were triggered by “stationary” or high intensity orographic rainfall confined on the upper slopes of the mountain and 64% of hyperconcentrated flows and water flows were generated by less intense but longer lasting migratory rainfall (Lavigne and Suwa, 2004). Overall, the findings indicated that rainfall intensity is the main factor in lahar generation, and for the Eliot Branch the lahar was triggered during the most intense period of the storm where at least 13 cm (5.4 mm/hr) of rain fell over November 6th, 2006. Additionally, an unknown amount of rain would have continued to fall between midnight and the time the lahar occurred during

the early part of November 7th, 2006. The minimum observed rate falls within the ranges from other volcanoes which includes ~3 mm/hr recorded over Chaiten volcano, Chile (Pierson et al., 2013), 6.4 mm/hr with prior ground saturation in the Santa Monica Mountains of Southern California (Costa, 1984), and 6.2 to 25 mm/hr at Mount Semaru, Indonesia (Lavigne and Suwa, 2004).

The storm that occurred in the first week of November, 2006 created debris flows across much of the Cascade Range. In addition to the Hood River Basin lahar-flood, seven of the eleven major drainages on Mount Hood experienced debris flows (Pirot, 2010). To the north of Mount Hood, debris flows occurred on eight of the sixteen drainages outside of the 1980 debris avalanche zone on Mount St. Helens (Olson, 2012), seven of eighteen drainages on Mount Adams (Williams, 2011), Mount Rainier had fourteen of eighteen drainages at Mount Rainier (Lindsey, 2015), and to the south, Mount Jefferson had at least one debris flow on the western flank (Sobieszczyk et al., 2008).

The occurrence of the Hood River lahar-flood and widespread lahars generated on other Cascade volcanoes in November of 2006 may challenge our understanding of hazards associated with volcanoes in the Pacific Northwest (Scott et al., 1997). According to Scott and others (1997), the majority of hazard models lean heavily on volcanoes that have recently erupted and deposited large deposits of loose unconsolidated sediment. Suwa and Yamkoshi (1999) indicated that erosion rates and

threat of debris flow decreases exponentially with time after eruption. It has been more than 200 years since the last major eruption of Mount Hood, 33 years since the lahar from a dome-building eruption at Mount St. Helens, and varying periods of inactivity for the other Cascade volcanoes and yet the debris flow activity occurred without prejudice over the Cascade Range affecting all volcanoes regardless of their eruptive history. For the Pacific Northwest region other factors such as storm intensity, time of season, and glacier retreat may be as equally important as time since last eruption.

Chapter 6

Conclusions

The November 7, 2006 lahar-flood on the Hood River was a complex multi-day rainfall-runoff flood, onto which was superimposed a brief spike in water and sediment discharge caused by a 10^6 m^3 lahar originating in the Eliot Branch (tributary of the Middle Fork Hood River). The Eliot Branch lahar was embedded within a larger regional flood that was occurring across the entire Hood River Basin. It was generated during a “Pineapple Express” rainstorm that delivered approximately 43 cm of rainfall over six days from November 2nd to 7th. November 6th received the highest total daily rainfall of 13.0 cm (5.4 mm/hr). The lahar initiated from at least two landslides with an approximate minimum volume of $3.2 \times 10^4 \text{ m}^3$ from lateral moraines near the terminus of Eliot Glacier at an elevation of 1835 m. Glacial retreat over the last century unbuttressed these moraines and could have contributed to their instability.

The lahar-flood evolved as it progressed downstream (Figure 74). High-elevation rainfall-runoff generated by the warm rain mixed with material from slope failures to generate a non-cohesive debris flow that, in the process of transforming to hyperconcentrated flow, traveled over a distance of 28 km from the landslide initiation point to the confluence with the West Fork Hood River. From the confluence of the West Fork Hood River the flow fully transformed into a water flood and traveled 20 km

farther to the apex of the Hood River delta where depositing sediments led to an expansion of the delta.

Dilution of the lahar by major inflowing tributaries initiated the key flow transformations and occurred through a number of processes including a decrease in flow velocity due to broadening reaches, incorporation of overtaken channel flow, and through the influx of water through the East and West Fork Hood rivers. The greatest contributor to flow dilution was through the mixing of the East and West Fork Hood rivers. Abrupt flow transformations can be seen in the depositional record downstream of each confluence. The debris flow was rapidly transformed with the influx of the East Fork Hood River to a hyperconcentrated flow. In this reach a hyperconcentrated flow deposit underlies a debris flow deposit that contains coarser particle sizes and poorer sorting. The debris-flow unit was then overlain by additional hyperconcentrated-flow sediments laid down by the more dilute tail of the flow. Downstream, the influx of the West Fork Hood River created a complete flow transformation to water flood and the end of the debris flow and hyperconcentrated flow phases.

During the lahar-flood the largest accumulation of debris flow deposits occurred at the Laurance Lake Road debris field site, where an area of approximately 0.8 km^2 was covered by multiple lobes of debris flow sediment. Estimates for the volume of the debris field at Laurance Lake range from $0.8 \times 10^6 \text{ m}^3$ to $2.4 \times 10^6 \text{ m}^3$. Farther downstream sediments continued to deposit along the length of the channel depending

on the depositional environment and flow type. When the lahar-flood reached the Hood River delta and flowed into the Bonneville Pool, bed-load transport of sand was halted and much of the remaining sediment was deposited. From this flood event on the morning of November 7th, 2006 the Hood River delta increased in area up to 0.3 km² and was aggraded by as much as 2.7 m. Total volume estimates of 0.7 million cubic meters ($7.0 \times 10^5 \text{ m}^3$) of sediment were deposited by the lahar-flood (USACE, 2010).

Sediment textures and sedimentary structures in the deposits emplaced by the lahar-flood were key to unraveling the story of its downstream evolution. Particle size distribution fractions changed for each flow type over distance downstream of the initiation point (Table 16). The percentage of clay was negligible at less than one percent for all flow types over the basin. As the debris flow traveled from the initiation zone down to its runout zone and end at the confluence of the East Fork Hood River, the gravel fraction dropped from 69.7% to 44.1% by weight. At the same time the sand fraction rose from 22.1% to 55.7% by weight, while the fines fluctuated from 7.8% to 4.7% to close to 0.1% at the confluence with the East Fork Hood River. Grain size statistics followed a similar trend. As the debris flow moved downstream the average graphic mean dropped from; -2.5ϕ , -1.75ϕ , 0.1ϕ , and -1.4ϕ . The debris flow deposits became progressively better sorted from values as high as 3.3ϕ (very poorly sorted) to as low as 1.8ϕ (poorly sorted). Skewness ranged from 0.1 to 0.8 indicating a nearly

symmetrical distribution of grain sizes from clay to gravel. Finally, kurtosis values ranged from being very platykurtic (0.6) to mesokurtic (0.9).

Table 16. Changes in particle size distribution with distance from the initiation zone and by flow type. (% by weight)

	Distance from source (km)	Gravel %	Sand %	Fines %
Debris Flow	8	69.7	22.1	7.8
	16	61.3	33.6	4.7
	24	36.0	55.9	7.4
	28	44.1	55.7	0.1
Hyperconcentrated Flow	8	26.0	66.8	6.9
	16	4.6	86.2	8.8
	24	1.3	89.5	7.4
	28	0	99.2	0
Water Flow	48	6.0	90.5	3.0

Hyperconcentrated flow deposits showed a decrease in particle size with increased distance downstream. The gravel fraction dropped from a high of 26.0% by weight to a complete lack of gravel at the West Fork Hood River confluence. Over this distance the sand fraction increased from 66.8% to a high of 99.2%. The fines fraction showed relatively little fluctuation until complete dilution occurred at the West Fork Hood River. The sorting improved with distance downstream from a high of 2.4 ϕ (very poorly sorted) to a low of 0.8 ϕ (moderately sorted). The graphic mean did not show a significant trend with distance as values ranged from 0.6 ϕ to 1.7 ϕ . Skewness went from being nearly symmetrical at 0.0 to being positively skewed with a high of 0.2 as the fines fraction increased. Overall, the grain size distribution remained mesokurtic throughout

Figure 74. Primary flow types documented over the length of the lahar-flood. Debris flow mainly occurred for 28 km. Hyperconcentrated flow overlapped with the debris flow and mainly occurred for 22 km. At the confluence with the West Fork Hood River lahar fully transitioned into a water flood and traveled another 20 km.

the length of the hyperconcentrated flow as size distributions remained at similar sorting values.

Once the lahar transformed into a water flood, the gravel fraction in bar deposits dropped to lower values. Deposits become dominated by sand at 90.5% by weight with fines making up just 3.0% by weight or less. The average grain size based on graphic mean was 1.2ϕ . The distribution was positively skewed towards a fine distribution with a value of 0.1. Overall sorting with distance downstream ranged from being poorly sorted (1.4ϕ) to moderately (0.6ϕ) sorted. The particle size distribution curve ranged from being platykurtic to leptokurtic as sorting improved with distance downstream.

The Eliot Branch lahar remained embedded within the greater flood that was occurring within the Hood River basin. Selective settling, water inputs from the main tributaries, and incorporated channel flow created dilution within the flow and caused the flow transformations to occur. These transformations occurred over distance downstream and are primarily associated with the confluences of the major tributaries. Time and distance were required for sufficient mixing to occur as the flow transformed. The sediment load carried by the lahar that mixed with the greater regional flood was preserved in deposits downstream of the point where the debris flow and hyperconcentrated flow deposits ended. The events of November 7th, 2006 display the ability for large volumes of a lahar generated sediment load to be transported long distances after flow transformation.

Future Work

This results of this study support previous work that addresses flow transformations in lahar-flood events. However, the number of studies that describe these flow transformations based on depositional characteristics are limited. Future work could focus on sedimentologic studies of similar lahar-flood events in volcanic terrain, as well as, debris flows in non-volcanic terrain to increase the data set for defining flow types. The grain size statistics boundaries between debris flow, hyperconcentrated flow, and water flood appear blurry and may in fact cross at times depending on other aspects of the flow. At this time no one grain size statistic or flow characteristic defines hyperconcentrated flow. There are many descriptions that attempt to create a defining characteristic. These descriptions tend to be relevant for each individual lahar-flood. A more comprehensive definition based on sedimentologic characteristics will require more study from other basins. Ultimately, more data will help define the parameters of each flow type and a comprehensive definition can be reached by compiling and comparing the various studies findings.

Analyzing hazards gives us the ability to make better informed decisions regarding where we build, what we build, and how we build infrastructure. Studying the characteristics and recreating the events of the 2006 Hood River lahar-flood gives insight into the ability for these discharge events to affect the landscape. The results of this study could be applied to hazard analysis in other similar basins. The more

information obtained regarding how these types of events are initiated allows us to be aware of future storm events and recognize areas susceptible to landslide that could mobilize debris flows down basins. Recognizing where these flows deposit their sediment load and to what extent that deposition affects where and how infrastructure should be constructed. Different flow types have different degrees of force capable of creating a hazard. Understanding where these transformations occur can enhance our understanding of how to deal with them. The goal of preventing future loss of life and property by comparing the findings of this study to other basins may help to reduce the hazards associated with living and building in these areas.

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Appendix

Particle Size Data

Sample_ID	Weight (g)											
	Gravel						Sand					Silt/Clay
	-6 ϕ	-5	-4	-3	-2	-1	0	1	2	3	4	5
	64 mm	31.5	16	8	4	2	1	0.5	0.25	0.125	0.063	<0.063
120625-1A (1of2)		124.5	31.2	9.5	11.8	8.9	10.3	11.3	12.6	9.3	5.8	
120625-1A (2of2)		91	13	19.8	7.3	9.6	15.3	16.6	15.1	13.3	9.8	
120625-2A (1of2)		170.2	39.1	14	6.2	7.5	12.2	14.9	14.6	13.1	8.9	
120625-2A (2of2)		109	30.3	9.6	5.5	5.3	8.9	12.3	13.1	12.4	8.3	
120625-4				12.8	6.1	11.9	17.2	15.5	17	18.4	10.9	
120625-5 (1of2)		92	71.9	17.6	6	8	12.3	13.8	13.5	11.7	8.9	
120625-5 (2of2)		101.1	58.1	14.4	6.6	7.3	10.2	11.1	10.4	9.2	6.7	
120625-6A			38.8	3.1	9	9.5	13.6	13.5	13.7	10.5	5.2	
120625-6B		109	27.5	30.8	18.8	10.3	10.4	11	12.8	13.3	8.1	
120625-7						10.7	29.2	95.3	114.7	84.6	48.7	36.2
120625-8						7.7	22.2	25.9	23	17.4	9.9	
120626-1A						0.2	0.5	26.3	69.7	55.6	16.8	8.5
120626-1B							0.7	30.7	44.6	22.7	9.6	
120626-1C					7.6	34.5	28.8	13.5	9.3	8.3	5.5	
120626-1D					6.4	17.7	31	23.3	16.8	11.6	6.7	
120626-1E				2.8	4.7	14.5	66.2	129.4	74.7	36.2	15.5	9.9
120626-1F						0.2	4.6	65.7	96.1	63.2	21.8	10.3
120626-1G							0.8	12.9	28.6	38.7	21.5	
120626-1H						0.6	5.6	37.6	33.3	17.4	7.6	
120626-1I						0.8	18.8	44.7	25.1	13.9	7.2	
120626-1J						10.8	29.4	30.1	19.6	12.7	7	
120626-1K				1.1	2.7	11	31.8	32	17.9	10.8	6.1	
120626-1L						1.5	6	35.4	80.3	94.7	39.2	
120626-2A							2.6	2.8	14.4	96.5	69.6	42.8
120626-2B							4.5	14.4	118.3	131.1	30.2	10.2
120626-2C						0.3	6	25.3	72.7	62	17.8	8.2
120626-2D					1.4	11	41.4	30.1	15.7	9.3	5.2	
120626-2E						10.3	42.2	27.1	14.5	9.6	6.1	

120626-2F						2.5	34.3	34.3	19	12.6	7.6	
120626-2G						0.3	0.6	26	46.4	23.8	10.8	
120626-2H						0.7	22.7	111.5	103.4	45.1	14.6	9.3
120626-2I						0.3	1.3	27.4	49.5	25.6	7.7	
120626-2J						3.9	32.5	37.3	19.2	12.4	6.9	
120626-2K							0.8	10.4	34.5	43.3	19.9	
120626-2L						1.2	16.5	43.3	29.1	14.8	6.8	
120626-2M						0.3	0.7	18.4	54.9	29.1	9.6	
120626-2N						0.2	1.1	8.7	20.6	32.6	33.9	27.5
120626-2O							5.9	28.4	53.8	53	27.3	22.5
120627-1A						1.6	3	38.6	180.6	132.3	34.8	8.4
120627-1B						0.5	5.7	57.8	173.4	124.1	36.8	10.8
120627-1C						0.3	0.5	5.3	83.4	165.2	73.5	30.3
120627-1D							0.2	0.5	4.4	37	50	32.9
120627-1E							1.3	46	118.6	72.2	18.3	6.4
120627-1F							0.2	4.9	167.8	160.5	37.2	10.2
120627-1G						0.3	0.9	6.3	122.6	202.3	58.7	
120627-3A					1.6	17.3	116.7	348.1	124.8	24.4	3.9	0.8
120627-3B						0.3	0.4	8.8	94.4	143.3	59.2	17.3
120627-3C						0.1	0.6	7.6	39.1	169.2	83.2	34.7
120627-3D							0.4	34.7	152.9	61.1	10.4	2.6
120627-3E							0.3	3	94.3	193.6	56.2	13.3
120627-3F				3.9	14.7	46.5	125.5	141.4	60.7	11.1	0.7	
120627-4A								0.5	1.5	14.3	69.7	66.9
120627-4B							0.8	3.3	52.9	187.3	80.1	29.9
120627-4C						0.4	10	98.3	140.4	61.9	14.3	4.6
120627-4D					1.1	9.7	129.7	182.2	79.9	34	9.9	3
120627-4E			91.2	68.5	74.7	141.2	146.3	101.4	61.9	21.2	4	0.8
120627-Paleosol A								8.4	23.8	114.3	89.6	40.0
120627-Paleosol B								9.2	97.2	183	63.3	18.1
120727-1		276.5	118.9	97	70	60.4	57.3	60.2	52.3	27.8	8.3	3.3
120728-1A							1.7	14.5	82.2	98	32.5	9
120728-1B						11.5	23	80.6	132.8	81.4	18.5	4.5
120728-2A		121.8	114.1	37.3	37.6	50.4	76.6	81.7	74.1	60.8	30.9	
120728-2B	62	85.7	19.1	4.5	4.3	10.4	12.3	18.3	17.4	13.3	9.5	
120927-1A						1.1	15.9	123.4	135.7	34.7	2.3	0.1
120927-1B			54.6	34.9	38.3	51	134.6	74.4	13.3	2.8	0.6	0.3
121102-1						1.7	13.9	101.8	154.4	48.8	7.6	15.1

121102-10A					4.1	19.3	113	152.4	60.6	19.1	1.5	0.1
121102-10B				1.5	9.6	20.1	61.2	204.5	170.9	28.2	0.5	0.1
121102-11A						0.6	1.5	48.8	236.5	47.5	0.8	
121102-11B						1.7	44	351.1	127.9	16.4	0.8	0.2
121102-12						9.2	91.1	349.8	134.3	15.5	0.7	0.3
121102-13A					0.3	11.7	100.1	124	59.4	11	0.2	0.2
121102-13B				0.6	24.4	156	319.1	41.9	11.7	6.6	0.3	
121102-13C						1.4	21.6	106.9	64.3	3.4		
121102-14A						0.9	59.6	130.3	8.6	0.4	0.1	
121102-14B						2	37.1	309.6	103.1	5.1	0.1	
121102-2A					9	27.7	90.1	157.4	88.9	20.6	3.6	1.3
121102-2B					1.3	11.1	55.9	148.2	65.9	20.1	16.4	5.1
121102-3			101.5	22.2	18.9	44.2	151.2	147.7	97.1	23.8	3.9	2.7
121102-4A					1.6	7.9	70.3	199.4	95.3	19	1	
121102-4B				10.5	4.6	8.3	26.1	203.9	161.9	24.2	2.1	0.2
121102-5						2.4	10.9	201.9	191.3	11.9	1.8	1.1
121102-6						4.9	43.2	181.6	146.7	44.6	12.6	4.4
121102-7			42.4	34.6	35.9	59.2	144	177.3	78.1	22.4	4.6	1.5
121102-8			10.8	13.6	9.3	25	125.3	157.5	104.6	32.7	5	0.7
121102-9A					13.1	29.5	115.3	101.7	50.9	20.2	2.3	0.4
121102-9B				3.3	5.6	37.2	156.3	183	112.7	27.5	2.3	0.3

	Weight Percent Retained (Coarser)																
	Gravel						Sand						Fines				
Sample_ID	-6 φ	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	
120625-1A (1of2)		51	13	4	5	4	4	5	5	4	2	1	1	1	1	0	
120625-1A (2of2)		38	5	8	3	4	6	7	6	6	4	3	3	2	2	1	
120625-2A (1of2)		50	11	4	2	2	4	4	4	4	3	3	2	3	2	1	
120625-2A (2of2)		46	13	4	2	2	4	5	5	5	3	3	2	2	1	1	
120625-4		0	0	11	5	10	15	13	14	16	9	3	2	0	1	1	
120625-5 (1of2)		34	27	7	2	3	5	5	5	4	3	1	1	1	1	0	
120625-5 (2of2)		40	23	6	3	3	4	4	4	4	3	3	2	1	1	1	
120625-6A		0	32	3	7	8	11	11	11	9	4	1	1	0	1	0	
120625-6B		41	10	11	7	4	4	4	5	5	3	2	1	1	1	0	
120625-7		0	0	0	0	3	7	23	27	20	12	9					
120625-8		0	0	0	0	7	19	22	20	15	8	3	2	2	2	1	

120626-1A		0	0	0	0	0	0	14	37	30	9	5				
120626-1B		0	0	0	0	0	1	26	38	19	8	4	1	2	1	1
120626-1C		0	0	0	7	30	25	12	8	7	5	3	2	1	1	1
120626-1D		0	0	0	5	15	26	19	14	10	6	1	2	1	1	1
120626-1E		0	0	1	1	4	19	37	21	10	4	3				
120626-1F		0	0	0	0	0	2	25	37	24	8	4				
120626-1G		0	0	0	0	0	1	11	25	34	19	5	2	2	1	1
120626-1H		0	0	0	0	1	5	34	30	16	7	1	2	1	1	1
120626-1I		0	0	0	0	1	16	38	21	12	6	2	2	1	1	1
120626-1J		0	0	0	0	9	25	26	17	11	6	3	1	1	1	1
120626-1K		0	0	1	2	9	27	27	15	9	5	1	2	1	1	0
120626-1L		0	0	0	0	1	2	12	28	33	14	4	2	1	0	0
120626-2A		0	0	0	0	0	1	1	6	42	30	12	3	1	0	0
120626-2B		0	0	0	0	0	1	5	37	41	9	3				
120626-2C		0	0	0	0	0	3	13	36	31	9	4				
120626-2D		0	0	0	1	9	34	25	13	8	4	2	1	1	0	1
120626-2E		0	0	0	0	9	36	23	12	8	5	2	2	1	1	0
120626-2F		0	0	0	0	2	29	29	16	11	6	2	2	1	1	1
120626-2G		0	0	0	0	0	1	22	39	20	9	3	2	2	1	1
120626-2H		0	0	0	0	0	7	35	33	14	5	3				
120626-2I		0	0	0	0	0	1	22	41	21	6	2	2	1	1	1
120626-2J		0	0	0	0	3	27	31	16	10	6	2	2	1	1	1
120626-2K		0	0	0	0	0	1	9	28	36	16	4	3	2	1	1
120626-2L		0	0	0	0	1	14	36	24	12	6	2	2	1	1	1
120626-2M		0	0	0	0	0	1	15	45	24	8	2	2	1	1	1
120626-2N		0	0	0	0	0	1	7	17	26	27	11	5	2	0	0
120626-2O		0	0	0	0	0	3	15	28	28	14	4	2	1	0	0
120627-1A		0	0	0	0	0	1	10	45	33	9	2				
120627-1B		0	0	0	0	0	1	14	42	30	9	3				
120627-1C		0	0	0	0	0	0	1	23	46	21	8				
120627-1D		0	0	0	0	0	0	0	4	32	43	14	4	0	1	0
120627-1E		0	0	0	0	0	0	17	45	27	7	2				
120627-1F		0	0	0	0	0	0	1	44	42	10	3				
120627-1G		0	0	0	0	0	0	2	30	50	14	4				
120627-3A		0	0	0	0	3	18	54	19	4	1	0				
120627-3B		0	0	0	0	0	0	3	29	44	18	5				
120627-3C		0	0	0	0	0	0	2	12	50	25	7	2	1	0	0
120627-3D		0	0	0	0	0	0	13	58	23	4	1				

120627-3E		0	0	0	0	0	0	1	26	54	16	4				
120627-3F		0	0	1	4	11	31	35	15	3	0	0				
120627-4A		0	0	0	0	0	0	0	1	9	45	29	13	0	0	0
120627-4B		0	0	0	0	0	0	1	15	53	23	8				
120627-4C		0	0	0	0	0	3	30	42	19	4	1				
120627-4D		0	0	0	0	2	29	41	18	8	2	1				
120627-4E		0	13	10	10	20	21	14	9	3	1	0				
120627-Paleosol A		0	0	0	0	0	0	3	9	41	32	10	3	0	0	0
120627-Paleosol B		0	0	0	0	0	0	2	25	47	16	5				
120727-1		33	14	12	8	7	7	7	6	3	1	0				
120728-1A		0	0	0	0	0	1	6	35	41	14	4				
120728-1B		0	0	0	0	3	6	23	37	23	5	1				
120728-2A		16	15	5	5	7	10	11	10	8	4	4	3	2	1	1
120728-2B	24	30	7	2	1	4	4	6	6	5	3	3	2	1	1	1
120927-1A		0	0	0	0	0	5	39	43	11	1	0				
120927-1B		0	13	9	9	13	33	18	3	1	0	0				
121102-1		0	0	0	0	0	4	29	45	14	2	4				
121102-10A		0	0	0	1	5	31	41	16	5	0	0				
121102-10B		0	0	0	2	4	12	41	34	6	0	0				
121102-11A		0	0	0	0	0	0	15	70	14	0	0				
121102-11B		0	0	0	0	0	8	65	24	3	0	0				
121102-12		0	0	0	0	2	15	58	22	3	0	0				
121102-13A		0	0	0	0	4	33	40	19	4	0	0				
121102-13B		0	0	0	4	26	54	7	2	1	0	0				
121102-13C		0	0	0	0	1	11	54	33	2	0	0				
121102-14A		0	0	0	0	0	30	65	4	0	0	0				
121102-14B		0	0	0	0	0	8	68	23	1	0	0				
121102-2A		0	0	0	2	7	23	39	22	5	1	0				
121102-2B		0	0	0	0	3	17	45	20	6	5	2				
121102-3		0	16	4	3	7	25	24	16	4	1	0				
121102-4A		0	0	0	0	2	18	50	24	5	0	0				
121102-4B		0	0	2	1	2	6	46	37	5	0	0				
121102-5		0	0	0	0	1	3	48	45	3	0	0				
121102-6		0	0	0	0	1	10	41	34	10	3	1				
121102-7		0	7	6	6	10	24	30	13	4	1	0				
121102-8		0	2	3	2	5	26	32	22	7	1	0				
121102-9A		0	0	0	4	9	35	30	15	6	1	0				
121102-9B		0	0	1	1	7	29	35	21	5	0	0				

Sample_ID	Σ Weight Percent Retained (Coarser)																
	Gravel						Sand					Silt/Clay					Σ
	-6 ϕ	-5	-4	-3	-2	-1	0	1	2	3	4	5.0	6.0	7.0	8.0	9.0	
120625-1A (1of2)	0	51	64	68	72	76	80	85	90	94	96	97.0	97.8	98.6	99.2	99.5	100
120625-1A (2of2)	0	38	44	52	55	60	66	73	79	85	89	92.4	94.9	97.1	98.6	99.8	100
120625-2A (1of2)	0	50	62	66	67	70	73	78	82	86	88	91.5	93.8	96.5	98.2	99.4	99
120625-2A (2of2)	0	46	58	62	65	67	70	76	81	86	90	93.0	95.1	97.0	98.4	99.3	99
120625-4	0	0	0	11	16	26	41	54	68	84	93	95.5	97.6	98.0	99.0	99.8	100
120625-5 (1of2)	0	34	61	67	70	73	77	82	87	92	95	96.5	97.7	98.6	99.3	99.7	100
120625-5 (2of2)	0	40	62	68	70	73	77	82	86	89	92	94.9	96.7	98.0	99.0	99.6	100
120625-6A	0	0	32	34	42	50	61	72	83	92	96	97.1	98.1	98.6	99.4	99.8	100
120625-6B	0	41	51	62	69	73	77	81	86	91	94	95.7	97.1	98.2	99.1	99.5	99
120625-7	0	0	0	0	0	3	10	32	60	80	91	99.9					100
120625-8	0	0	0	0	0	7	25	48	67	82	90	93.1	95.5	97.0	98.6	99.4	99
120626-1A	0	0	0	0	0	0	0	15	52	82	91	95.4					95
120626-1B	0	0	0	0	0	0	1	26	64	83	91	94.9	95.9	97.6	98.6	99.3	99
120626-1C	0	0	0	0	7	36	61	72	80	87	92	94.5	96.2	97.7	98.6	99.4	99
120626-1D	0	0	0	0	5	20	46	65	79	88	94	95.4	97.0	98.0	98.7	99.4	99
120626-1E	0	0	0	1	2	6	25	61	83	93	97	100					100
120626-1F	0	0	0	0	0	0	2	27	63	87	96	99.6					100
120626-1G	0	0	0	0	0	0	1	12	37	70	89	93.8	95.4	97.0	97.7	98.4	98
120626-1H	0	0	0	0	0	1	6	40	70	86	93	94.7	96.4	97.8	98.8	99.5	99
120626-1I	0	0	0	0	0	1	16	54	75	87	93	94.9	97.0	97.8	98.7	99.8	100
120626-1J	0	0	0	0	0	9	34	60	76	87	93	95.6	96.9	98.4	99.2	99.7	100
120626-1K	0	0	0	1	3	12	39	66	80	89	95	95.6	97.3	98.4	99.2	99.7	100
120626-1L	0	0	0	0	0	1	3	15	43	76	90	93.7	95.5	96.3	96.6	96.7	97
120626-2A	0	0	0	0	0	0	1	2	9	50	80	92.4	95.4	96.4	96.6	96.7	97
120626-2B	0	0	0	0	0	0	1	6	43	84	94	96.8					97
120626-2C	0	0	0	0	0	0	3	16	52	83	92	95.9					96
120626-2D	0	0	0	0	1	10	44	69	82	90	94	96.1	97.5	98.4	98.8	99.6	100
120626-2E	0	0	0	0	0	9	44	67	79	87	93	94.8	96.4	97.8	98.9	99.4	99
120626-2F	0	0	0	0	0	2	31	59	75	86	92	94.2	96.5	97.7	98.6	99.3	99
120626-2G	0	0	0	0	0	0	1	23	62	82	91	94.2	96.4	98.0	99.1	100	100
120626-2H	0	0	0	0	0	0	7	43	75	90	94	97.1					97
120626-2I	0	0	0	0	0	0	1	24	64	85	92	93.5	95.0	95.9	97.2	97.7	98
120626-2J	0	0	0	0	0	3	30	61	77	87	93	95.4	96.9	98.2	99.1	99.8	100
120626-2K	0	0	0	0	0	0	1	9	38	73	89	93.6	96.5	98.2	99.0		100
120626-2L	0	0	0	0	0	1	15	51	75	88	93	95.3	97.0	98.2	98.8	99.5	99
120626-2M	0	0	0	0	0	0	1	16	61	85	93	95.0	96.8	97.7	98.6	99.2	99
120626-2N	0	0	0	0	0	0	1	8	25	51	78	88.9	93.9	95.9	96.2	96.5	96
120626-2O	0	0	0	0	0	0	3	18	46	74	88	92.3	94.3	95.2	95.7	96.0	96

120627-1A	0	0	0	0	0	0	1	11	56	89	98	99.9					100
120627-1B	0	0	0	0	0	0	2	16	58	88	97	99.9					100
120627-1C	0	0	0	0	0	0	0	2	25	71	92	100					100
120627-1D	0	0	0	0	0	0	0	1	4	37	80	93.7	97.6	97.9	98.5	98.6	99
120627-1E	0	0	0	0	0	0	0	18	63	90	97	99.7					100
120627-1F	0	0	0	0	0	0	0	1	45	87	96	98.8					99
120627-1G	0	0	0	0	0	0	0	2	32	82	96	99.9					100
120627-3A	0	0	0	0	0	3	21	76	95	99	99	99.6					100
120627-3B	0	0	0	0	0	0	0	3	32	76	95	99.8					100
120627-3C	0	0	0	0	0	0	0	2	14	64	89	96.5	98.2	98.8	99.2	99.3	99
120627-3D	0	0	0	0	0	0	0	13	71	95	99						100
120627-3E	0	0	0	0	0	0	0	1	27	81	96	99.8					100
120627-3F	0	0	0	1	5	16	47	82	97	100							100
120627-4A	0	0	0	0	0	0	0	0	1	11	55	84.0	97.1	97.3	97.6		98
120627-4B	0	0	0	0	0	0	0	1	16	69	91	99.6					100
120627-4C	0	0	0	0	0	0	3	33	75	94	98	99.8					100
120627-4D	0	0	0	0	0	2	31	72	90	97	99	100					100
120627-4E	0	0	13	22	33	53	73	88	96	99	100						100
120627-Paleosol A	0	0	0	0	0	0	0	3	12	53	86	96.0	98.9	99.1	99.2		99
120627-Paleosol B	0	0	0	0	0	0	0	2	27	74	91	95.3					95
120727-1	0	33	47	59	67	75	81	89	95	98	99	99.6					100
120728-1A	0	0	0	0	0	0	1	7	41	83	96	100					100
120728-1B	0	0	0	0	0	3	10	32	69	92	97	98.7					99
120728-2A	0	16	31	36	41	47	57	68	77	85	89	93.7	96.3	98.3	99.6	100	100
120728-2B	24	54	60	62	63	67	71	78	84	88	91	94.1	96.1	97.6	98.7	99.4	99
120927-1A	0	0	0	0	0	0	5	45	88	99	100						100
120927-1B	0	0	13	22	32	44	77	96	99	100	100						100
121102-1	0	0	0	0	0	0	5	34	79	93	95	99.4					99
121102-10A	0	0	0	0	1	6	37	78	94	100							100
121102-10B	0	0	0	0	2	6	19	60	94	100							100
121102-11A	0	0	0	0	0	0	1	15	86	100							100
121102-11B	0	0	0	0	0	0	8	73	97	100							100
121102-12	0	0	0	0	0	2	17	75	97	100							100
121102-13A	0	0	0	0	0	4	37	77	96	100							100
121102-13B	0	0	0	0	4	31	85	92	94	95	95	95.1					95
121102-13C	0	0	0	0	0	1	12	66	98	100							100
121102-14A	0	0	0	0	0	0	30	95	100	100							100
121102-14B	0	0	0	0	0	0	9	76	99	100							100
121102-2A	0	0	0	0	2	9	32	71	93	98	99	99.7					100
121102-2B	0	0	0	0	0	4	21	66	86	92	97	98.5					98
121102-3	0	0	16	20	23	30	55	79	95	98	99	99.6					100
121102-4A	0	0	0	0	0	2	20	70	95	99	100						100
121102-4B	0	0	0	2	3	5	11	57	94	99	100						100

121102-5	0	0	0	0	0	1	3	51	96	99	99	99.7					100
121102-6	0	0	0	0	0	1	11	52	86	96	99						100
121102-7	0	0	7	13	19	29	53	82	95	99	100						100
121102-8	0	0	2	5	7	12	38	70	92	99	100						100
121102-9A	0	0	0	0	4	13	47	78	93	99	100						100
121102-9B	0	0	0	1	2	9	38	73	94	99	100						100

Particle Size Grading Curves

Laurance Lake Road Site

Sample	Mode	5%	16%	25%	Median	75%	84%	95%	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis
120625-1A (1of2)	-5	-5	-5	-5	-5.0	-1	1	3	-3.1	2.7	1.0	0.9
120625-1A (2of2)	-5	-5	-5	-5	-3.3	1	3	6	-1.8	3.6	0.6	0.7
120625-2A (1of2)	-5	-5	-5	-5	-5.0	0	3	6	-2.5	3.6	1.0	0.9
120625-2A (2of2)	-5	-5	-5	-5	-4.7	1	3	6	-2.4	3.5	0.9	0.8
120625-4	-3	-3	-2	-1	0.7	2	3	5	0.6	2.4	0.0	0.9
120625-5 (1of2)	-5	-5	-5	-5	-4.4	-1	1	4	-2.7	2.9	0.8	0.8
120625-5 (2of2)	-5	-5	-5	-5	-4.5	-1	2	5	-2.7	3.2	0.9	0.9

Red Hill Road Site

Sample	Mode	5%	16%	25%	Median	75%	84%	95%	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis
120625-6A	-4	-4	-4	-4	-1.0	1	2	4	-1.0	2.7	0.1	0.6
120625-6B	-5	-5	-5	-5	-4.1	-1	2	5	-2.5	3.1	0.8	0.9
120625-7	2	-1	0	1	1.6	3	3	4	1.8	1.6	0.1	1.0
120625-8	1	-1	-1	0	1.1	3	3	5	1.3	1.8	0.2	1.0

Dee Lumber Mill Site

Sample	Mode	5%	16%	25%	Median	75%	84%	95%	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis
120626-1A	2	0	1	1	2.0	3	3	5	2.1	1.3	0.2	1.3
120626-1B	2	0	1	1	1.6	3	3	5	1.8	1.4	0.3	1.2
120626-1C	-1	-2	-2	-1	-0.4	1	3	6	0.1	2.2	0.5	1.1
120626-1D	1	-2	-1	-1	0.2	2	3	5	0.5	2.0	0.3	1.1
120626-1E	1	-1	0	0	0.7	2	2	4	0.8	1.4	0.1	1.2
120626-1F	2	0	1	1	1.6	3	3	4	1.7	1.2	0.1	1.0
120626-1G	3	0	1	2	2.4	3	4	6	2.4	1.5	0.2	1.3
120626-1H	1	0	0	1	1.3	2	3	5	1.5	1.4	0.3	1.2
120626-1I	1	-1	0	0	0.9	2	3	5	1.2	1.6	0.4	1.3
120626-1J	1	-1	-1	0	0.6	2	3	5	0.9	1.7	0.3	1.0
120626-1K	1	-2	-1	-1	0.4	2	2	4	0.7	1.7	0.2	1.1
120626-1L	3	0	1	1	2.2	3	4	6	2.3	1.4	0.2	1.4
120626-2A	3	1	2	2	3.0	4	4	6	3.2	1.2	0.3	1.3
120626-2B	3	1	1	2	2.2	3	3	4	2.1	1.0	0.1	1.1
120626-2C	2	0	1	1	1.9	3	3	5	2.0	1.2	0.2	1.3
120626-2D	0	-2	-1	-1	0.2	1	2	5	0.6	1.7	0.4	1.2
120626-2E	0	-1	-1	-1	0.3	2	3	5	0.7	1.8	0.5	1.1
120626-2F	1	-1	-1	0	0.7	2	3	5	1.0	1.8	0.4	1.2
120626-2G	2	0	1	1	1.7	3	3	6	1.9	1.4	0.3	1.4
120626-2H	1	0	0	1	1.2	2	3	4	1.4	1.3	0.3	1.3
120626-2I	2	0	1	1	1.7	3	3	6	1.8	1.5	0.3	1.6
120626-2J	1	-1	-1	0	0.7	2	3	5	0.9	1.7	0.4	1.2
120626-2K	3	1	1	2	2.3	3	4	6	2.4	1.4	0.2	1.3
120626-2L	1	-1	0	0	1.0	2	3	5	1.2	1.5	0.4	1.4
120626-2M	2	0	1	1	1.8	3	3	5	1.9	1.2	0.3	1.4
120626-2N	4	1	1	2	3.0	4	5	7	3.0	1.7	0.1	1.3
120626-2O	3	0	1	1	2.1	3	4	7	2.2	1.8	0.3	1.5

East Fork and West Fork Hood River Confluence Site

Sample	Mode	5%	16%	25%	Median	75%	84%	95%	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis
120727-1	-5	-5	-5	-5	-3.8	-1	0	2	-2.8	2.4	0.6	0.7
120927-1A	2	0	0	1	1.1	2	2	3	1.1	0.8	0.0	0.9
120927-1B	0	-4	-4	-3	-0.8	0	0	1	-1.4	1.8	-0.4	0.8

Mount Hood Railroad Bridge Site

Sample	Mode	5 %	16 %	25 %	Median	75 %	84 %	95 %	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis
120627-1A	2	0	1	1	1.9	3	3	4	1.9	0.9	0.1	1.1
120627-1B	2	0	1	1	1.8	3	3	4	1.9	1.0	0.1	1.1
120627-1C	3	1	2	2	2.5	3	4	4	2.6	1.0	0.1	1.1
120627-1D	4	2	2	3	3.3	4	4	5	3.3	1.0	0.1	1.1
120627-1E	2	0	1	1	1.7	2	3	4	1.8	1.0	0.1	1.1
120627-1F	2	1	1	2	2.1	3	3	4	2.1	0.8	0.1	1.0
120627-1G	3	1	1	2	2.4	3	3	4	2.3	0.8	0.0	1.1
120627-3A	1	-1	0	0	0.5	1	1	2	0.6	0.9	0.0	1.3
120627-3B	3	1	1	2	2.4	3	3	4	2.4	1.0	0.1	1.0
120627-3C	3	1	2	2	2.7	3	4	5	2.8	1.0	0.2	1.2
120627-3D	2	0	1	1	1.6	2	3	3	1.7	0.8	0.1	1.2
120627-3E	3	1	2	2	2.4	3	3	4	2.4	0.8	0.0	1.2
120627-3F	1	-2	-1	-1	0.1	1	1	2	0.1	1.1	0.0	1.0
120627-4A	4	2	3	3	3.9	5	5	6	4.0	1.0	0.2	1.0
120627-4B	3	1	2	2	2.7	3	4	4	2.8	0.9	0.2	1.2
120627-4C	2	0	0	1	1.4	2	2	3	1.4	1.0	0.1	1.0

120627-4D	1	-1	-1	0	0.5	1	2	3	0.5	1.1	0.2	1.1
120627-4E	0	-4	-4	-3	-1.1	0	1	2	-1.4	2.0	-0.1	0.8
120627-Paleosol A	3	1	2	2	2.9	4	4	5	3.0	1.0	0.1	1.1
120627-Paleosol B	3	1	2	2	2.5	3	4	5	2.5	1.1	0.2	1.4

Hood River Delta Site

Sample	Mode	5%	16%	25%	Median	75%	84%	95%	Graphic Mean	Inclusive Graphic Standard Deviation	Inclusive Graphic Skewness	Graphic Kurtosis
121102-7	1	-4	-3	-1	-0.1	1	1	2	-0.5	1.8	-0.3	1.2
121102-2A	1	-2	-1	0	0.5	1	2	2	0.4	1.2	0.0	1.1
121102-2B	1	-1	0	0	0.7	1	2	4	0.9	1.1	0.4	1.4
121102-1	2	0	0	1	1.4	2	2	4	1.4	1.1	0.2	1.3
121102-3	0	-4	-4	-2	-0.2	1	1	2	-1.0	2.3	-0.3	1.0
121102-5	1	0	0	0	1.0	2	2	2	1.0	0.7	0.0	0.7
121102-4A	1	-1	0	0	0.6	1	2	2	0.6	0.9	0.1	1.1
121102-4B	1	-1	0	0	0.8	1	2	2	0.9	0.9	-0.1	1.2
121102-8	1	-3	-1	-1	0.4	1	2	2	0.4	1.4	-0.1	1.3
121102-10A	1	-1	-1	0	0.3	1	1	2	0.3	1.0	0.0	1.0
121102-10B	1	-1	0	0	0.8	1	2	2	0.8	1.0	-0.1	0.9
121102-9A	0	-2	-1	-1	0.1	1	1	2	0.2	1.2	0.1	1.1
121102-9B	1	-2	-1	0	0.3	1	2	2	0.4	1.1	0.0	1.0
121102-6	1	-1	0	0	0.9	2	2	3	1.0	1.0	0.1	1.1
121102-12	1	-1	0	0	0.6	1	1	2	0.6	0.8	0.1	1.3
121102-11A	2	0	1	1	1.5	2	2	3	1.5	0.6	0.0	1.4
121102-11B	1	0	0	0	0.6	1	1	2	0.7	0.7	0.2	1.2
121102-13A	1	-1	-1	0	0.3	1	1	2	0.4	0.9	0.1	0.9
121102-13B	0	-2	-2	-1	-0.6	0	0	3	-0.7	1.1	0.1	1.9
121102-13C	1	-1	0	0	0.7	1	2	2	0.8	0.8	0.0	1.0
121102-14A	1	-1	0	0	0.3	1	1	1	0.2	0.6	-0.2	0.9
121102-14B	1	0	0	0	0.6	1	1	2	0.7	0.7	0.1	1.3