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Using Repeat Terrestrial Laser Scanning and Photogrammetry to Monitor Reactivation of
the Silt Creek Landslide in the Western Cascade Mountains, Linn County, Oregon

by

Justin Craig McCarley

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

Master of Science
in
Geology

Thesis Committee:
Adam Booth, Chair
Scott Burns
Susan Shaw

Portland State University
2018

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Abstract

Landslides represent a serious hazard to people and property in the Pacific Northwest. Currently, the factors leading to sudden catastrophic failure vs. gradual slow creeping are not well understood. Utilizing high-resolution monitoring techniques at a sub-annual temporal scale can help researchers better understand the mechanics of mass wasting processes and possibly lead to better mitigation of their danger. This research used historical imagery analysis, precipitation data, aerial lidar analysis, Structure from Motion (SfM) photogrammetry, terrestrial laser scanning (TLS), and hydrologic measurements to monitor displacement of the Silt Creek Landslide in the western Cascade Mountain Range in Linn County, Oregon. This landslide complex is ~4 km long by ~400 m wide. The lower portion of the landslide reactivated following failure of an internal scarp in June 2014. Precipitation was measured on site and historical precipitation data was determined from a nearby SNOTEL site. Analysis of aerial lidar data found that the internal scarp failure deposited around $1.00 \times 10^6 \text{ m}^3$ of material over an area of $1.20 \times 10^5 \text{ m}^2$ at the uppermost portion of the reactivated slide. Aerial lidar analysis also found that displacement rates on the slide surface were as high as $3 \frac{\text{m}}{\text{yr}}$ during the 2015 water year, which was the year immediately following the failure. At the beginning of the 2016 water year, very low altitude aerial images were collected and used to produce point cloud data, via SfM, of a deformed gravel road which spans a portion of the reactivated slide. The SfM data were complimentary to the aerial and TLS scans. The SfM point cloud had an average point density of >7500 points per square meter. The resulting cloud was manipulated in 3D software to produce a model of the road prior to

deformation. This was then compared to the original deformed model. Average displacement found in the deformed gravel road was 7.5 m over the 17 months between the scarp failure and the collection of the images, or $\sim 3 \frac{m}{yr}$. TLS point clouds were collected quarterly over the course of the 2016 water year at six locations along the eastern margin of the reactivated portion of the landslide. These 3D point cloud models of the landslide surface had an average density of 175 points per square meter. Scans were georeferenced to UTM coordinates and relative alignment of the scans was accomplished by first using the iterative closest point algorithm to align stable, off-slide terrain, and then applying the same rigid body translation to the entire scan. This was repeated for each scan at each location. Landmarks, such as tree trunks, were then manually selected at each location and their coordinates were recorded from the initial scan and each successive scan to measure displacement vectors. Average annual displacement for the 2016 water year ranged from a maximum of $0.92 \frac{m}{yr}$ in the uppermost studied area of the slide, to a low of $0.1 \frac{m}{yr}$ at the toe. Average standard deviation of the vectors of features on stable areas was 0.039 m, corresponding to a minimum detectable displacement of about ± 4 cm. Displacement totals decreased with increasing distance downslope from the internal scarp failure. Additionally, displacement tended to increase with increasing distance laterally onto the slide body away from the right margin at all locations except the uppermost, where displacement rates were relatively uniform for all landmarks. Volumetric discharge measurements were collected for Silt Creek in 2016 using salt dilution gauging and found that discharge in the upslope portion of the study area was

$\sim 1 \frac{m^3}{s}$ and increased to $\sim 1.6 \frac{m^3}{s}$ in the downslope portion. Landslide displacement rates were found to be much lower during the 2016 water year than during the 2015 water year, despite higher precipitation. This suggests that the over-all displacement trend was decoupled from precipitation values. Displacement rates at all locations on the slide decreased with each successive scan period with some portions of the landslide stopping by autumn of 2016, suggesting the study captured the slide as it returned to a state of stability. The spatial and temporal pattern of displacement is consistent with the interpretation that the landslide reactivation was a response to the undrained load applied by the internal scarp failure. This finding highlights the importance of detailed landslide monitoring to improve hazard estimation and quantification of landslide mechanics. This study provides new evidence that supports previous research showing that internal processes within landslide complexes can have feedback relationships, combines several existing 3D measurement tools to develop a detailed landslide monitoring methodology, uses a novel approach to landslide surface deformation measurements using SfM, and suggests that landslide initiation models which rely heavily on precipitation values may not account for other sources of landslide activation.

Dedication

This work is dedicated to Alice and Jay McCarley,
who believed in me.

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1 Introduction

1.1 Background and Motivation

Landslides pose a significant risk in the Pacific Northwest (Keaton and Wartman, 2014). To better understand this risk, it is necessary to understand the mechanics that give rise to slope failures. Generally, slope failure can be divided into two forms; fast catastrophic failure, such as debris flows, topples, and falls, and slower creeping movement such as earthflows. The faster variety can pose serious risks to human safety in populated areas (Petley, 2012), but slower ones can also have a heavy negative impact on infrastructure and property (Fell et al., 2005). Complex landslides exhibit multiple types of slope movement within one system, often having both these slow and fast failures at separate locations within the slide occurring independently or simultaneously (Highland and Johnson, 2004).

Increased pore water pressure, typically due to precipitation infiltration into soil and increased groundwater levels, is generally understood to be a major contributing factor to slope failure (Caine, 1980). For this reason, precipitation tends to factor heavily in landslide prediction models (Coe et al., 2004, Pagano et al., 2010). There has been much work done to better constrain processes and traits that cause sudden or gradual slope failure, including investigating the interplay between soil grain size and its effect on pore pressure (Iverson, 2005), slope angle, and precipitation rates (Guzetti et al., 2007). However, landslide mobility can be highly sensitive to these various traits, which may be expressed in dramatically diverse ways even within a single slide complex. Therefore, building a better understanding of the interplay between various processes that may lead

to slope failure within a landslide is valuable for understanding landscape evolution and estimating the hazards associated with these failure events.

This study aimed to efficiently and accurately measure landslide displacement using applied field geology methods. This began with using previously collected aerial lidar to measure deposition resulting from a scarp failure as well as displacement of the surface of a landslide. Then, these displacement values were supplemented with a three-dimensional (3D) model derived from photogrammetric data, which provided a point cloud resolution far greater than anything offered by lidar. Terrestrial laser scanning (TLS) was used to create high accuracy 3D landslide surface models that could be collected rapidly and for a fraction of the cost of an aerial lidar collection mission. Finally, hydrology measurements were conducted on Silt Creek to determine groundwater discharge rates on the landslide. Together, these techniques worked in concert to provide insight into the mechanics of the Silt Creek Landslide in the western Cascades, Oregon, and helped illuminate the relationship between catastrophic slope failure and creeping movement.

1.1.1 Factor of Safety

Understanding the behavior of any landslide feature begins with an exploration of the physics governing the slope stability. The following few sections explore the mathematical modeling of several of the factors governing slope stability, soil compaction, groundwater pore pressure, and applied load due to increased overburden. These equations were used in the analysis of results from the study and provide context

for the implications in the discussion section.

In a most basic sense, a landslide can be thought of as the failure of some thickness of material on an infinite flat plane. Slope stability on this theoretical infinite plane is modeled with the factor of safety formula:

$$F = \frac{c' + (\gamma z \cos^2 \beta - r_u \cdot \gamma_w z) \tan \alpha}{\gamma z \sin \beta \cos \beta} \quad (1)$$

where the slope is considered unstable for all F values less than 1, c' is the effective soil cohesion, γ is the unit weight of the soil, z is the vertical depth of the soil to the failure plane, β is the slope angle from horizontal, α is the angle of internal friction, and r_u is the ratio between pore pressure and the weight per unit area of the soil column (Selby, 1993). The governing relationship that predicts the likelihood that a slope will fail is the ratio between the friction behaving as a resisting force and the driving forces acting to move the slope mass downhill. The numerator in the above formula represents the resisting force portion of the relationship and is a combination of the soil cohesion and the effective normal stress (the expression in parenthesis):

$$\tau_{ss} = c' + (\gamma z \cos^2 \beta - r_u \cdot \gamma_w z) \tan \alpha \quad (2)$$

where τ_{ss} is the resisting shear strength. The denominator represents the driving stress portion of the relationship:

$$\tau = \gamma z \sin\beta \cos\beta \quad (3)$$

where τ is the shear stress.

As long as the resisting forces remain greater than the driving forces (and the ratio is greater than 1), the slope is expected to remain stable. As such, the factor of safety equation provides a first-order model for estimating slope stability given various site conditions, such as soil cohesion and mass, slope angle, and ground water level. Equation (1) shows that all other factors remaining constant, a slope is expected to become less stable as slope gradient increases, cohesion decreases, or groundwater level increases. It also highlights the relative effect that these different attributes can have on slope stability.

1.1.2 Pore Water Pressure

One of the key variables in equation (1) is r_u , the ratio between pore water pressure and the weight per unit area of the soil column. From that equation, we can see that for any given slope, an increase in pore water pressure leads to a decrease in resisting forces, and thus has a destabilizing effect, assuming all other variables are held constant. As r_u increases, the effective normal stress, the quantity in parenthesis in equation (3), decreases, and in some cases can even reduce to zero, indicating soil liquefaction. Pore water pressure is the force per unit area exerted on neighboring soil grains by the groundwater between them. As pore water pressure increases, it exerts enough force that it can counteract the frictional forces acting on the grains, reducing the frictional strength of the soil. Once all frictional strength and cohesion is lost, the material can liquify, such

as occurs in debris flows or liquefaction of sediments during earthquakes. Water is a fluid, meaning it does not provide resistance to shear stresses, so as the slope mass becomes supported more by pore water pressure and less by the soil skeleton it becomes more likely to slide due to the shear driving force acting to move the soil mass downslope. (Selby, 1993). Pore water pressure can transiently increase due to a rise in groundwater level, instantaneous application of overburden or load, or a decrease in soil void space (soil compaction).

Because of this relationship between pore water pressure and slope stability, precipitation is an influential factor in the occurrence of mass wasting events (DeGraff et al., 2008, Iverson, 2000). Steady rainwater infiltration increases groundwater levels over time, which in turn increases the pore pressure at any saturated level in the soil column (Iverson, 2000). However, shallow, rapid slope failure typically occurs during transient periods of heavy rainfall under already saturated conditions and not during long duration gradual groundwater increase (Iverson, 2000). Deep-seated landslides tend to be more responsive to long term trends in groundwater levels over seasonal or longer timescales (Iverson and Major, 1987). For this reason, precipitation tends to factor heavily in landslide prediction models (Cain, 1980). The likelihood that any given slope will fail is highly variable and dependent on geology, and slope stability response to rainwater infiltration can vary even within a single catchment (Von Ruetten et al., 2014). This results in the tendency of earthflows, which represent an intermediate form of slope failure between creeping movement and rapid debris flows, to undergo sudden periods of movement at different distinct locations and at different times (Prior and Stephens, 1970).

We can model the change in pore water pressure caused by infiltration of precipitation, assuming already saturated conditions with steady, uniform subsurface flow, by using the following equation derived from Darcy's Law:

$$\Delta P = -\frac{Q\mu_w L}{kA} \quad (4)$$

where, ΔP is the change in pressure, Q is the discharge, μ_w is the viscosity of water, L is the length over which ΔP occurs, k is the coefficient of permeability of the soil, and A is the cross-sectional area (Arora, 2003). The coefficient of permeability, k , is heavily dependent on the grain size of the soil and is expressed in units of distance over time (Arora, 2003). From this equation, we can see that with all other variables remaining constant, wherever there is an increase in groundwater level (i.e., a negative discharge), there will be a corresponding, and proportional, positive increase in water pressure.

1.1.3 Soil Void Dilation and Compaction

In addition to an increase in groundwater level, pore water pressure is also responsive to changes in soil void space. For undrained conditions, compaction (wherein soil void space decreases) causes a resulting increase in pore water pressure, while conversely, dilation of soil void spaces leads to a decrease in pore water pressure. Compaction can result from soil grain settling under shear strain (Iverson and LaHusen, 1989), seismic shaking, and from long term compression of a soil layer (Duncan et al., 2005).

The value that allows us to estimate the settling rate of a buried soil is called the coefficient of consolidation. Soil consolidation, or settling, is strictly tied to the rate at which water can drain from a soil. This is because:

$$C_v = \frac{k}{\gamma_w m_v} \quad (5)$$

where C_v is the coefficient of consolidation, and m_v is the coefficient of volume decrease (Terzaghi, 1943). The coefficient of volume decrease for a soil is derived from the following equation:

$$m_v = \frac{\frac{\Delta e}{-\Delta p_e}}{1 + e_0} \quad (6)$$

where Δe is the change in the ratio of void space within a soil, e_0 is the initial ratio of void space within a soil, and Δp_e is the change in effective stress within a soil (Terzaghi et al., 1996). Effective stress is the amount of stress from overburden supported by intergranular contact minus the pore water pressure. It should be noted that the expression $\frac{\Delta e}{-\Delta p_e}$ is also known as the coefficient of compressibility. The coefficient of compressibility value is distinct for different types of soils and is typically found experimentally. Generally, when effective stress increases, there is a corresponding decrease in the soil void space ratio. The magnitude is larger and the rate at which this

occurs is faster for large grained soils such as sand and less for fine grained soils such as clays, assuming all other variables are the same. It follows then, that void space reduction from soil compression results in an increase in pore water pressure. From equations (5) and (6), we see that the rate at which a soil can settle, as determined by the coefficient of consolidation, is directly related to the permeability of the soil and the compressibility of void space within the soil. Furthermore, all other variables remaining constant, a more permeable soil will settle faster because fluid can be expelled from the void spaces more rapidly.

1.1.4 Undrained Loading

An undrained load is any instantaneous or transient load applied to a slope in which the groundwater is incapable of evacuating in response at a timescale associated with the loading (Duncan et al., 2005). This results in a transient increase in the pore water pressure in the area beneath the applied load (Terzaghi et al., 1996). This inability of the groundwater to evacuate is directly related to the coefficient of compaction of the soil. In a permeable soil, such as sand, the voids between soil grains are larger, which allows the groundwater to evacuate more quickly, resulting in either no spike or a small spike in the pore water pressure. However, for a soil with smaller void spaces such as a clay, the groundwater is unable to quickly respond to the load, resulting in a spike in the pore water pressure. This relationship can be modeled with the following equation:

$$u = \left(\frac{w_i + w_a}{A} \right) - p_e \quad (7)$$

where u is the pore water pressure, w_i is the initial weight of the overlying soil and groundwater, w_a is the weight of the applied load, A is the area over which the weight is applied, and p_e is the effective stress (Terzaghi, 1943, Holbrook, 1998, Skempton, 1970). Because effective stress in an undrained soil is not affected by application of overburden in the short term, it can therefore be assumed that:

$$\Delta u = \frac{w_a}{A} \quad (8)$$

This equation implies that the change in pore water pressure, Δu , is directly proportional to the stress of the instantaneously applied load. This should make sense when considering the previously mentioned coefficient of compressibility. Without a change in effective stress, there is no change in soil void space, and therefore all increase in normal stress must be balanced by the pore water pressure.

When calculating changes in pore water pressure due to an applied load, we must first have a way to estimate the steady state pore water pressure prior to application. This is done with the equation:

$$u_0 = \gamma_w \cdot h \quad (9)$$

where u_0 is the pore water pressure at time zero, and h is the height of the water table (Duncan et al., 2005).

Combining equations (8) and (9), we see that the equation for total final pore water pressure is:

$$u = (\gamma_w \cdot h) + \frac{w_a}{A} \quad (10)$$

In other words, final pore water pressure after the immediate application of a load during undrained conditions is equivalent to the pore water pressure before the load was applied plus the stress added from the load.

1.1.5 Draining Time

If this overburden is applied for a long enough duration, as would be the case for a mass of soil deposited by a landslide onto a slope, it has the effect of driving out some of the groundwater and reducing pore water pressure to a new steady state level. This behavior is modeled by the following equation:

$$T_{99} = 4 \frac{D^2}{C_v} \quad (11)$$

where T_{99} is the time required for the groundwater to reach 99% equilibration following the application of the load, D is the length of the shortest linear path by which the

groundwater can drain, and C_v is the soil's coefficient of consolidation (Duncan et al., 2005). Complete equilibration can take many years to decades, depending on soil grain size, so it is useful to calculate the 99% equilibration value (Duncan et al., 2005). From equation (11), we can see that either a shorter drainage path (shallower depth to failure plane) or a more permeable soil both result in shorter drainage times.

1.2 Lidar

Understanding landslide mechanics first requires an effective method for monitoring deformation and internal slide processes. Historically, there have been many different methods employed to monitor landslide surface deformation. These range from the simple total station survey, to embedded inclinometers and extensometers, to complex equipment such as stationary GPS units and satellite imagery (Masood, 2016). Recently, however, lidar has become one of the primary tools for identifying landslides and monitoring their deformation (Burns and Madin, 2009). This is due to its relatively high accuracy (meter to millimeter precision), large coverage area capability, and its ease of use with 3D modeling and mapping software.

Lidar uses a laser beam, fired repeatedly at very high spatial and temporal intervals over a wide angle to create a 3D model of a surface or object. Lidar is collected via either an airborne or terrestrial based platform. Both types of these lidar are accurate to a millimeter to decimeter scale depending on the range from the scanner to the target and have seen an increased adoption in their use to identify landslide deposits and measure displacement using lidar derived image differencing (Ventura et al., 2011). For

example, airborne lidar has been used extensively for over a decade to identify landslides and monitor their evolution, especially in heavily vegetated areas, because of its ability to produce a bare-earth model (Glenn et al., 2005).

Terrestrial laser scanning (TLS) has also been used to monitor landslide surface displacement. A study of the Pisciotta landslide in Italy found that differencing of repeat scans could be used to measure deformation of the surface of the slide (Barbarella and Fiani, 2013). The process typically involves collecting several scans of a slope surface at periodic intervals, aligning those scans using visual identification of features and an iterative closest point algorithm, and then measuring the difference between point coordinates within scans. These changes in coordinate values represent changes in vertical elevation or horizontal feature location, and thus areas of deformation, deposition, or erosion. A few primary concerns in these types of studies are line of sight to features used for identification, proper alignment, and GPS accuracy for absolute georeferencing (Jaboyedoff et. al., 2010).

With current technology, a mid-range terrestrial laser scanner is capable of scan distances from 2 to 800 m, while higher end TLS equipment is capable of very long (6000 m) scan distances (Favorskaya and Jain, 2017).

1.3 Structure from Motion Photogrammetry

Structure from Motion (SfM) Photogrammetry provides an alternative method for modeling topography, and therefore can work in conjunction with, or in place of, lidar (Westoby et al., 2012). SfM is the use of optical images to reconstruct surface topography

of a target (Furukawa and Ponce, 2010). These images can be collected by hand or from a variety of platforms, including airplanes, unmanned aerial vehicles (UAV), weather balloons, and even painters' poles. Once collected, they are processed through either open source or proprietary software to produce a 3D point cloud. The software produces the point cloud by using multi-view stereo algorithms (Niethammer et al., 2012). Essentially, an algorithm is used to produce a 3D model in much the same way as the brain does, by determining spatial relationships between objects from multiple images at different oblique angles to the objects. Several recent studies have used SfM to monitor slide movement (Lucieer et al., 2013, Niethammer et al., 2012). SfM studies benefit from being relatively cost effective, easy and fast to implement, and site specific (Lucieer et al., 2013). However, unlike multiple return aerial lidar data, SfM methods do not typically penetrate vegetation, and therefore do not produce a point cloud capable of deriving an accurate bare-earth model.

1.4 Study Site: Silt Creek Landslide, Oregon

The site for this study, commonly called the Silt Creek Landslide, is a 3.8 km long complex landslide in the western Cascade Mountain Range (fig.1). The slide is 12 km directly south of the town of Mill City, Oregon and within the Thomas Creek Watershed. It encompasses an area of 2.3 km² and is intermittently forested, with some areas clear-cut, some in various stages of timber regeneration following harvest, and some areas forested. The slide is partially on public land managed by the Bureau of Land Management (BLM), and partially on land owned and managed by Weyerhaeuser

Figure 1: Silt Creek Landslide and nearby vicinity. Showing the location of the Silt Creek Landslide, and the Little Meadows SNOTEL site. The closest populated area, Mill City, is around 12 km to the north. Image source: Google Earth

Company, a privately-owned forest products company. The upper portion of the slide area, including the head scarp, upper benches, and upper transport zone, are managed by BLM. The land the study was conducted on is owned by Weyerhaeuser.

The slide trends towards the north-northwest direction (fig. 2). The source area is comprised of an approximately 1 km long rotational slump and forms a perched amphitheater shape of approximately 600 m in width (fig. 3). The lower edge of the source area is bounded by an internal scarp of about 135 m height and 495 m width which failed in June of 2014 and deposited material below it (fig. 3). At the beginning of

Figure 2: Overview of the Silt Creek Landslide. The slide trends towards the north-northwest, with a smaller currently inactive portion that trends more directly northward. The slide is nearly 4km long.

Figure 3: Comparison of the source area before and after the June 2014 failure. Derived from 2012 and 2015 lidar. Note the failure at the head scarp in the left of the image. The location of the internal scarp failure and resulting deposit are in the lower right.

this study period, November of 2015, this amphitheater area contained sag ponds and

debris from the upper head scarp. These remained visible in aerial photos as late as June 2016. During the summer of 2017, those sag ponds had completely drained (Allen, Bryan, Portland State University graduate student, personal communication, 2017), however, standing water had returned by the winter of 2017 (Shaw, S., Weyerhaeuser geologist, personal communication, 2018) suggesting that these ponds may undergo seasonal water level changes.

Below the source area, the lower 3 km of the complex is an earthflow with an average of ~9% slope over an elevation change of about 270 m (fig. 4). This earthflow

Figure 4: Topographic profile of the Silt Creek Landslide. Profile extracted from airborne lidar data. A to A' can be seen in the slide overview map in figure 2. Note the change in slope angle near the base of the debris deposits from the upper scarp failure, changing from a value of ~25% to ~9%.

landform bifurcates at 1600 m downslope from the head scarp into a smaller northward trending earthflow (fig. 2) and the primary flow, which proceeds north-northwest at about N20W. Only the main NW trending flow was active during the study period. The main

earthflow is 280 m wide at its narrowest point through the transport area, 2 km downslope from the head scarp, and extends to a maximum width of 1.2 km wide at the toe. Both the primary earthflow and the smaller secondary earthflow terminate at Thomas Creek. The toe of the primary flow has offset Thomas Creek by approximately 300 m to the north.

A catastrophic failure occurred at the internal scarp in June of 2014 (fig. 5). This

Figure 5: Image showing the results of the scarp failure. Image shows head scarp, internal scarp, and debris deposition resulting from the June 2014 slope failure. Image source: Google Earth

created a debris deposit of 0.11 km^2 with a runout length of 450 m, an average width of 250 m, and an elevation drop of around 140 m. Aerial imagery analysis showed that a

similarly sized failure had also occurred at the head scarp by June 2014, and anecdotal evidence suggests that the head scarp failure also occurred in the spring of 2014 (Shaw, S., Weyerhaeuser geologist, personal communication, 2017), although there are no data to precisely constrain the relative timing of the head scarp failure or its sequence of occurrence relative to the internal scarp failure. The primary earthflow reactivated at approximately the same time as the internal scarp failure.

The climate at this site is typical of the Western Cascades. The area receives most of its precipitation from moist Pacific marine air condensing as it ascends the Cascade Mountain Range (WRCC, 2014). The winter and spring months are generally wetter with dry summers (fig. 6). At the closest SNOTEL weather station to the study site, Little

Figure 6: Precipitation chart for Little Meadows SNOTEL site. Includes the water years preceding and following the study period. Note that the scan period, 2016, has the wettest December while 2015, when most displacement occurred, is the driest over-all year.

Meadows, precipitation averages around 38 cm per month between December and April

(USDA, 2014). Precipitation during the summer and early fall months reduces to nearly zero on average (USDA, 2014). According to this monitoring station, the total precipitation during the 2014 water year was 294 cm, 2015 was 243 cm, and 2016 was 305 cm (fig. 7). Yearly average for this site is 293 cm.

Figure 7: Total yearly accumulated precipitation at the Little Meadows SNOTEL site. Average value is 293 cm. Note that 2014, 2015, and 2016 are all generally average years, with 2015 the driest of the three and 2016 the wettest.

Silt Creek is sourced from springs on the bench downslope of the head scarp and proceeds along the right margin of the primary earthflow down to Thomas Creek.

Thomas Creek, in turn, is a tributary within the South Santiam watershed (fig. 1) and empties into the Santiam River (USGS and USDA, 2013).

In November of 2015, Weyerhaeuser Company installed a weather monitoring station on the toe of the Silt Creek Landslide. This monitoring station reported a total precipitation of about 224 cm during the 2015 water year (not including the month of October). The monthly trend matched that reported by the Little Meadows SNOTEL site remarkably well, with Silt Creek reporting slightly lower (79%) monthly values, most likely due to its lower elevation (fig. 8). This suggests that the Little Meadows site can

Figure 8: Graph comparing precipitation levels at the SNOTEL Little Meadows Site vs. the Silt Creek site. Note the strong correlation of values, and that Little Meadows has consistently higher values. This is probably due to its higher elevation (~900 m).

provide a good proxy for precipitation levels at Silt Creek prior to the installation of the monitoring station there (fig. 9).

As previously noted, precipitation is closely tied to slope stability. Hillslopes near this study site are particularly susceptible to failure during especially wet winter storm events such as those which occurred in 1996 and 2004 (Sobieszczyk, 2010). Additionally,

Figure 9: Plot of accumulated precipitation measured at the SNOTEL Little Meadows site vs. the Silt Creek site. The good linear fit shows that there is a high degree of correlation between the two data sets, suggesting that Little Meadows data is a good proxy for precipitation values at Silt Creek.

studies done using satellite imagery to measure displacement within Cascade landslide complexes to the north also found that movement is seasonal, with activation occurring in the early winter months (Tong and Schmidt, 2016, Hu et al., 2016). However, failure of the internal scarp occurred in June of 2014, when precipitation was low, therefore the Silt Creek Landslide scarp failure may be related to some other, yet undetermined, factor.

The underlying geology of the slide source area is mapped as tuffaceous volcaniclastics and basalt/andesite of the Little Butte Volcanics Terrane. These deposits consist of air-fall or ashflow tuffs and basaltic flows or domes (Walker and Duncan, 1989). The terrane is typical of an ancestral Cascade volcanic setting and is interbedded to the west with sedimentary rock and overlain in the east by Cascade Mountain volcanic deposits (Sherrod, 1989). These volcanic deposits are most likely early Miocene in age,

22- 17 Mya. (Sherrod, 1989). Images of the source area show apparent bedding and folding (fig. 10) and columnar basalt blocks within the slide deposit and head scarp agree

Figure 10: Image showing apparent bedding and folding within the head scarp at the Silt Creek Landslide. Image source: Google Earth.

well with the mapped geology. Debris deposits from the internal scarp failure consist of poorly sorted clasts of weathered and friable pumice or scoria.

1.5 Previous Work

In addition to a broad understanding of the physics of slope stability and the mechanics of landslides described in the previous sections, it is valuable to have an understanding of previous work dealing with landslides complexes that exhibit similar patterns of displacement activity. This includes work that informs the mechanics and

relationships between internal processes within landslides, especially those in the Cascade Mountains, and studies that deal with undrained loading.

1.5.1 Other Studies at this Site and in the Cascades

One study specifically looking at creeping landslides located in the western Cascade Mountain Range found a complex and dynamic relationship between areas of different rates of movement within individual slides (Swanson and Swanston, 1977). This study, which looked at areas similar to the Silt Creek Landslide, found that discrete blocks within the slide body translate downslope at different rates and different times, resulting in irregular creep rates for different locations within the slide. Movement was again found to correlate with precipitation levels, suggesting that pore water pressure may be the dominant movement trigger.

Swanson and Swanston (1977) also found that deeply weathered and highly altered volcanoclastic materials were highly susceptible to mass-movement, and that slide configuration was heavily influenced by bedrock structure and material. Crucially, the study found that slow creeping landslides may spur the initiation of rotational slumps. These slumps then act in concert with the creeping portion of the slide to produce a landslide complex that exhibits periodic rapid failure along with continual gradual movement.

Another study used aerial lidar to study sediment sources in the Little North Santiam River Basin and found that earthflows and slumps were common in some sections of the basin, with 37% of the lower basin showing slide activity (Sobieszczyk,

2010). This work found that the majority of landslide displacement within a single complex in this basin could occur as pulses which occur episodically spaced over decadal scale intervals. Although Silt Creek is not within the Little North Santiam River watershed, it is only 11 km to the south, and has a similar topographical and climatic regime.

At the Silt Creek Landslide site, Booth et al. (2017), used aerial lidar correlation and field surveys to find displacement values for the Silt Creek Landslide surface for dates immediately prior to and during this study period. Aerial lidar correlation was done by using the phase correlation method on lidar datasets collected in October 2012 and October 2015. The phase correlation method uses a surface patch matching algorithm between two aligned datasets to determine the offset present between them. The minimum detectable amount of displacement using this method was 0.5 m.

Results from the correlation study were inconclusive for the upper portion of the study area at the source zone and the base of the internal scarp failure. This is because the topography changed radically during the failure, which prevented the surface matching algorithm from recognizing features (Booth et al., 2017).

Results from the earthflow portion of the complex better expressed the displacement on the slide surface. The maximum observed rate of displacement was 13 m over 17 months near the upper part of the transport zone. Displacement decreased with increasing distance downslope towards the toe and was within the minimum measurable amount of displacement for the western half of the toe (Booth et al., 2017). The maximum annual displacement rate determined by this study was $9.17 \frac{m}{yr}$.

Results from field surveys, taken along the landslide's eastern margin at the upper part of the transport zone, show little to no measurable movement between the failure of the internal scarp in June of 2014 and November of that year (Booth et al., 2017). Between November 2014 and October 2015, displacement rates increased, and the location underwent a total of about 5 m of displacement along the margin. The western margin of the slide at the same elevation underwent a maximum displacement rate of 0.6 m per month in July of 2014 and slowed to 0.1 m per month in November of that year. Between November of 2014 and October of 2015 there was a total of 7.7 meters of displacement measured (Booth et al., 2017). The difference in displacement amounts between the two margins is assumed to result from a diffuse shear zone along the eastern margin and a discrete shear zone along the western one. These disparate shear zone types are clearly visible on site and may stem from differences in underlying geology, differences in pore water pressures, differences in soil types, or some other factor.

1.5.2 Previous Relevant Work

Previous research that informs an understanding of the relationship between applied loads, undrained soil conditions, increased pore water pressure, and landslide surface deformation are useful background for later discussion of the results from this study. There are relatively few studies capturing slide reactivation due to an applied load, but several investigating the relationship between displacement on upper and lower slopes. This shows that while the effects of undrained loading are well researched, capturing these transient periods of deformation is somewhat difficult. The following summary of research emphasizes studies that deal with slope displacement triggered by

undrained loading or increased pore water pressure due to internal slide processes, and serve to provide context to the implications reached at the end of this project.

Hutchinson and Bhandari (1971) first documented the effects of undrained loading using piezometers to show that pore water pressure in a mudslide could increase as a result of the deposition of material from debris flows in an upper section of the slide. The study used two landslide sites and found that pore water pressure increased substantially after undrained loading from material deposition on the upper portions. The increase was substantial enough to make the pore water pressure strongly artesian and in some locations near the geostatic value. The results of the study point out that evidence of this strong increase in pore water pressure could possibly manifest on the surface of the terrain as mud volcanoes until the pressure has dissipated enough to return below the geostatic value (Hutchinson and Bhandari, 1971). The authors conclude that the increase in pore water pressure caused by material deposition in the upper section of the slide lead to displacement on the lower section of the slide, even though the slope angle there was low enough that movement would not be expected under typical conditions.

A study done in 1989 along the coast of England found that pore water pressure increases during the study period were always coincident with slide surface downslope movement and that these pore water pressure increases could stem from internal self-loading of the slide (Allison and Brunsden, 1990). This study used ground stakes attached to potentiometers via filament and aligned along a temporary framework to collect displacement measurements for the transport zone and toe of a coastal mudslide. Pore water pressure data were collected coincidentally using steel diaphragm pressure

transducers. The results of the study showed that an earthflow can undergo multiple unique complex patterns of downslope movement and that a corresponding pattern of increase in pore water pressure should be expected along with these patterns of displacement.

Additionally, the Allison and Brunsden (1990) study found that a slide can self-load. This concept is similar to that presented by Hutchison and Bhandari (1971), with the exception that the loading does not require the deposition of material in the upper slide area. Allison and Brunsden (1990) suggest that the surface deformation in the upper portion of the slide results in an increase in pore water pressure in lower sections of the slide. This increase in pressure has a destabilizing effect in the lower sections and can lead to displacement there as well. In this way, displacement can propagate downslope. Their results also showed that landslide downslope surface movement is related to a combination of pore pressure changes stemming from internal slide mechanisms and external precipitation patterns.

Massey et al. (2013), studied the Utiku Landslide in New Zealand using continuous GPS (cGPS) units, inclinometers installed in drilled bore holes, and piezometers to monitor pore water pressure. The cGPS units had a relatively high accuracy (± 9 mm) and monitored displacement continually. The study found a correlation between increased pore water pressure and displacement rate, with periods of faster displacement corresponding to periods of precipitation initiated pore water pressure increase.

Displacement rates at the Utiku Landslide were highly variable, with the majority

of overall displacement occurring during a few episodic “fast displacement” events. The upper value for total displacement on the slide was 2.75 m with “fast displacement” events lasting several days accounting for as much as 1.2 m of this total. The authors found that seasonal variations in pore water pressure were coincident with periods of movement and attributed this to shrink/swell behavior of the clay-rich soil at the site. Wet periods resulted in soil swelling and downslope movement, while dry periods led to soil contraction from drying out, during which the authors witnessed a smaller upslope “rebound”. They concluded that reactivated slides within similar climate and topographic regimes may be expected to undergo a similar pattern of fast deformation along basal slip surfaces, slow internal plastic deformation of the slide material, and alternating periods of downslope movement and upslope rebound stemming from shrink/swell behavior of the soil.

Overall, these studies show that landslides can exhibit intricate deformation patterns and relationships between areas of differing displacement rates within individual complexes. They serve to highlight the importance of pore water pressure in relationship to displacement velocities within a landslide, and show how that pore water pressure can be affected by the slide’s own internal processes. Finally, they lay a groundwork for interpretation of results from this study.

1.6 Purpose of Study

Applied geology benefits from faster, more efficient, and more accurate tools to assess the previous and future expected displacement of landslides. Aerial lidar collection

provides geologists with accurate (generally on the order of 1 m resolution) topographic data that have revolutionized our ability to locate and delineate geomorphological features such as landslides (Burns and Madin, 2009). However, aerial lidar collection is relatively expensive, is heavily weather and groundcover dependent, and requires many hours to prepare and complete. These limitations make it a poor candidate for rapid-response or short temporal scale repeat data collection. Terrestrial laser scanning and photogrammetric data can provide a cheaper, faster solution that is more targeted and therefore more efficient (Abellan et al., 2009, Fonstad et al., 2013). This project sought to use these technologies to develop an effective method for sub-annual temporal scale monitoring of active landslide deformation.

Additionally, this project used a novel photogrammetric method to reconstruct the displacement of the earthflow after the scarp failure but prior to the scanning period. This included dissection, reconstruction, and measurement of a 3D model of a portion of a gravel road which had been deformed due to landslide displacement.

Gaining a clearer understanding of the mechanics that exist within these large, dynamic landslides can better inform our expectations of the mechanics of similar slides in other locations. Therefore, this project also sought to illuminate any potential relationship between the failure at the internal scarp and the earthflow below it by providing insight into how the lower portion of the slide reacted following the deposition of the material from the slope failure.

2 Methods

Methods are discussed in the chronological order of the occurrence of displacement events at the Silt Creek Landslide, and not necessarily in the order in which the measurement techniques were conducted. This is to help provide a clearer image of the evolution of displacement rates at the site over time.

First, historical photo analysis was conducted on aerial images of the site spanning from the 1950's to current. This provided insight into past displacement and context for the current deformation at the site. Additionally, this initial investigation provided insight into potential locations for conducting field scans.

Next, aerial lidar datasets of the slide collected in 2012 and 2015 were used to determine the scope of the catastrophic internal scarp failure and the displacement which had occurred afterwards in the reactivated lower slope. The purposes of this analysis were both to determine a numerical estimate of the volume of material deposited from the scarp failure, and to measure displacement that occurred on the slide surface following the failure but prior to the highly detailed TLS scans. This not only provided new data, but also served to provide additional displacement values to reinforce the results of the TLS and photogrammetric work.

Following the aerial lidar analysis, Structure from Motion photogrammetry was used to resolve displacement values for a portion of the reactivated landslide prior to the beginning of the TLS point cloud collection period but after the scarp failure. Images used for the photogrammetry were collected in November of 2015.

Terrestrial laser scanning at the slide began in October of 2015. Initial TLS data

were collected at several locations along the eastern margin of the Silt Creek Landslide, and these scans were repeated at three-month intervals. These were used to create 3D point clouds that allowed for the selection of landmark features which were then used to track surface displacement. Tracking was done by recording landmark coordinates and deriving displacement vectors.

Finally, salt dilution gauging was used to measure the volumetric discharge of Silt Creek. This aimed to provide insight into the relative groundwater discharge of Silt Creek at locations corresponding to those where landslide displacements were measured in the other portions of the study.

2.1 Historical Imagery Analysis

Images of the location were compared using orthorectified aerial imagery in ArcMap and in Google Earth's historical imagery. Images used in ArcMap were downloaded from the USGS EarthExplorer data repository. These image datasets were collected in 1955, 1976, 1981, 1994, 2001, 2012, and 2014. Images viewed in Google Earth were collected in 1994, 2000, 2005, 2011, 2013, and 2016.

Images were evaluated to find changes in the head scarp location, emplacement and displacement of gravel roads at the site, debris deposits, presence of sag ponds and other landslide related terrain, and estimated date range of any scarp failures on the slide. Any detectable displacement was measured and recorded. This was done manually using the tools available within ArcMap and Google Earth.

2.2 Aerial Lidar Analysis

Aerial lidar was utilized to determine the average depth of the deposits stemming from the June 2014 slope failure, as discussed in section 2.2.1, and to derive displacement estimates for the gravel road measured as part of the photogrammetry, as discussed in section 2.2.2. This was done using aerial lidar datasets from 2012 and 2015. The lidar collected in 2012 had an average deviation of ± 0.03 m in the vertical direction and a median horizontal accuracy of 0.04 m (DOGAMI, 2012). Uncertainty for lidar collected in 2015 had a fundamental vertical accuracy of 0.07 m and a horizontal accuracy of 0.30 m.

2.2.1 Debris Deposition Measurement

Two lidar raster images were used to determine the average depth of the deposits from the June 2014 failure. The first was collected in October of 2012 and was downloaded from the Oregon Department of Geology and Mineral Industries lidar viewer. The second was collected by Weyerhaeuser in October of 2015.

The lidar datasets were imported into ArcMap and clipped to the study area. A third raster image was created from the two by vertically differencing them using the ESRI raster math toolset (fig. 11). Settings for the tool subtracted the raster value for pixels from the 2012 lidar from the raster value for pixels from the 2015, and then exported those values to a new difference raster. This difference raster contained the change in surface elevation at any given location on the slide surface.

Figure 11: Map showing areas of material deposition and removal. Image is the result of the aerial lidar differencing. Note the large down-dropped area at the center of the head scarp and the increase within the deposit area. The deposit area polygon outlines the debris deposited by the internal scarp failure. Values are in meters.

Using the 2015 image, a polygon was constructed that outlined the deposits from the internal scarp failure. A 15 m by 15 m grid of points was then created within this polygon using the ArcMap fishnet tool. The fishnet tool creates a grid of a given spacing over a given area and creates centroid points for each square in the grid. These centroid points were used to derive raster values. Using the extract to points tool, the raster pixel value for the 2012-2015 surface difference image was recorded for each of the centroid points. In this way, an evenly spaced sample of elevation change in meters for locations

within the deposition area was collected. This elevation change represents deposition thickness. In all, 5784 values were recorded and used to calculate an average deposition thickness. This deposition thickness was then used to calculate mass of the deposit. Due to uncertainty within the aerial lidar datasets, this mass value represents an estimate of the deposited material only.

2.2.2 Road Displacement Measurement

Aerial lidar was also used to estimate the displacement of a gravel road about midway down the slide to validate the results of the later SfM analysis (section 2.3). Both the 2012 and 2015 lidar datasets were used for this process. The lidar images were already georeferenced prior to use. They were imported into ArcMap and transparency was applied to both datasets to allow for comparison of the superimposed images (fig. 12).

The measurement tool was used to manually find horizontal displacement values between the 2012 and 2015 images. This was done using the edge of a pixel within the earlier image as a marker and visually estimating the closest corresponding pixel edge location on the later image. Pixel size corresponds to 1 m^2 .

This process was repeated for seven locations along the road, covering an area beginning at the eastern margin and continuing around 100 m onto the active slide surface. Selected measurement points were spaced evenly over the 100 m. This corresponds to the same area of road studied in the following SfM section (2.3).

Figure 12: Gravel road displacement image. Made from lidar datasets from 2012 (in yellow shades) and 2015 (in brown shades) overlain with transparency applied. Note that road displacement decreases to zero in the right of the image where the road turns to the north. This corresponds with the edge of the right margin.

2.3 Structure from Motion Photogrammetry

The SfM portion of the study was completed at the beginning of the TLS collection period, November 11, 2015, along a short stretch of a gravel road that crossed the slide laterally about midway down, and corresponded to TLS scan location 2. SfM was done to model deformation of the gravel road at this location. The deformation occurred after reactivation of the slide in June 2014 (Hinkle, J., Weyerhaeuser geologist, personal communication, 2015), but before the beginning of the TLS study. The modeled section of road extended laterally from ground assumed to be stable, through the right

margin, onto the surface of the slide. A total distance of 105 meters and an average width of 4.3 meters was covered.

Images for SfM were collected with a 12-megapixel Cannon Powershot A1200 digital camera set on a ten-foot-high painter's pole. The operating system was set to capture images at two second intervals as the camera was moved along the road. A total of 979 images were collected. The resolution of these images was 4000 by 3000 pixels. Images were captured with a mix of oblique and vertical orientations to reduce long length scale warping errors common in long, narrow datasets where only vertical look directions are used. The camera CCD sensor format is $\frac{1}{2.3}$ inch and the focal length used was 5 mm. This resulted in an average field of view for each image of 4 m by 3 m.

Locations on the road that had cracks or deformation received a higher density of image collection than did flat undeformed areas. This ensured greater point density for these areas in the final point cloud. Blurred, underexposed, and out of focus images were removed from the final set of images used to process the point cloud. This was done to reduce errors during the cloud creation process and within the final point cloud.

The final set of images contained 841 pictures. These were processed through an open source software workflow that included Bundler (<http://www.cs.cornell.edu/~snively/bundler/>), Clustering Views for Multiview Stereo (CMVS) (<https://www.di.ens.fr/cmvs/>), and Patch-based Multiview Stereo Software version two (PMVS2) (<http://www.di.ens.fr/pmvs/>). Processing involved first running the images through Bundler (Snively et al., 2006) to produce a sparse point cloud. Bundler uses input image sets and given camera parameters to relate objects in 3D and create a

low-resolution point cloud. The resulting output was then run through CMVS software (Furukawa et al., 2010). CMVS is preprocessing software that is used in conjunction with PMVS2 and is designed to speed up workflows that have large image sets by clustering images to make them easier to manage. The output of CMVS was then processed through PMVS2 which produces a dense point cloud (Furukawa and Ponce, 2010). The result of this process was a point cloud with 3.4 million points. Overall average point density was just under one point per square centimeter (about 7600 points per square meter).

Once the point cloud was created, it was imported into CloudCompare software. The point cloud was scaled and aligned to the location 2 TLS scan (described in section 2.4) by selecting four matching points within the location 2 point cloud and the gravel road SfM point cloud. While the SfM point cloud was initially unitless, this alignment to the TLS scan georeferenced the SfM point cloud to the same metric coordinates as the TLS scan, thereby allowing for accurate measurement of dimensions and displacements.

The point cloud was then cut into sections using the CloudCompare segment tool (fig. 13). Fifteen existing joints in the displaced gravel road were used as guides for the segmentation process. This resulted in a total of 16 blocks; one to be used as a stable reference and 15 to be adjusted. In this way, terrain that had been displaced as discrete solid blocks could be manipulated independently. The segmented road model was then reassembled to replicate the conditions of the road prior to displacement. This was done by selecting and manipulating either the X, Y, or Z dimensions independently and

Figure 13: Image showing the location of each of the 15 joints used to partition the road point cloud. Actual cloud division was done to preserve the shape of each joint and does not exactly match the lines above.

aligning them manually. Rotation about the Z axis was used to correct for block rotational displacement, but was avoided for both the X and Y axes for simplicity. The result was a point cloud that was representative of the gravel road immediately prior to the internal scarp failure in June 2014.

The original collected point cloud was imported into the workspace and compared against the reconstructed model, in much the same way as the TLS analysis was completed, to create displacement vectors. Objects were manually selected using point picking in the reconstructed road point cloud and the coordinates were recorded. That object was then reselected in the original deformed point cloud, and the new coordinates were recorded. Vectors were created and measured for these object displacements. The result was a set of 13 vectors that indicated the amount of displacement undergone by the gravel road between the time of the internal scarp failure, June 2014, and the beginning of the study, November 2015.

2.4 Terrestrial Laser Scanning

Terrestrial laser scanning (TLS) was conducted with a FARO Focus 3D X330 laser scanner at six locations along the right flank of the slide (fig. 14). The FARO Focus

Figure 14: Map of TLS scan locations. Outlines show the position and field of view of each of the final five locations used for the TLS portion of the study. Although six locations were originally selected, and scans were completed at all six locations, location 5 was omitted from the study due to alignment error arising from vegetation growth between scans.

3D scanner is considered a mid-range scanner (Favorskaya and Jain, 2017). Scan locations were selected to ensure that the scanner would reside on ground assumed to be stable while maximizing the scanner's view of portions of the slide that were assumed to

be mobile. Determination of stable and unstable ground was made based on surficial expression of characteristic landslide features such as hummocky topography, irregularly leaning trees, and especially the presence of lateral shear margins which were visible in the field. A preference was given for scan locations that were at higher elevation than the slide surface, thereby providing a better overview of the location and a greater number of trackable objects to monitor on the slide surface. These scan locations were flagged to ensure exact replication during later scans.

It should be noted that the terms “point cloud” or “scan” are used interchangeably within this paper to refer to a single terrestrial laser scan taken on a specific date at a specific location. The term “collection” refers to all scans from a particular date. The term “scene” refers to all scans from a particular location.

A total of four scans were completed at each of the six locations over the course of the 2016 water year. Scans were temporally spaced by approximately three months to provide even interval monitoring periods. Due to access limitations, collection 1 was conducted on two dates, with the scan at location 1 occurring on October 16, and the scans at all other locations occurring on November 21, 2015. Collection 2 was conducted for all locations on March 8, 2016. Collection 3 was conducted for all locations on June 27, 2016. The study was completed with the fourth and final collection on October 10, 2016. The result was a total of twenty-four point clouds grouped into four collections and six scenes.

Given the time available for scanning, the scanner was set at a resolution and a quality level that would ensure that trackable features would be resolved, and

uncertainties were likely to be much smaller than actual displacements. Resolution is a measurement of the density of the point cloud produced by the scanner, while quality is a measurement of the amount of noise reduction processing done on the resulting point cloud (FARO, 2015). These settings are adjusted at the time of collection. In both cases, these settings were one step down from the scanner's maximum possible quality and resolution. This resulted in a final scan with around one-quarter of the resolution possible with this scanner at maximum settings. These scan settings were necessary due to time constraints, and were selected so that each scan duration took approximately 30 minutes. These time constraints stemmed from battery capacity and the requirement to complete each collection within one day. With each scan taking about 30 minutes and six scan locations, the total on site scan time was about three hours, not including equipment preparation time and time required to relocate between scans. These settings produced an average point cloud density of 175 points per square meter for all scans in the study, or equivalently, an average point spacing of about 8 cm. Point spacing was least near the position of the scanner and increased with increasing distance from it. The maximum scannable distance was 330 m, which was comparable to the lateral width of the slide. Scan fields of view were restricted from a full 360 degrees to include only non-stable slide surfaces and nearby stable surfaces and to remove distant unrelated terrain that would represent unnecessary additional data. This ensured a more manageable file size would result from the scan. In addition to collecting point cloud data, the scanner also collected .jpg format digital images in 360 degrees for all locations. These images were used to colorize the resultant point cloud.

The TLS scan raw data were imported into FARO Scene software for initial processing. All four scans for each location were added to a location workspace. The first operation performed was “apply pictures”. This operation uses images collected by the scanner at the end of the point cloud data collection to colorize the point cloud. The next operation performed was a general alignment of the three subsequent scans to the initial scan. This was done by setting the first scan to the “reference scan” in the scan properties and then using the “place scans” tool in the registration operations menu. The “cloud-to-cloud” version of the FARO Scene “place scans” tool was used for this process. This had the result of aligning all subsequent scans to the initial scan. However, because the point clouds used for this alignment included displaced sections of the landslide surface, the alignment quality was poor and was only used for the purposes of removing compass direction error which occurred during the cloud collection process. UTM coordinates collected by the scanner’s internal GPS were noted for the first scan at each location in order to later georeference the scans in an absolute sense.

Once this initial alignment was complete, each point cloud was exported as a comma separate value (CSV) text file and imported into CloudCompare software (<http://www.danielgm.net/cc/>) for fine alignment. This was a multistep process. For each location, stable, off-slide terrain was clipped out of each scan point cloud into a separate point cloud object. Care was used to ensure that all the resulting stable terrain clouds used the same area. All further alignment processing used these stable terrain point clouds with the location’s first point cloud used as a reference. An initial manual alignment was completed by selecting a minimum of four matching points, based on landmarks common

to each cloud, and then updating the cloud placement. This was fine-tuned using the root mean square error (RMSE) that resulted from the alignment process. RMSE is a measurement of the average offset between each point in the model point cloud (in this case the point cloud from collection 1) and the nearest point in the aligning point cloud (in this case, the point clouds from all subsequent collections) and represents the error inherent in aligning two randomly spaced point clouds. Fine tuning the alignment was done by removing and reselecting points which had a high resulting RMSE until the overall RMSE was less than 0.02 m. The alignment process was then completed with a fine alignment which used an automated iterative closest point (ICP) algorithm. The ICP algorithm adjusts the rotational and translational position of the aligning point cloud (the ones from the subsequent collections) to the model cloud (from the first collection at any given location) to produce the lowest possible RMSE. The ICP algorithm used for this process was set to use a random sampling limit of 500,000 points, adjust X, Y, and Z rotation and translation, not adjust scale, and to ignore farthest points. The resulting rigid body roto-translation matrix and RMSE were recorded and the same roto-translations were applied to the original unclipped point clouds, thereby aligning each complete scan to the initial one for all locations. The RMSE value produced during the ICP algorithm alignment process not only applied to stable, non-slide surfaces, but also pertained to the entire point cloud and represents the inherent error arising from the random spacing of points within two clouds collected in different scans.

Displacement vectors in the X and Y direction were then created via a point picking method. Landmarks were identified on the slide and points were selected from

each of these landmarks in each scene. Landmark points were selected to be as close to the ground as possible to ensure that the resulting displacement vectors did not include errors from tree trunk swaying. Displacements in the Z direction were not calculated since vegetation growth between scans forced selection of points higher up on landmarks in successive scans, thereby imparting error in any final changes in Z values. Exactness in repeat point selection on landmarks within each scene was limited by the RMSE and increased point spacing on more distant landmarks. A minimum detectable difference (MDD) value was calculated using stable terrain landmarks to establish uncertainty. The MDD represents the minimum value that can be considered valid measured displacement within each scan, and any vectors below this value were omitted from the final calculations. This was calculated using coordinates for ten immobile landmarks on stable terrain, such as tree trunks and stumps, which were recorded from the initial scan and then located and re-recorded for each successive scan at each location. The MDD value was derived by measuring the apparent displacements of these ten landmarks and averaging them. MDD values were calculated first in the X and Y directions, and then an over-all value was derived using the following equation:

$$E_{MDD} = \sqrt{E_X^2 + E_Y^2} \quad (12)$$

where E_{MDD} is the overall minimum detectable difference, E_X is the average offset of stable landmarks in the X direction, E_Y is the average offset of stable landmarks in the Y direction.

These calculations provided an estimate of the misalignment present in each direction and cumulatively once the clouds were completely processed and aligned. Coordinate values were in meters and were relative to the scanner location origin point, so they represented a measurement of uncertainty within the reference frame of the scan, rather than uncertainty in an absolute georeferenced coordinate system. Differences in landmark point location from scan to scan that were greater than the MDD represented actual displacement of the slide surface and any values that were less than the MDD were removed.

In addition to using the MDD to define actual landslide displacements, an additional criterion was applied to locations 3, 4, and 6, that the apparent displacement direction had to be consistent with the known downslope direction of landslide motion. These locations had a high degree of variability in displacement vector direction compared to the other scans. This stemmed from vegetation growth between collections requiring selection of higher points on landmarks in successive scans, thereby inserting landmark lean into the final vector value. The strike of the margin of the landslide was used to calculate the estimated direction of downslope movement, and vectors that were greater than 22.5 degrees obliqueness to this direction were removed from the final calculations. This eliminated measurements that were biased from measuring at different elevations on landmarks such as tree trunks, which often tilted in directions other than the displacement direction. Tree tilt is a common occurrence in topography where landslide activity has occurred (Wistuba, et al., 2013).

A total of 457 landmarks were monitored during this study: 109 at location 1, 76

at location 2, 83 at location 3, 119 at location 4, zero at location 5 (vegetation growth at location 5 reduced alignment quality so much as to necessitate its removal from the study.), and 20 at location 6.

The coordinates for each landmark in each of the four collections were entered into a spreadsheet and stored in a CSV file before finally being converted to UTM coordinates using excel. UTM coordinate calculations were based on the values recorded from the scan sensor in FARO Scene, specifically by translating the scan origin point (0,0,0) for each point cloud to the easting and northing values recorded with the scanner's internal GPS and then updating all other point coordinate values based on their reference to the new origin coordinates. Absolute accuracy in point locations was limited by the GPS accuracy to 3.81 m. The points were then imported into ArcMap for vector creation. This was done by creating a polyline feature class that connected each landmark coordinate for each scan in the order of collection. While each successive scan within a scene was precisely aligned to the first scan, point clouds for neighboring scenes were not aligned to each other. This was due to inconsistency of $\pm 6^\circ$ from the compass sensor. This slight rotational error meant that overlapping landmark displacement vectors from neighboring locations did not line up in the final vector maps. Therefore, at this point the final displacement vectors for each location were rotated about the origin to align correctly with the scans from neighboring locations. This was done under the assumption that aligning overlapping landmarks from neighboring scan locations would result in accurate north/south alignment of the all final vectors for all overlapping locations.

Final processing of the displacement vectors included removal of aberrant values

caused by human error during point picking. This human error could derive from incorrect coordinate recording or erroneous selection of landmarks. A total of 28 landmark displacement vectors were discarded due to human error: 16 at location 1, five at location 2, two at location 3, two at location 4, zero at location 5, and three at location 6. After removing these human error vectors, removing the vector values below the MDD, and applying a directional threshold to locations 3, 4, and 6, the number of displacement vectors used in calculations was reduced to 139 for location 1 (87% of all collected vectors), 54 for location 2 (71% of all collected vectors), 27 for location 3 (33% of all collected vectors), nine for location 4 (8% of all collected vectors), zero for location 5, and five for location 6 (25% of all collected vectors).

Final displacement values were plotted in excel to determine if any trends existed. A linear trendline was applied to displacements relative to downslope position within the slide. A logarithmic trendline was applied to displacement values relative to lateral distance from the margin within the slide.

2.5 Hydrologic Measurements

Understanding the hydrology of the site, especially measuring where groundwater discharge was greatest, was a key component of this study. Finding the stream discharge volume of Silt Creek at locations corresponding to TLS locations provided insight into groundwater recharge and discharge rates. Since groundwater levels are an important factor in landslide stability (Iverson, 2000), having insight into which locations on the slide have a higher groundwater discharge rate would better constrain the relationship

between groundwater levels and deformation of the Silt Creek Landslide.

Discharge volume was found using a salt dilution gauging method (Moore, 2003). Salt dilution gauging involves injecting a saline solution into a waterway and monitoring downstream changes in conductivity of the water. Changes in conductivity are directly proportional to changes in the concentration of salt ions within the stream water. This change in concentration allows for the calculation of the volumetric discharge of the stream. Salt dilution gauging is useful in that it requires very little equipment, and materials are inexpensive. However, it is effective only for smaller waterways, and not for a stream with discharge greater than $\sim 100 \frac{m^3}{s}$ (Moore, 2003). It can also lose effectiveness when measuring long stretches of a turbulent waterway (>100 m length), since the saline solution becomes diffuse and the change in conductivity is harder to detect.

Four locations were selected corresponding to four of the locations used for the TLS portion of the study (fig. 15). At each of these four locations, an array of three conductivity meters was used to measure discharge values for Silt Creek.

Prior to collection of the discharge volume, it was necessary to determine the K value for the water within Silt Creek (Moore, 2003) as expressed in the following equation:

$$Q = \frac{V}{K \Delta t \sum_n [EC(t) - EC_{bg}]} \quad (13)$$

Figure 15: Map of the hydrology measurement locations. Shows relationship between Silt Creek and the four locations selected for salt dilution gauging. Note that location 4 is the highest elevation location and corresponds to TLS location 1.

where K is the value of the slope of the relationship between the relative concentration (RC) of salt within the stream water and its electrical conductivity (EC); Q is discharge, V is volume of injected saline solution, t is time, and EC_{bg} is the background electrical conductivity (Moore, 2005). The K value must be found experimentally using water from the stream held at a temperature as close as possible to that of the stream. This was done by collecting stream water, measuring its background EC , and then monitoring the EC while adding controlled amounts of diluted saline solution. This quantifies the linear

relationship between EC and RC . Once the K value was found, it was used in calculating the RC of the diluted saline solution within Silt Creek based on the EC .

All conductivity measurements were collected using a Vernier LabQuest 2 interface with a Vernier CON-BTA conductivity probe. This probe was set to mid-range measuring $0\text{--}2000 \frac{\mu S}{cm}$. The sensor has automatic temperature compensation from $0\text{--}35^\circ C$ and has an accuracy of $\pm 3\%$ for readings using the mid-range setting (Vernier, 2016). Stream water conductivity was recorded at one second intervals.

Three sensors were used at each location and were placed at 10 m intervals. Saline injection occurred 10 m upstream from the first sensor. Fifteen liters of saline solution were prepared with an initial concentration of $1000 \text{ mg } \frac{Cl}{L}$ and injected at a rate of about $3 \frac{L}{s}$. Initial concentration of the saline solution was selected based on recommended final stream water concentration of $600 \text{ mg } \frac{Cl}{L}$ or less (Moore, 2003). This suggested concentration is based on health limits for freshwater organisms (Moore, 2003). Sensors were allowed to collect data until conductivity values returned to a constant value.

Discharge was calculated from the conductivity measurements using equation (13). Uncertainty values were calculated by using the 3% sensor error per measurement given in the Vernier documentation for a total uncertainty value of 17% per discharge value.

3 Results

Results are once again reported in chronological order, similar to the methods section. They include information collected during the historical imagery analysis, displacement and debris deposition values derived from aerial lidar, analysis of the SfM portion of the study, analysis of the TLS portion of the study, and results of the hydrologic measurements. Additionally, error or uncertainty values associated with each of these portions of the project are reported.

3.1 Historical Imagery Analysis

Historical imagery analysis of the site showed relative stability of the source area and lower portions of the Silt Creek Landslide between 1955 and 1994 (fig. 16). The

Figure 16: Aerial Images from 1955, 1976, and 1981. These images show the relative stability of the source area of the Silt Creek Landslide. Note the presence of infrastructure in 1976 indicating the gravel roads have been in place since at least that year.

image from 1955 also clearly showed the position of Silt Creek as a linear gap in the tree canopy that runs along the eastern edge of the slide area. Imagery showed that previous failures at both the internal scarp and head scarp occurred in the period between 1994-2001 (fig. 17) and 2012-2014 (fig. 18, 19). In total, the downslope displacement for

Figure 17: Aerial photo of source area from 1994. Note the relatively small amount of displacement at the head scarp.

portions of the source area were up to 158 m over the course of the sixty years for which images were available. This occurred mainly during periods of sudden sliding over the 1994-2001 period and the most recent failure in 2014.

Due to there being several years between images, it is impossible to say with certainty exactly when the failure occurred between 1994 and 2001, although anecdotal evidence suggests that previous scarp failures may have also occurred during dry periods rather than during periods of high precipitation (Shaw, S., Weyerhaeuser geologist, personal communication, 2017).

Figure 18: Aerial photo of the source area from 2012. Note that the head scarp has retrogressed and the source area is displaced to the North.

Aerial images show that the road infrastructure at the site has existed in its pre-2014 state since at least 1976 and that there does not appear to be substantial migration of the Thomas Creek channel (fig. 16). Movement on the main body of the slide, including the middle section (which typically undergoes higher rates of movement on slides of this type (Keefer and Johnson, 1985)), were either negligibly low, or else non-measurable due to a lack of consistent markers. Analysis suggests that the upper perched section is a rotational slump feature which then feeds into the earthflow lower down the slide (Highland and Johnson, 2004). Large sections of uniformly back rotated trees on the large block in the middle of the upper section as well as the ponded water visible within the source area as far back as 2005, further support this interpretation.

Figure 19: Aerial photo of the source area from 2014. Note the substantial retrogression of the head scarp back into the slope and the debris deposits within and below the source area.

3.2 Aerial Lidar Analysis

Analysis of the aerial lidar datasets from 2012 and 2015 included measurement of the debris deposited by the internal scarp failure and measurement of the displacement of the gravel road at location 2. This analysis was completed in ESRI ArcMap.

3.2.1 Debris Deposition Measurement

Debris deposit surface elevation change was measured to estimate the amount of material deposited during the June 2014 slope failure prior to any erosive removal. The purpose of this was to determine the change in soil mass at the location. Measurements

were done only within the polygon covering the area immediately below the internal scarp failure (fig.11). Given the uncertainty present in the aerial lidar datasets, and using equation (12), overall uncertainty in the final elevation change values was found to be ± 0.08 m.

Within the deposit area, the maximum elevation increase was 22.4 m and the maximum decrease was a drop of 9.5 m. On average, the surface elevation change within the deposition area was 8.3 m (fig. 20). However, given that the measured area was the

Figure 20: Histogram of values derived from the debris deposition analysis. Value bins represent the range of values for each bar. Note the highest number of occurrences corresponds to the (8,9] value bin, corresponding to the average depth of 8.33 m.

runout area of the debris flow deposit, negative elevation changes are unlikely, and probably represent sections of the internal scarp that decreased in elevation when the failure occurred, but were inadvertently caught in the analysis area polygon. From figure 20, it is clear that negative values represent a very small portion of the total measured

values. For this reason, negative values were removed from the final calculation of debris deposition. The result is an average deposition of 8.7 m depth (fig. 21). The area of the

Figure 21: Histogram of all positive values from the debris deposition analysis. Each value bin represents the number of depth value points recorded within that value range. Note that the average value, 8.7 m, is not captured within the highest bar, but that the lower values are heavily weighted with higher amounts of lower deposit values.

deposition was $1.21 \times 10^5 \text{ m}^2$. This leads to a total estimated deposition volume of $1.05 \times 10^6 \text{ m}^3$ of material. Assuming a loose soil density of $1200 \frac{\text{kg}}{\text{m}^3}$ (USDA and NRCS, 2008), this leads to a total estimated added mass of $1.26 \times 10^9 \text{ kg}$ or an applied load of $1.04 \times 10^4 \frac{\text{kg}}{\text{m}^2}$, or in terms of stress, $\sim 100 \text{ kPa}$. The effects of this increased stress are discussed further in the discussion section.

3.2.2 Road Displacement Measurement

Results from analysis of the aerial lidar at the gravel road near TLS location 2

revealed a maximum displacement value of 7.13 m at 100 m distance from the right margin (fig. 22). Average displacement was $4.18 \text{ m} \pm 2 \text{ m}$. Assuming that displacement

Figure 22: Plot of values recorded during the road displacement aerial lidar analysis. This plot highlights the increased displacement rate for interior slide points.

initiated in June of 2014, and given that the final lidar image was collected in October

2015, this lead to an average displacement rate of $2.95 \frac{\text{m}}{\text{yr}}$. This represents the

displacement rate at location 2 in the time prior to the beginning of the TLS study.

Uncertainty was based on the aerial lidar pixel resolution of 1 m. Given that two pixels were used to measure displacement, over-all error was $\pm 2 \text{ m}$.

3.3 Structure from Motion Photogrammetry

The displacement measured by the SfM model of the gravel road increased with increasing lateral distance from the margin onto the slide body. The range of values varied from approximately 2 m immediately inside the active slide zone, to a maximum

of 10.5 m at a distance of 100 m from stable terrain (fig. 23). This is consistent with a

Figure 23: Image of the displacement vectors measured during the SfM study. Displacement rates increase progressively with distance laterally from the margin to 100 m distance into the slide interior.

diffuse deformation zone along the margin, and is also consistent with communication from Weyerhaeuser geologists at the beginning of the study regarding road deformation characteristics. Overall average displacement measured here was 7.5 m.

The model was divided into a total of 16 individual blocks, 15 of which were then rearranged to estimate the road's initial condition. This adjustment occurred along the 15 joints used to separate the blocks. Assuming an uncertainty in adjustment along the Y direction (direction of downslope displacement) of 10 cm for each block, and propagation of error towards the center of the slide (the direction in which the blocks were aligned), the error in the measurements on the block nearest the center of the slide are 39 cm in the Y direction (table 1).

Joint	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Uncertainty (m)	0.10	0.14	0.17	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.33	0.35	0.36	0.37	0.39

Table 1: Table of error calculated for each successive block manipulated to reconstruct the gravel road at location 2.

Assuming that displacement began immediately after the June 2014 slope failure event, this location underwent an average of $7.5 \text{ m} \pm 0.39\text{m}$ of movement over 17 months, leading to an average displacement rate of $5.3 \frac{\text{m}}{\text{yr}}$. The location had a maximum displacement rate of $7.4 \frac{\text{m}}{\text{yr}}$ near the center of the slide (fig. 24).

Figure 24: Plot of the displacement values measured using the SfM analysis. Uncertainty increases for measurements made on blocks towards the center of the slide.

3.4 Terrestrial Laser Scanning

Results for the TLS portion of the study are reported in general terms first and then in location order, proceeding from location 1 in the upslope southern part of the

study area to location 6 in the downslope northern part of the study area (fig. 14).

Location 1 corresponds to the internal scarp failure location near the base of the source area, location 2 corresponds to the gravel road which crosses the slide laterally 500 m further downslope from location 1. Locations 3 and 4 are clustered near location 2, with location 3 being 40 m further downslope from location 2, and location 4 being 155 m downslope from location 3. Vegetation growth at location 5 prevented confident displacement measurements and is omitted from the results. Finally, location 6 is at the toe of the slide and 870 meters downslope from location 4.

3.4.1 General Trends in the TLS Scans

The final average alignment RMSE for all scans was 0.025 m. The average standard deviation of features on stable sections, or equivalently the MDD, of the scan areas was ± 4 cm, although this varied widely from one scan to the next (table 2).

However, overall uncertainty was larger than this since vegetation growth did not always allow for selection of exactly the same point as previous scans, and tree lean may have biased some displacement vectors. Additionally, point density decreased with increased distance from the scanner, resulting in greater error in point picking for objects that were at a greater distance.

In general, there were several trends in displacement (table 3) that were found for the entire slide. These trends were repeated at each of the TLS scan locations.

Location	Period	RMSE (m)	X STD (m)	Y STD (m)	MDD (m)
1	1	0.056	0.012	0.006	0.044
	2	0.051	0.023	0.014	0.062
	3	0.028	0.040	0.002	0.044
2	1	0.008	0.021	0.010	0.016
	2	0.006	0.038	0.022	0.027
	3	0.023	0.022	0.003	0.022
3	1	0.014	0.007	0.001	0.015
	2	0.014	0.009	0.001	0.013
	3	0.018	0.008	0.004	0.017
4	1	0.094	0.052	0.025	0.069
	2	0.126	0.080	0.061	0.118
	3	0.052	0.039	0.010	0.056
6	1	0.006	0.033	0.010	0.019
	2	0.022	0.084	0.017	0.063
	3	0.024	0.021	0.025	0.028

Table 2: Table showing error for each scan. It lists the root mean square error derived from the automated ICP algorithm, the standard deviation of stable landmark coordinates in the X and Y directions, and the average over-all minimum detectable difference.

Displacement rates for each scan location were typically greater than the MDD, which ranged from 1 to 12 cm, and displacement decreased with each successive scan (table 3). At every site, the majority of the displacement that occurred during the study period happened during the first scan period (fig. 25). On average, this encompassed 69% of the total displacement. The second period averaged 23% of the total measured displacement on the slide. The final period averaged 8%.

Location	Period	MDD (m)	Average Cumulative Displacement (m)	Displacement Difference (m)	Percent Change	Total Cumulative Displacement (m)
1	1	0.044	0.632	0.632	69	0.922
	2	0.062	0.941	0.309	33	
	3	0.044	0.922	-0.019	-2	
2	1	0.016	0.240	0.240	60	0.399
	2	0.027	0.421	0.182	45	
	3	0.022	0.399	-0.022	-6	
3	1	0.015	0.194	0.194	66	0.296
	2	0.013	0.270	0.076	26	
	3	0.017	0.296	0.026	9	
4	1	0.069	0.111	0.111	76	0.146
	2	0.118	0.098	-0.014	-9	
	3	0.056	0.146	0.049	33	
6	1	0.019	0.064	0.064	67	0.095
	2	0.063	0.085	0.022	23	
	3	0.028	0.095	0.010	10	

Table 3: Table showing detectable displacements for each scan location and period. MDD is the value for the minimum detectable displacement. Average Cumulative Displacement represents the total measurable displacement within each scan period. Displacement Difference is the change between scan periods. Total Cumulative Displacement is derived from the measurable displacement in the final scan period. Scan period 1 ended on March 8, 2016, period 2 ended on June 27, 2016, and period 3 ended on October 10, 2016.

However, displacement rate change was not equivalent for all scan locations (fig. 26). Displacement rate decrease between scan periods was linear at location 1 and more erratic at all other scan locations, although given the uncertainty values for each scan, a linear trend cannot be ruled out (fig. 26). Location 2 underwent less percentage of a displacement rate decrease between period 1 and 2, than did locations 3 and 4. Given the MDD values for location 4, it is possible that the pattern in displacement rate was similar to those at locations 2 and 3, but displacement values were simply smaller than the uncertainty for the site, and therefore the pattern could not be resolved.

Figure 25: Change in TLS measured displacement values for each location over each period. Note that the majority of displacement occurred during the first period, and displacement values decreased substantially for each successive period. Based on table 3 values.

Figure 26: Change in normalized displacement for each location. Locations 1, 2, 3, and 6 underwent a relatively constant rate of decrease in displacement rates between periods. The more erratic results from location 4 are due to displacement rates being near the MDD. Date values correspond to the end of each scan period.

Over-all average and maximum displacement rates decreased with increasing distance downslope from the 2014 debris flow deposit (fig. 27). This trend was consistent

Figure 27: Plot of all displacement values relative to location downslope from internal scarp failure. This plot clearly highlights the decreasing maximum displacement values for downslope locations. Trend line is based on the highest 10% of displacement values for each location.

for every location studied, even those with a high degree of overlap, such as locations 2, 3, and 4. This trend matches with previous similar studies of slow-moving earthflows (Allison and Brunsden, 1990, Prior and Stephens, 1970).

Displacement rates for each individual location increased with increasing lateral distance onto the slide body. While the change in displacement rates at location 1 was immediate at the margin, and rates relatively remained constant laterally across the slide surface, all other locations suggested an increase in maximum displacement rates from the margin up to 100 m onto the slide surface, and then a constant rate of displacement for the remainder of the scanned distance (fig. 28).

The TLS scans revealed evidence for a discrete margin at scan location 1 and diffuse margin zones for all other scan locations. At location 1, there is an abrupt change in displacement rate moving from stable terrain onto the slide surface, while at all other

Figure 28: Plot of all measured displacement values relative to their lateral location on the slide surface. The chart highlights the trend for displacement rates to be highest within the interior of the slide, nearer the center. And shows the diffuse nature of the margin at locations 2 through 6.

locations there is a trend of gradual increase in displacement rate in relationship to lateral distance onto the slide surface (fig. 28). This trend is explained in greater detail in the following sections highlighting results for each individual location. This trend is also supported by observations at the site, where location 1 appears to show a distinct linear shear zone with very little widespread deformation nearby, while all other scan locations had jumbled, blocky, distorted margins. Furthermore, within the point clouds for location 1, there was unambiguous evidence of a discrete margin, including a fallen tree which bridged the margin and was rotated over time.

3.4.2 TLS Location 1

Displacement at location 1, corresponding to the base of the internal scarp and run out area of the 2014 debris flow (fig. 29), was the greatest of any location measured

Figure 29: Map of displacement vectors for location 1 derived from TLS scans. Vectors trend downslope and around the small ridge in the top center of the map. Vectors are exaggerated 100x and stable off-slide landmarks are not mapped.

during the study. The average total displacement here was 0.92 m over the entire study period (table 3). The average RMSE for the point cloud alignment for all location 1 scans was 3.9 cm. The MDD for the final scan relative to the origin was 4.4 cm (table 2).

Most of the displacement measured at location 1 occurred during the first scan period, October 2015 through March 2016. The average total displacement during this

period was 63 cm, and comprised 69% of the total average displacement for the study period (table 3). The RMSE for both periods 1 and 2 was about 1.5 cm, which is substantially less than the average displacement for this location.

Over the next period, March 2016 through June 2016, the cumulative displacement increased by 30 cm, 33% of the total.

During the final period, June 2016, through October 2016, there was no increase in displacement, suggesting that slide activity had ceased here. Displacement difference values for this period are negative (table 3), but given that the change in value from period 2 to period 3 is below the MDD, this displacement value can be considered zero. The final period also had the highest RMSE for location 1, of 8.8 cm. RMSE was large because vegetation growth between scans 3 and 4 required the scanner location be shifted 4 m to the south to maintain visibility of the entire scan area. This shifted view resulted in a point cloud which showed slightly different faces of landmark objects, and therefore a precise alignment between clouds could not be achieved.

Overall, the displacement direction at location 1 was consistent to the north-northwest. Displacement vectors both on the debris deposit and immediately below and beside it trended in the steepest downslope direction at an average magnitude of approximately 1 m over the entire period (fig. 29). This indicates that after debris flow deposition, a deeper failure plane in the underlying landslide complex accommodated motion, rather than the base of the debris flow deposit. In essence, since displacement within the debris deposit and on the nearby landslide surface were equal, it suggests that they were moving in unison as a single mass, therefore suggesting that the landslide was

“rafting” the deposit downslope.

In contrast to the consistent displacement direction, there were a few trends in displacement magnitude that correlated with landmark location on the slide. In general, the measured landmark displacement was greatest near the upper area of the debris deposit, around 150 m from the internal scarp (fig. 30). Maximum total displacement

Figure 30: Location 1 displacements relative to downslope position of landmark. Maximum displacement values appear greater near the middle of the site. Error bars are derived from the MDD for the final scan. The linear trendline highlights slight decrease in displacement rates vs location downslope.

generally trends downward towards the end of the scan site area farthest from the internal scarp. The highest measured displacement at location 1 was 1.4 m at about 140 m from the top of the study area.

Location 1 displacement measured as a function of lateral distance from the right margin averages about 1 m on the slide surface (fig. 31). This value remains flat and consistent with only a slight possible upward trend towards the center of the slide,

Figure 31: Location 1 displacements relative to lateral position on the slide. Note the sharp delineation in displacement rates immediately on the slide surface, with only a slight upward trend moving towards the slide center. Error bars are derived from the MDD for the final scan. The linear trend suggests a slight increase in displacement values moving laterally across the slide.

suggesting that the slide surface at location 1 is translating downslope at an equivalent rate for any given lateral distance. Small displacements below 0.5 m that do not follow this trend represent landmarks that are either off the slide or immediately at the margin, or which are errors arising from the previously mentioned need to shift the TLS scanner location for the final scan. However, since these measurements are greater than the MDD, they are included here.

3.4.3 TLS Location 2

Displacement at location 2 (fig. 32), within the upper transport zone of the earthflow and corresponding to the site of the gravel road used for the SfM portion of the

Figure 32: Map of displacement vectors for location 2. Note the apparent displacement on the stable slide in the top right of the map. Vectors are exaggerated 100x and stable off-slide landmarks are not mapped.

project, averaged a total displacement of 0.39 m over the study period (table 2). The average RMSE for the point cloud alignment for all location 2 scans was 1.7 cm. The average MDD for all scans was 2.2 cm (table 3).

Again, most of the displacement measured at location 2 occurred during the first scan period, November 2015 through March 2016. The total average displacement during that period was 24 cm, and comprised 60% of the total for the study period (table 2). The RMSE for period 1 was 1.2 cm.

Over the next period, March 2016 through June 2016, the cumulative detectable

displacement increased by 18.2 cm, or 45% of the total, with an RMSE of 1.8 cm.

During the final period, June 2016 through October 2016, the total displacement decreased. However, the magnitude of decrease was equal to the MDD, suggesting that there was no slide movement. The RMSE for this period was 2.0 cm.

Overall, the displacement vector direction was more variable than at location 1, but had a clear downslope trend (fig. 32). This trend was tempered by landmarks to the northeast of the slide surface which produced irregular displacement vectors that do not appear to be related to the displacement of the main slide. Location 2 also corresponds to the site where the slide bifurcates to the north and these landmark displacements may be related to potential deformation of that smaller slide.

Again, there were several trends in displacement that correlated with landmark location on the slide (fig. 33). In general, the maximum measured displacement was

Figure 33: Location 2 displacements relative to downslope position. Note the wide variety in values. Error bars are derived from the MDD for the final scan. The trend line suggests a slight increase in displacement values with respect to downslope location.

greatest in the central portion of the scan area and the overall trend showed no significant change with respect to downslope location. In contrast to location 1, the displacement rates varied much more widely, since the landslide has a wide lateral shear zone at location 2 as opposed to the narrow shear zone at location 1 (fig. 31). The highest measured displacement at location 2 was 0.91 m at about 750 m downslope from the internal scarp failure.

At location 2, displacement measured as a function of distance from the right margin does not have an abrupt immediate change such as recorded at location 1, but rather an increasing trend in displacement with increasing lateral distance from the margin, suggesting a more diffuse shear margin zone (fig. 34). Furthermore, the increase

Figure 34: Location 2 displacements relative to lateral position on the slide surface. Note the trend upward in displacement immediately past the margin revealing a gradual increase in displacement and not an abrupt change like location 1. Error bars are derived from the MDD for the final scan. The logarithmic trendline highlights the increase in displacement values moving away from the margin and mimics the results found during the aerial lidar and SfM analysis.

is consistent with a logarithmic trendline, suggesting a pattern of deformation similar to that observed during the SfM and aerial lidar analysis portion of the project. The increase from no displacement to 0.8 m of displacement over a horizontal distance of 20 m gives an average shear strain of $0.04 \frac{m}{m}$ across the lateral margin. Displacement values outside the active slide area are all less than 0.3 m and immediately trend upward once on the slide surface. Points to the east of the margin that show displacement correspond to the displacement vectors measured for landmarks that may be on the smaller northern slide. The average displacement for this location is nearly 14 times smaller than the displacement measured through the SfM portion of the study, indicating a rate that decreased substantially from 2015 to 2016.

3.4.4 TLS Location 3

Location 3 was approximately 20 m downslope from location 2, which resulted in considerable overlap, and had comparable results. Total displacement at location 3 averaged 0.30 m over the study period (table 2). The average RMSE for the point cloud alignment for all location 3 scans was 2.3 cm. The average MDD for all scans was 1.5 cm.

Again, most of the displacement measured at location 3 occurred during the first scan period, November 2015 through March 2016. The total average displacement during that period was 19 cm, and comprised 66% of the displacement for the study period (table 2). The RMSE for period 1 was 2.2 cm.

Over the next period, March 2016 through June 2016, the total displacement

increased by 7.6 cm, 26% of the total. The RMSE for period 2 was 2.5 cm.

During the final period, June 2016 through October 2016, the displacement continued to increase by 2.6 cm. The RMSE for this period was 2.3 cm.

Overall, the displacement direction was less consistent than at location 1 and 2, but still trended downslope (fig. 35). At this location, displacement vectors became

Figure 35: Map of all displacement vectors at location 3. At this location, the downslope trend continued, with increasingly easterly displacement in vectors towards the lower portion. Vectors are exaggerated 100x and stable off-slide landmarks are not mapped.

erratic towards the downslope portion of the site. This is due to vegetation growth in the area. Forest undergrowth increased during the latter half of the study period, which forced selection of points higher up on tree trunks. Because most trees lean, especially in

landslide topography, this led to increased error in the final displacement vectors, biasing them towards the direction of the tree lean. This was more pronounced in scan locations 3, 4, and 6, although it occurred everywhere to some extent.

A directional threshold of 45 degrees, centered on the margin strike direction, was applied to the vectors at this location. This removed measurements that didn't reflect realistic downslope movement and were potentially erroneous. The resulting set of 27 vectors was a subset of the original 83 (fig. 36), and was used for final calculations of

Figure 36: Subset of displacement vectors at location 3 within threshold used to calculate displacement rates. This set of vectors is limited to a 45-degree angle of displacement parallel to the right margin.

displacement values at location 3.

At location 3, there were trends in displacement that correlated with landmark location on the slide. Once more, the maximum measured displacement was greatest at the upslope portion of the scan area and less at the downslope portion (fig. 37). The

Figure 37: Location 3 displacements relative to downslope position. Based on subset of vectors within MDD and directional threshold. Note the general decrease in maximum displacement towards the lower portion of the site. Error bars are derived from the MDD for the final scan. The linear trend suggests a relatively sharp decrease in displacement relative to downslope location.

maximum displacement decreased with increasing distance from the internal scarp.

Similar to location 2, the displacement rates varied substantially because of the wide shear margin. The highest measured displacement at location 3 was 0.67 m at about 780 m from the internal scarp failure.

At location 3, there was again evidence of a diffuse margin on the eastern side of the slide, although it is much less pronounced here. Displacement measured as a function of distance from the right margin shows an increasing trend in displacement with

increasing distance from the margin, abruptly reaching a maximum value of approximately 0.67 m (fig. 38). The increase from no displacement to 0.67 m of

Figure 38: Location 3 displacements relative to lateral position on the slide. Based on subset of vectors within MDD and threshold. Note the generally increasing trend in displacement away from the margin highlighted by the logarithmic trendline. Error bars are derived from the MDD for the final scan.

displacement over a horizontal distance of about 10 m gives an average shear strain of $0.067 \frac{m}{m}$ across the lateral margin.

3.4.5 TLS Location 4

Location 4 was approximately 20 m downslope from location 3, and had comparable results in terms of spatial and temporal trends, but a lower magnitude of displacement. Total displacement at location 4 averaged 0.15 m over the study period (table 1), which is about half of the total displacement at location 3. The average RMSE for the point cloud alignment for all location 4 scans was 2.3 cm. The average MDD for all scans was 8.1 cm. This is much larger than any of the other locations and is due to

vegetation growth between scans. Specifically, vegetation growth on stable terrain made it difficult to identify landmarks from one scan to the next. Additionally, the difference between scans caused by the additional vegetation growth caused the automated closest point algorithm to align the point clouds less precisely. This resulted in a final alignment that was less precise than the other locations, but was still sufficient to confidently measure displacements of tens of centimeters or greater.

Following the trend for all sites, most of the displacement measured at location 4 occurred during the first scan period, November 2015 through March 2016. The total average displacement during that period was 11 cm, and comprised 76% of the total average displacement for the study period (table 2). The RMSE for period 1 was 2.4 cm. The MDD was 6.9 cm (table 3).

Over the next period, March 2016 through June 2016, the measurable displacement was below the MDD, resulting in a negative value. The RMSE for period 2 was 2.2 cm and the MDD was 11 cm, the largest of any scan in the study. Since a negative change in cumulative displacement would indicate upslope movement of the landslide, which is physically unreasonable, displacement should be interpreted as indistinguishable from zero during this time period. This is attributable solely to the high MDD value, and does not suggest that the slide activity had ceased during this period.

During the final period, June 2016 through October 2016, the total displacement increased by 4.9 cm, 33% of the total. The RMSE for this period was 2.3 cm and the MDD was 5.6 cm, so displacement was once more indistinguishable from zero.

Overall, the displacement direction at location 4 was not very consistent (fig. 39).

Figure 39: Map of all displacement vectors at location 4. Note the trend in the lower portion of the site for displacement to be directed away from the slide. This is most likely an artifact of tree lean and vegetation growth between scans. Vectors are exaggerated 100x and stable off-slide landmarks are not mapped.

Displacement vectors became pointed uniformly to the east towards the downslope portion of the site. In addition to the previously mentioned alignment error due to vegetation growth at this location, the increased height of undergrowth in the forest made it necessary to select subsequent scan points at higher locations on tree trunks. This imparted error in the displacement vectors biased towards the direction of tree lean. This may be the cause of the abnormal easterly trend for vectors in this location.

A directional threshold of 45 degrees, centered on the margin strike direction, was

applied to the vectors at this location. This removed measurements that didn't reflect realistic downslope movement and were potentially erroneous. The resulting set of 14 vectors was a subset of the original 108 (fig. 40), and was used for final calculations of

Figure 40: Subset of displacement vectors at location 4 within threshold used to calculate displacement rates. This set of vectors is limited to a 45-degree angle of displacement parallel to the right margin.

displacement values at location 4.

Displacement trends at location 4 were less obvious than at previous scan locations (fig. 41). This may be due to the relatively low number of final useable vectors

Figure 41: Location 4 displacements relative to downslope position at the site. Here there is no strong trend for displacement to decrease or increase downslope, however; maximum displacement remains relatively constant. Error bars are derived from the MDD for the final scan. The trendline highlights the lack of a significant trend in displacement value relative to downslope location.

for location 4. The trend overall suggests a relationship between location downslope and decreased landmark displacement, but is not statistically significant. The maximum recorded displacement value is in the upper portion of location 4. At location 4, as with all the other locations, displacement vectors were greatest in the interior of the slide, and less near the margin, suggesting a diffuse margin zone. Therefore, many of the lower displacement values witnessed at location 4 may be an artifact of that trend and do not actually reflect a relationship between displacement and downslope position of the landmark. This trend towards higher displacement in the interior of the slide can also clearly be seen in figure 42. The highest measured displacement at location 4 was 0.27 m at about 970 m downslope from the internal scarp failure.

At location 4, there was evidence of a diffuse margin on the eastern side of the

slide. Displacement measured as a function of distance from the right margin reveals an increasing trend in displacement with increasing distance from the margin, reaching a maximum value of approximately 0.27 m (fig. 42). This pattern is similar to the ones seen

Figure 42: Location 4 displacements relative to lateral position on the slide. Note the trend for displacement to increase with increasing distance onto the slide. Error bars are derived from the MDD for the final scan. The logarithmic trendline highlights the increasing trend in displacement moving away from the margin.

at locations 2 and 3. The increase from zero displacement to 0.27 m of displacement over a horizontal distance of 22 m gives an average shear strain of $0.012 \frac{m}{m}$ across the lateral margin.

When considering the potential trends in displacement rates with respect to position downslope or from the margin, the relatively low number of data points for this location should be taken into account. However, it should be noted that while the number of data points for this location is lower than those of the other locations, the results match well with observations made at the site.

3.4.6 TLS Location 5

During the alignment process, location 5 was dismissed due to a lack of visible stable landmarks and extensive vegetation growth between scans, leading to poor alignment. Attempts were made to align the scans manually by locking each axis in CloudCompare and aligning them individually, but this did not provide alignment that would allow for measurable displacement vectors. When the automated alignment process was attempted for scans at location 5, the resulting RMSE was 0.24 m, which is an order of magnitude higher than the average of all other locations. This resulted in an alignment that was deemed to be unusable for measuring displacement vectors. Since it would not be possible to sufficiently align scans at this location using the same method as the other locations, this site was discarded from the study.

3.4.7 TLS Location 6

Location 6 corresponded to a section of gravel road and a bridge across Silt Creek at the eastern margin of the toe (fig. 43) and is about 0.9 km downslope from location 4. Total displacement values at location 6 were the smallest recorded for anywhere in the study, averaging 9.5 cm over the entire period (table 2). The average RMSE for the point cloud alignment for all location 6 scans was 2.2 cm. The average MDD for all scans was 3.7 cm (table 3).

Figure 43: Map of all displacement vectors for location 6. Vectors are exaggerated 100x and stable off-slide landmarks are not mapped.

Most of the displacement measured at location 6 occurred during the first scan period, November 2015 through March 2016. The average cumulative displacement during that period was 6.4 cm, and comprised 64% of the cumulative displacement for the entire study period (table 2). The RMSE for period 1 was 1.9 cm.

Over the next period, March 2016 through June 2016, the cumulative displacement increased by 2.2 cm. The MDD for this period was 6.3 cm, and since measured displacement was below this value, it is indistinguishable from zero. The RMSE for period 2 was 2.6 cm.

During the final period, June 2016 through October 2016, the cumulative displacement increased by 1 cm. The MDD for this period was 2.8 cm, and therefore measured displacement was once again indistinguishable from zero. The RMSE for this period was 2.1 cm.

Displacement vector direction was generally to the northwest, but quite erratic at this location (fig. 43). This is most likely due to most of the displacement measurements being near the MDD.

For this reason, similar to locations 3 and 4, a 45-degree directional threshold was applied to the vectors at location 6 to remove any potential error (fig. 44). The final set of

Figure 44: Subset of displacement vectors for location 6 within the threshold used for calculations. This threshold represents a forty-five degree angle of displacement directions parallel to the right margin.

vectors was a subset of the original and was used to complete all calculations for cumulative displacement values and graphs.

At location 6, there were again some trends in displacement that correlated with location on the slide. Here, displacement increased with increasing distance downslope (fig. 45). This is opposite of trends seen at all the other locations, but may be misleading

Figure 45: Location 6 displacements relative to downslope position. Although the number of monitored landmarks at this location was relatively small, there does appear to be a trend for displacement to increase towards the lower portion of the site. Error bars are derived from the MDD for the final scan.

given the low number of data points. Similar to all locations except location 1, the displacement rates vary widely. The highest measured displacement at location 6 was 0.12 m at ~1.92 km downslope from the internal scarp failure.

Displacement measured as a function of distance from the right margin shows a possible increasing trend in displacement with increasing distance from the margin,

reaching a maximum value of 0.12 m by 70 m from the right lateral margin (fig. 46). The

Figure 46: Location 6 displacements relative to lateral position on the slide. Once more, there appears to be a trend of displacements increasing with increasing lateral position towards the center of the slide surface. Error bars are derived from the MDD for the final scan.

increase from zero displacement to 0.12 m of displacement over a horizontal distance of 70 m gives an average shear strain of $0.0003 \frac{m}{m}$ across the lateral margin.

Similar to location 4, when considering the potential trends in displacement rates with relationship to position downslope or from the margin, the relatively low number of data points for this location should be taken into account. Again, it should be noted that while the number of data points for this location is lower than those of the other locations, the results match well with observations made at the site.

3.5 Hydrologic Measurements

Hydrologic measurements for Silt Creek were collected on October 21st, 2016, near the end of the study period. The total accumulated precipitation value for that month,

around 68 cm, was one of the highest amounts in the previous four years (fig. 6). Weather conditions during the data collection were dry, but there had been recent rainfall. There was no visible snow in any of the upper elevations. Although the month in which the measurements were collected was relatively wet, the preceding five months were quite dry, each receiving an average total precipitation of 15 cm or less (fig. 6). For this reason, it is unlikely that the groundwater levels were relatively high when the collection occurred, and therefore much of the water volume in Silt Creek was probably from recent rainfall. Visually, the water level in Silt Creek was lower than had been observed during the winter or spring months, but higher than summer.

The K value for Silt creek was found to be $3.364 \times 10^{-6} \mu S^{-1} cm^{-1}$ (Fig. 47).

Figure 47: Chart used to calculate K value for Silt Creek. Shows the relationship between relative concentration of the salt tracer in water taken from Silt Creek versus the electrical conductivity of the resulting solution. The slope of the trend line for this relationship is the K value.

This value is the slope of the relationship between RC and EC from equation (13).

At the first hydrologic measurement location on the right margin of the landslide's

toe (fig. 15), only sensor 2 functioned properly, resulting in one conductivity curve for that site (fig. 48). The discharge calculated from this curve was $1.63 \frac{m^3}{s}$. Uncertainty for

Figure 48: Conductivity curve for location 1, sensor 2. The increase in conductivity is sudden as the salt tracer plume arrives, and tapers off as the plume disperses.

this location was $\pm 0.27 \frac{m^3}{s}$. Maximum conductivity recorded by this sensor was $282 \frac{\mu S}{cm}$.

At the second hydrologic measurement location, all three sensors functioned properly and recorded conductivity curves (Fig. 49). However, internal date/time stamps were not synchronized, so it was therefore impossible to calculate the relative plume arrival time by finding the difference in curve initiation. Conductivity curves clearly highlight the increased diffusion of the saline solution through stream mixing, with the saline pulse taking approximately 47 seconds to pass sensor 1, and 104 seconds to pass sensor 3 (Fig. 49). Sensors 1 and 3 were placed 20 m apart. The average discharge

Figure 49: Conductivity curves for all sensors from location 2. Sharp drops in conductivity values are due to the sensor bobbing up out of the stream in turbulent water. Note the dissipation of the salt tracer plume as it moves from sensor 1 to sensor 3. Also note, absolute time stamps were not synchronized, so curve relative placement has been reconstructed to illustrate plume movement.

calculated for location 2 was $1.39 \frac{m^3}{s}$. Uncertainty was $\pm 0.24 \frac{m^3}{s}$.

At the third hydrologic measurement location, only sensors 2 and 3 functioned properly and recorded conductivity curves (Fig. 50). However, once again absolute

Figure 50: Conductivity curve for both sensors at location 3. The spread in the curve from sensor 3 indicates a more diffuse plume. The sharp drops in conductivity are artifacts of the sensor bobbing up out of the stream due to water turbulence.

date/time stamps were not synchronized, and it was not possible to calculate the relative plume arrival times. Changes in the conductivity curves' width and height at location 3 again highlight the increased downstream diffusion of the saline solution through stream mixing (Fig. 50). The average discharge calculated for location 3 was $1.19 \frac{m^3}{s}$.

Uncertainty was $\pm 0.21 \frac{m^3}{s}$.

At hydrologic measurement location 4, once again only one sensor functioned properly and recorded a conductivity curve (fig. 51). The average discharge calculated for

Figure 51: Conductivity curve for location 4. This location was the highest elevation monitored during this study and corresponds to the depositional area from the internal scarp failure.

location 4 was $0.93 \frac{m^3}{s}$. Uncertainty was $\pm 0.16 \frac{m^3}{s}$.

Given that sensor 2 was the only sensor to function properly at all locations, that sensor's results were the only data selected to perform final calculations for discharge.

The resulting hydrologic measurements collected from all four locations found a steady

increase in stream discharge from hydrologic measurement location 4, near the debris deposit, to hydrologic measurement location 1, about 2 km downslope from the head scarp at the toe (fig. 52). While the largest discharge rate increase occurred between

Figure 52: Chart showing volumetric discharge of Silt Creek along the eastern margin of the Silt Creek Landslide. Note that the rate of increase in discharge is greatest between locations 1 and 2, near the upper portion of the slide, and linear below that. Error bars are based on propagation of the three percent error given in the sensor documentation, giving an average error of 17%.

locations 3 and 4, the fastest increase occurred between locations 1 and 2. Discharge rate increase remained relatively constant from location 2 all the rest of the way down to Thomas Creek. This suggests that the stream drains the surrounding landslide material, providing a mechanism to keep the subsurface pore pressures low. Furthermore, the faster increase in discharge between location 1 and 2 suggests that pore water pressures are likely higher at the uppermost location near the internal scarp failure than in the rest of the slide.

4 Discussion

Results from this study suggest that the combination of methodologies used provide an accurate and highly flexible way to monitor landslide displacement. Understanding and mitigating sources of error can improve the results of future projects. Point cloud analysis errors generally arise from alignment issues, but also include inherent limitations of the technology. Assessment of sources of error is key in utilizing this methodology.

This project initially endeavored to measure landslide displacement at high accuracy level using technology that allows for rapid response at a relatively inexpensive cost. In so doing, slide deformation trends and displacement rates were found that appear to fit well with currently understood slide mechanics and can illuminate the relationship between catastrophic failure, debris deposition, and slide reactivation within a single slide complex.

4.1 Errors in Analysis

Uncertainty values within the aerial lidar datasets used for deposition and road displacement measurement prevent exact reporting of the values for these analyses. Furthermore, the method used for deposition measurement does not provide exact values of the amount of material within the deposit area and constitutes an estimate only. More in-depth analysis of the difference raster derived from the two lidar datasets may improve the final volumetric measurement for the material. However, the results from the method used in this study were sufficient for the final analysis covered in this discussion section.

Absolute georeferencing of the point cloud model in a Geographic Information System (GIS) software, such as ArcMap, is heavily dependent upon the GPS coordinates of the TLS scanner. For this reason, it is important to get highly accurate GPS data when scanning. During the course of this project, it was found that, although scan locations were flagged, and great care was taken to ensure that each successive scan was performed at the same exact location, the GPS coordinates recorded within the scan data for successive scans were slightly different each time. On average, the absolute position accuracy was 3.81 m, although standard deviation of GPS coordinates in the X and Y directions for a single scan location varied widely from as much as 6.8 m to as low as 0.25 m. This variability resulted in the use of the GPS coordinates recorded in the initial scan for each location as an absolute reference point to which all successive scans were relocated.

When the rotation of the final scans was corrected using the compass data recorded within the scans, it was found that this directional data was also slightly different for each scan, with an average uncertainty of $\pm 6^\circ$. Combined, the rotational differences and the GPS location difference represent a source of error in the raw data arising from the accuracy of the instruments within the TLS scanner. This relative error between pairs of scans was minimized by using the first scan at each location as a reference scan, and then using the FARO and CloudCompare software to align all successive scans to the reference scan. However, due to inaccuracies in the GPS location and compass alignment within the first scan, final georeferencing had to be adjusted manually in ArcMap to ensure that overlapping landmarks in scans from different

locations were positioned in the same place. Therefore, locations of displacement measurements and displacement orientation values reported in this study should be conservatively viewed as relative to the initial scan at each location. Additionally, the accuracy of the displacement magnitude is governed by the relative accuracy of the alignment of the scans to each other, while the accuracy of the displacement direction is governed by the accuracy of the absolute georeferencing of the initial scan.

Displacement was measured as a change in coordinates of landmarks from one scan to the next. This was done by selecting a single point within a landmark and then selecting the closest representative point in the successive scan. For this reason, anything that causes a difference in selected point location on landmarks between scans represents a source of error. This could stem from human error in the point picking process, from individual lidar pulses reflecting from different locations on the object, from point spread on objects farther from the scanner, or from changes within the landscape between scans that obscured landmark features. For example, scan four at location 1 had a higher RMSE because vegetation growth between scans required that the scanner be set up in a location slightly offset from where the previous scans were conducted. Vegetation growth between scans was the largest source of this type of error and was found to be most problematic during the latter half of the scanning period, in the summer and fall of 2016, when vegetation was highest. Specifically, as undergrowth, shrubs, and grasses grew up, they blocked the TLS line of sight to landmarks. Initially in the study, points were selected as low on the landmark feature as possible to minimize position distortion from swaying and wind interference. Extensive height increases in forest undergrowth later in the study

period forced selection of comparison points higher up on landmarks. This change in point location was highly variable and depended on the degree to which new vegetation blocked the scanner view of landmark features. In most instances, the vertical change was within about 0.3 m, but could range as high as 3 m. As a result of this, tree lean or wind distortion could lead to apparent displacement when none existed or could mask displacement which actually occurred. Additionally, point picking is a manual process, requiring skillful selection of landmarks between scans, so human error is an ever-present possibility. Erroneous coordinate values resulting from human error tended to be grossly incorrect, obvious, and were removed from the end results as much as possible.

The precision of measured displacements from this project depended heavily on the precision of the point cloud alignment within CloudCompare. The alignment process used a closest iterative point algorithm for the final alignment, but required manual alignment first. The quality of this manual alignment influenced the quality of the final automated one and could therefore import error in the processing. This was mitigated by ensuring that the automated alignment was not started until the manual alignment RMSE value was 0.02 m or smaller. This ensured that the quality of the input to the automated alignment was consistent for all scans.

While these sources of error did have an effect on final displacement vector values, the average overall RMSE for all scan alignments was 2.5 cm, while the average MDD value for all scans was 4 cm. This shows that despite these sources of error, TLS provides a highly accurate way to measure displacement, and with a few improvements to the methodology, could be even better.

Finally, the SfM portion of this study relied heavily on manual alignment of the deformed gravel road point cloud. Existing cracks were used as guides for the reconstruction process. However, manual manipulation can result in errors in the final results. This error most likely increases towards the center of the slide, as the alignment process was begun near the margin and each following block alignment relied on the accuracy of the previous one.

4.2 Improvements to Methods

Alignment of the point clouds was the largest source of error in this project. For that reason, addressing any issues that cause alignment problems should be the primary focus of improving this process.

Using a dedicated high accuracy Differential Global Positioning Satellite (DGPS) unit in conjunction with the TLS scanner to collect the origin point location coordinates would be an excellent improvement to this process. The scanner's internal GPS unit was not accurate enough to provide repeatable coordinates between successive scans. A GPS unit with differential correction is often capable of centimeter scale positional accuracy and could result in better absolute georeferencing of the final scan. Additionally, the use of GPS mission planning software can increase the level of GPS accuracy by ensuring the maximum number of satellites overhead during the scanning period.

Rotational alignment issues stemming from the scanner internal compass could be mitigated by always selecting scan locations that overlap. If a high accuracy DGPS unit is used to collect the scanners' coordinates to a centimeter accuracy and the derived point

clouds always overlap, then scans can be corrected for rotational errors by aligning them to the neighboring scan.

Finally, the scan alignment process would be greatly improved by the inclusion of standardized, permanent targets within the stable portion of the scanned terrain. Preferably these would consist of painted or printed highly durable plates with multiple cross-shaped targets, each mounted and immobile for the duration of the study period. FARO software can recognize and align clouds based on the location of proprietary targets. Within CloudCompare, these targets would provide a consistent, easily recognized, and pre-selected alignment landmark. This would not only speed the alignment process, but would ensure more accurate results.

Creating target markers on mobile landmarks, potentially by painting symbols on their surfaces, would also assist in the identification and selection of landmarks in successive scans. Permanent targets would be impractical when dealing with a large number of landmarks, and should be reserved for those on stable terrain which are necessary for proper alignment.

4.3 Over-all Implications of Research

The Silt Creek Landslide site has undergone dynamic changes since the failure of an internal scarp in June of 2014. Historical imagery shows that this site has a history of slope instability in the upper reaches of the complex over the last decade. However, the lower portion has not shown evidence of extensive movement prior to the 2014 event. This suggests that the June 2014 scarp failure is most likely the triggering event for the

reactivation of the lower portion of the slide complex.

The results of this study have provided a glimpse into this possible relationship, a measure of the change at the site during the period immediately following the failure, and have highlighted several trends in the slide's mechanics. Below, the results and data reported previously are interpreted, and several other analyses are carried out in order to test the hypothesis that the internal scarp failure triggered the reactivations of the lower portion of the Silt Creek Landslide. More specifically, material deposited from the failure lead to an applied load under undrained conditions within the area at the base of the internal scarp, and this in turn spurred reactivation at that location and further downslope.

While it is possible that the material which triggered the reactivation was sourced from a coincident failure at the head scarp rather than the internal scarp, there is no evidence from this study to support or refute this, and functionally the source of the material is not important, since the mechanics behind the reactivation are the same regardless of the source of the material. However, further investigation to determine the exact source area of the material within the deposit would be worthwhile for gaining a more complete understanding of the dynamics within the Silt Creek Landslide.

It is clear from the precipitation data for the area (fig. 7) that the Silt Creek Landslide received a lower amount of precipitation during the 2015 water year, than it did during the following year, 2016, when the TLS portion of this study was conducted. However, the site underwent substantially more displacement during the 2015 water year than it did during the 2016 water year. This suggests that the over-all displacement trend was not precipitation driven. While seasonal increases in groundwater levels almost

certainly had some effect on short-term slide movement, the long-term movement trend since June 2014 was likely caused by some other factor.

Figure 26 shows that the normalized rate of change in displacement between scans was greatest during period 1 and decreased for each location over time. This change was linear at location 1. However, normalized displacement rates did not decrease at a constant rate for any other location, and were, in fact, different for each location. This suggests that, although the general trend in displacement is the same for all locations, relative localized displacement rates may not be equivalent everywhere on the landslide, but can be variable depending on the location. This shows that areas within the slide may undergo displacement at different times and at different rates from each other.

Over-all displacement rates within the study area were highest at location 1, which was closest to the 2014 debris flow deposit. This also supports the hypothesis that the June 2014 internal scarp failure, or its resulting debris deposit, was the triggering event for the slide reactivation within the lower portion of the slope studied during this project. Since slide instability is most likely related to a change in the ratio between pore water pressure and the soil column, and displacement was greatest at the location near the debris deposit, it follows that either the additional weight of the debris deposit in the soil column or a change in pore water pressure due to the failure was the direct cause of the reactivation of the lower portion of the slide.

Equation (8) shows that, in a soil with no change in consolidation, all increases in stress from overburden result in an equivalent increase in pore water pressure. This is valid only for a location with poorly draining soils of a fine grain size. The estimated

normal stress applied by the debris flow deposit is around 100 kPa. In equation (1) it was shown that an increase in R_u , the ratio of pore water pressure to the weight of the soil column, can result in a corresponding drop in the factor of safety value for a slope. Assuming an initial steady state pore water pressure value of 50 kPa, as would be the case for a saturated landslide surface with an assumed depth of 5 m to the failure plane, then an applied load of 100 kPa in a soil column that changes from 5 m depth to 13 m depth (based on the average measured material deposition in the aerial lidar analysis) would increase the R_u ratio from 0.83 to 1.26. Such a change could alter the factor of safety value from 1.19 (indicating stability) to 0.82 (indicating instability). It should be noted that R_u values greater than one indicate artesian pressures that are greater than what can be achieved during fully saturated, steady-state flow. This increase grows larger as the initial depth to the failure plane increases. These values show that the slope stability can be reduced due to an applied load. Specifically, under undrained conditions, the applied load causes an equivalent increase in pore water pressure, which counteracts any increase in effective normal stress resulting from the additional mass of the load. However, the applied load does increase the shear stress acting as a downslope driving force. This unbalancing of conditions can lead to slope instability and may be the mechanism responsible for the reactivation of the Silt Creek Landslide, especially when using results from this study to account for an applied load similar to the debris deposit from the internal scarp failure.

At all scan locations, it was found that displacement rates decreased with each successive scan (fig. 25). Additionally, the displacement rates for the period between the

scarp failure and the beginning of the TLS scans were found to be substantially higher than those measured during the scans. Towards the end of the TLS portion of the study, the displacement rate dropped to a fraction of what it was during the first scan period, and by the end of the study continued displacement was not measurable. This suggests that over the course of the study the slide began to approach equilibrium between the shear stresses acting as downslope driving forces and the shear strength or frictional forces acting to hold the slide stable. Referring back to equation (1), assuming soil cohesion, unit weight, vertical depth to the failure plane, slope angle, and angle of friction are all constant for the duration of the study, the change in slope stability is attributable to a change in the ratio between pore water pressure and weight of the soil column. Additionally, conservatively assuming that the soil column weight is effectively unchanged, then a reduction in pore water pressure is the probable cause of the decrease in movement of the slope over time. If the soil column weight has been substantially reduced due to erosion, this would not only lead to a decrease in pore water pressure, but also in the driving force acting in the downslope direction and an overall quicker return to slide stability.

Further evidence of a transient increase in pore water pressure can be found in the discharge measured in Silt Creek. The largest increase in discharge was found between the measurements taken at the base of the debris deposits, and the measurements near the gravel road which crosses the slide. This suggests groundwater discharge, and thus pore water pressure, may have been higher in this area. Furthermore, in December of 2015, Weyerhaeuser geologists witnessed mud volcanoes downslope of the deformed gravel

road near the upper part of the toe of the landslide (Shaw, S., Weyerhaeuser geologist, personal communication, 2017). This suggests that pore water pressure was at least temporarily increased farther downslope as well. Hutchison and Bhandari (1971) suggest that features such as these may manifest on landslides with increased pore water pressure due to undrained loading.

The timescale for pore pressure diffusion in equation (11) provides a way to measure the expected amount of time required for displacement to cease on a landslide which has reactivated due to an undrained load. Using this equation, assuming an average landslide thickness of 10 m, and thus a D value of 5 m, with an assumed C_v value of $5 \frac{cm^2}{hr}$ (which is in the range of clays $(1-100 \frac{cm^2}{hr})$ (Selby, 1993)), we get a T value of 27 months. This matches well with the timeline of displacement witnessed during this study, and roughly matches the period between the internal failure and displacement cessation at TLS locations 1 and 2.

Reactivation of the slide may be accounted for by the increased mass added to the soil column by the debris deposited in June 2014. It is possible that this could affect the R_u ratio in such a manner as to initiate reactivation. In essence, keeping resisting forces unchanged while downslope driving forces are increased due to the applied load. However, the slide deformation decreases substantially from the initial time of deposit to the end of this study period. Assuming that the mass of the deposit has remained essentially unchanged during that time, it appears unlikely that this alone has led to the reactivation of the lower portion of the slide complex. Rather, increased pore water pressure, as well as its eventual decrease due to groundwater evacuation, provides a

probable mechanism for the pattern of deformation recorded after the initial scarp failure and during the TLS scan periods. Specifically, movement of the lower part of the landslide was likely controlled by a combination of additional downslope driving stress due to the debris flow loading directly beneath the debris flow deposit and a reduction of effective normal stress downslope from the debris flow deposit as elevated pore pressures diffused in the downslope direction.

The broader implications of the results from this research are that complex landslides, such as the Silt Creek Landslide, can undergo systematic changes in stability as a response to discrete internal changes in material load. Internal processes in upper elevations, such as scarp failures, can lead to reactivation in other portions of the slide due to applied load, even in locations where the slide has been stable for several decades. This reactivation can present a hazard to infrastructure and life safety. However, this research also suggests that the reactivation period is transient, with a majority of the displacement occurring within a brief time frame after the load is applied, depending on the ability of the groundwater to evacuate, with the slide eventually returning to stability.

Additionally, displacement rates during reactivation do not appear to be related to precipitation rates. Pore water pressure increases can result from applied internal loads, rather than rainfall or snowmelt, making prediction of slide deformation rates more difficult. During this study, displacement rates were greatest during the drier year and less during the wetter year, suggesting that cumulative displacement was largely decoupled from precipitation. This implies that current landslide deformation and sediment delivery models which rely heavily on precipitation values may not capture all potential

mechanics and processes leading to slope instability.

4.4 Implications for Site Management

Infrastructure on the Silt Creek landslide includes three gravel roads and a bridge. These gravel roads include a first, uppermost road studied in the SfM portion of the project, a second road approximately 0.5 km downslope from the first, and a third road which crosses the toe at location 6. The bridge is in place at location 6, where the third road crosses Silt Creek. The third road is a mainline access road for forestry practices, during hunting season, and gets daily usage. The other two roads either provide access to an area of less than 1 km^2 or can be easily accessed from the opposite direction.

Following reactivation of the landslide, displacement was measured at all three roads. The first two roads were extensively damaged due to displacement downslope and heavy erosion from the landslide gully network. Reparation of these two roads may be relatively costly and largely unnecessary, since the areas they access can be easily reached from the other end of the road or are small enough that a new access route could be constructed. Damage to the third road was much less than the first two, with a measured displacement in that area of a few centimeters, and it has continued to function as a mainline access route during the reactivation.

Displacement was also measured at the bridge. This bridge is a concrete slab design of about 20 m length which straddles Silt Creek, and rotated several centimeters during the slide reactivation. This rotation occurred because the western abutment is on the surface of the landslide while the eastern abutment is on stable terrain.

Over the course of this study period, the displacement at the Silt Creek Landslide reached appears to have reached cessation. This suggests that continued damage to this infrastructure in the near term has also ceased. However, given the previous history of the Silt Creek Landslide, future periods of reactivation and deformation are likely. Furthermore, future reactivation will most likely result in further damage to this infrastructure. This damage should be expected to again be greatest at the first and second road, and less at the third road.

While the uppermost two roads are unlikely candidates for repairs, the lower mainline road is an essential arterial route for the forestry industry and should be maintained. Displacement in the lower road was relatively minimal, up to several centimeters. For this reason, the lower road could be repaired as needed, and continue carrying traffic. While this road could be relocated to the opposite side of Thomas Creek, and thus off the Silt Creek Landslide entirely, potentially unstable slopes on the opposite bank mean the possibility of damage from landslides would still be present. Given that cost of relocation is much higher than repairs, and that the potential for damage still remains, it seems preferable to keep the road in its current general location.

Relocation of the bridge traversing Silt Creek is unlikely to remove the potential for damage should the landslide reactivate in the future. This is because Silt Creek follows the margin of the landslide for the entire lower kilometer of the slide. Essentially, there is no “better” location for the bridge. Additionally, any relocation further upslope would only result in greater expected damage to the bridge should reactivation occur again. For this reason, the best course of action with regards to the bridge, based on the

results of this study, is to check for and repair any damage that occurred to the concrete slab and then realign the slab on its abutments.

Despite changes or repairs to the infrastructure on the Silt Creek Landslide, future damage due to slide reactivation is an ever-present concern. Given that that lower road is a relatively heavily traveled route and important to industry, it is imperative that the slide be regularly monitored for activity. The results of this study showed that displacement is likely to begin in the uppermost portion of the slide area. For this reason, monitoring should focus heavily on the condition of the source area, the upper head scarp, and the internal scarp. Should reactivation or slope failure occur there again, displacement along all three roads and the bridge is to be expected.

4.5 Future Work

The methodology used in this study provides a framework for studies at other landslides. However, improvements could be made to decrease error due to TLS misalignment. A high accuracy DGPS unit should be used to ensure that absolute georeferencing of the final point cloud is as accurate as possible. Targets should be used on stable terrain that are immobile, easily identifiable, durable, and are positioned such that future vegetation growth will not obscure them. Additionally, these stable terrain markers should be placed at a variety of distances from the scanner location, but with a preference for locations farther from the scanner.

Additional scans of the Silt Creek Landslide should be done to validate results of

this study which suggest that the slide has returned to a state of stability. The final TLS scan done during this study suggested displacement had ceased at the uppermost locations and was nearing stability in the lower locations. A further round of scans at all locations, one or two years following the final scan from this study, would provide more evidence for these displacement rate changes.

This study suggests that reactivation of the Silt Creek Landslide occurred due to slope failure, however the cause of this failure is uncertain. This failure occurred in June, during a period of low precipitation, under conditions where such a large catastrophic failure would not be expected. Anecdotal information from area residents suggests that additional such failures may have occurred during previous dry periods, specifically a slope failure may have occurred in September or October during the mid-1980's (Shaw, S., Weyerhaeuser geologist, personal communication, 2018). This suggests that mechanisms controlling the stability of the Silt Creek Landslide source area may not yet be fully understood. Additionally, failure of the internal scarp appears to have occurred coincidentally with failure of the head scarp, although the temporal relationship between the two failures is uncertain. Determining with certainty whether the material deposited on the reactivated portion of the slide was sourced from the internal scarp or the head scarp would help clarify expectations of future failures. For these reasons, study of the source area, the head scarp, and the internal scarp would shed valuable insight onto the mechanisms at play within this landslide complex. This should include a study of the geology, hydrology, and repeat collection of SfM or TLS data near the upper most reaches of the Silt Creek Landslide. A more in depth lidar elevation differencing analysis,

including volumetric measurements of material deposition and erosion areas, could better constrain material source areas.

5 Conclusions

This project, which combined terrestrial laser scanning, aerial lidar analysis, and Structure from Motion photogrammetry-derived point cloud analysis, allowed for relatively inexpensive landslide monitoring at a higher temporal resolution than many other methods. Each monitoring method used in the study provided different challenges and strengths, but when used in tandem, resulted in a powerful method of study with high accuracy, quick deployment, and low cost.

Aerial lidar analysis of the material deposition from the June 2014 internal scarp failure found an estimated average deposit depth of around 9 m. This leads to a deposit volume of $1.05 \times 10^6 m^3$. This is sufficient, along with an associated increase in pore water pressure, to decrease the factor of safety value from expected stable to expected unstable conditions.

Aerial lidar analysis of the displacement of a gravel road across the transport zone of the slide showed that displacement here averaged 4.18 m, reaching a maximum value of 7.13 m over 17 months. Uncertainty in measurements was ± 2 m. Displacement increased with increasing lateral distance onto the slide, with the highest values nearer the center of the slide. Average annual displacement rate was $2.95 \frac{m}{yr}$.

The photogrammetric portion of this project was used to measure displacement in the same area as the aerial lidar analysis, which followed the internal scarp failure, but occurred prior to the TLS scans. Average measured displacement was 7.5 m, with a maximum value of 10.53 m. Uncertainty was ± 0.39 m. The calculated annual displacement rate for this location was $5.3 \frac{m}{yr}$. Results generally correlated with the

estimates from aerial lidar analysis and site surveying. Errors resulting from the manipulation of point cloud features can be mitigated by increasing the number of collected images to increase the point density of the cloud. Generally, photogrammetric methods provide a very inexpensive, very rapid method for modeling topography at a wide range of scales.

The TLS portion of this project provided highly accurate displacement measurements along a 2 km stretch of the slide surface. Generally, the minimum detectable displacement for landform features was 4 cm. Measured average displacement during the 2016 water year ranged from 0.92 m in the upper portion of the study area, to about 9 mm near the toe. Displacement amounts were greatest in the first scan period and decreased over time with each successive scan. Displacement rates were highest in the upslope slide area and near the lateral center of the slide. Displacement ceased in the upper part of the slide by the end of the TLS study period. Alignment and vegetation growth presented the two largest sources of error. Altering the methodology by adding fixed targets and high accuracy GPS to allow faster, more accurate alignment during the analysis period, and selecting a scanner placement to minimize interference from vegetation growth will mitigate some of this error. This will provide an effective method by which landslide dynamics can be studied with high detail and rapid-response.

Hydrology measurements showed that discharge in the upper most measured portion of Silt Creek was $0.92 \frac{m^3}{s}$, and that discharge increased downslope to a maximum value of $1.6 \frac{m^3}{s}$. Increase in discharge was greatest between the uppermost location and the second location suggesting that groundwater discharge is greatest near the base of the

internal scarp failure, and thus pore water pressure is potentially higher there.

The results of the study reveal a complex and dynamic landslide. The study results can be used to illuminate the interplay between catastrophic slope failure, debris deposition, and earthflow mechanics within a single site. It also showed patterns of deformation within the earthflow portion of the complex, highlighting the wide range of movement rates along major axes of an active earthflow. The study showed that deformation rate changes do not necessarily occur contemporaneously within the slide complex, but rather may vary temporally and spatially. The study also showed that at the Silt Creek Landslide, displacement rates appeared to be largely decoupled from precipitation rates, suggesting an alternative cause for increased pore water pressure.

The study provided an example of an earthflow which reactivated in response to an undrained load applied by debris deposited from the failure of an upslope internal scarp. Additionally, it measured the change in deformation rates over time as the slide responded to evacuation of groundwater and the return of the pore water pressure to steady state. It was supported by conclusions from previous studies (Allison and Brunsten, 1990, Hutchison and Bhandari, 1971, Prior and Stephens, 1970) suggesting slides can reactivate due to undrained loading, and captured an individual slide as it returned to stability.

Landslides are a costly hazard in the Pacific Northwest. They can have highly detrimental effects on road infrastructure, forestry operations, can threaten public and private property, and pose a life-safety risk. This study provided evidence constraining the complex relationship between rapid slope failure, debris deposition, and creeping

deformation within a single slide complex. Furthermore, it presented a method whereby landslide monitoring can be accomplished at a sub-annual temporal scale, and with centimeter level displacement measurement accuracy. Finally, this study showed that pore water pressure due to an applied internal load can result in a period of relatively rapid deformation downslope, which decreases gradually over time as groundwater levels return to a hydrostatic level. Overall this project methodology serves as a model for future possible landslide monitoring and provides new insight into landslide mechanics.

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Appendix A: Raw Coordinate Values

Location 1		Coordinates		
Scan	Point	X coordinate	Y coordinate	Z coordinate
1	Origin	0	0	0
1	1	-4.964600	-1.143000	691.674377
1	2	-2.114300	-12.141700	690.654114
1	3	-8.846000	-14.646600	688.154785
1	4	-6.428600	-19.297899	688.713074
1	5	4.015900	-27.806999	690.503296
1	6	2.768700	-31.886101	689.000488
1	7	-12.984400	-17.601101	687.313782
1	8	-20.485800	-11.595000	685.753723
1	9	-13.624500	-0.311200	687.957703
1	10	-2.146400	-12.149600	690.700500
1	11	-5.808500	-6.351500	690.948425
1	12	-3.697800	-3.464700	691.273315
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3	59	-119.808624	-21.462410	667.821900
3	60	-117.509644	-18.344957	668.190063
3	61	-136.247406	27.357346	663.985168
3	62	-139.961060	33.969425	662.170959
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3	64	-150.663742	63.737610	656.705444
3	65	-174.381149	126.872208	645.384827
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3	67	-170.874466	122.734886	649.162415
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3	69	-177.416458	83.339020	652.959717
3	70	-179.972855	80.980515	652.654358
3	71	-181.618423	74.786774	653.340027
3	72	-181.866287	70.954826	653.209717
3	73	-180.226151	69.780823	653.632568
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3	75	-174.701080	63.413567	654.872864
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3	77	-174.009430	58.050850	653.975403
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3	155	38.808743	-237.526291	681.421997
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4	70	-180.002670	81.138390	651.947876
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4	73	-180.165176	69.753914	652.652161
4	74	-178.897644	68.371216	652.687439
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4	94	-155.938751	14.641253	659.917419
4	95	-124.804543	0.972603	668.019348
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4	103	-162.353928	-27.339645	659.411072
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4	114	-109.319443	-48.789238	668.911926
4	115	-114.812660	-58.242142	668.491699
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4	117	-67.672722	-48.557270	678.381653
4	118	-109.371078	-74.573387	668.761292
4	119	-101.896881	-72.949554	671.407715
4	120	-106.015236	-76.581352	671.044189
4	121	-99.826416	-75.726273	673.879211
4	122	-99.811821	-81.700005	668.306702
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4	136	-190.694183	-189.396744	670.733459
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4	139	-196.185120	-170.407806	674.710388
4	140	-193.073624	-189.329956	
4	141	-172.102829	-193.813660	671.576050
4	142	-161.872894	-199.006470	674.278809
4	143	-161.145432	-202.673782	674.050842
4	144	-158.277802	-203.823654	674.414673
4	145	-156.508698	-208.105042	674.329041
4	146	-151.355377	-213.819016	673.808411
4	147	-148.162125	-219.208023	677.688721
4	148	-141.903381	-224.270813	671.847412
4	149	-128.482605	-221.968002	674.868652
4	150	-121.378662	-223.377716	671.505066
4	151	-120.635361	-227.494324	672.117920
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4	153	-94.965836	-255.108673	677.561523
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4	155	38.769100	-237.608078	682.688354
4	156	71.818115	-194.928772	678.614868
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Location 2		Coordinates		
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1	7	-6.731100	7.499300	534.727783
1	8	-4.693600	30.572701	538.306213
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1	18	-10.031200	-31.148500	531.567505
1	19	-10.206100	-31.751801	531.693726
1	20	17.645300	-52.636101	532.918396
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1	26	5.954000	-56.513401	532.382874
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1	29	-4.678100	-52.794899	532.705627
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2	13	-34.801516	-31.924515	529.629578
2	14	2.679200	-26.392584	533.216064
2	15	-1.225531	-26.079861	532.944519
2	16	7.669069	-31.585777	535.487976
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2	18	-10.034675	-31.146570	531.579285
2	19	-10.210032	-31.752724	531.686279
2	20	17.668846	-52.629230	532.966492
2	21	14.708145	-50.617432	534.415100
2	22	14.131021	-51.001801	535.178284
2	23	9.955432	-51.384408	535.213806
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2	25	7.706174	-53.386639	532.746216
2	26	5.952904	-56.533657	532.391357
2	27	4.340906	-57.409290	532.212646
2	28	-2.350572	-55.468716	533.005127
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2	31	-19.567722	-66.896408	533.472595
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2	34	-40.144341	-72.364502	534.318787
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2	40	-55.593689	-50.195126	530.045776
2	41	-56.644840	-46.648972	529.397217
2	42	-48.557564	-49.956219	529.670959
2	43	-70.217239	-58.098274	530.006714
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2	49	-88.450241	-30.186710	529.739563
2	50	-88.114212	-25.110834	531.317505
2	51	-83.676071	-20.254311	527.980774
2	52	-85.613579	-12.534765	527.721680
2	53	-85.830078	-8.684212	526.828064
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2	56	-56.840519	-11.995066	525.290222
2	57	-62.314262	-10.270754	524.375183
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2	61	-69.774780	12.914112	523.064880
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3	36	-54.210266	-73.236275	535.657401
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3	40	-55.613319	-50.093945	530.073364
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3	69	-64.596245	23.744631	524.934631
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4	18	-10.059849	-31.145578	531.591919
4	19	-10.225372	-31.758173	531.678101
4	20	17.715475	-52.607231	533.142578

4	21	14.633892	-50.519512	534.481750
4	22	14.095770	-50.926704	535.116150
4	23	9.996083	-51.906311	535.289490
4	24	9.842182	-51.864964	533.171997
4	25	7.599782	-52.972988	532.971497
4	26	5.971651	-56.576347	532.380249
4	27	4.315835	-57.394520	532.264099
4	28	-2.611236	-54.517433	533.215881
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4	31	-19.613394	-66.662788	533.363342
4	32	-26.613495	-66.855370	532.596619
4	33	-35.789436	-69.453880	533.432312
4	34	-40.194153	-72.216087	534.380188
4	35	-42.062996	-72.813583	535.477112
4	36	-54.188446	-73.294977	535.626465
4	37	-58.141602	-70.209976	534.712585
4	38	-60.791157	-67.689369	532.308960
4	39	-67.414444	-66.088554	532.176331
4	40	-55.708401	-50.086185	530.122131
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4	52	-85.107826	-12.212994	527.371338
4	53	-85.665657	-8.440498	526.878845
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4	55	-87.745193	3.201067	525.145386
4	56	-56.793713	-11.774294	525.309326
4	57	-62.264717	-10.032078	524.302979
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4	66	-70.990868	18.859018	527.018250
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4	69	-64.695953	23.706556	524.945251
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4	71	-52.710781	49.906166	532.643494
4	72	-49.635826	52.671680	532.538391
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Location 3		Coordinates		
Scan	Point	X coordinate	Y coordinate	Z coordinate
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1	6	-13.495600	-17.558201	534.026611
1	7	-15.825900	-13.671800	534.428284
1	8	-16.333200	-8.732700	534.112305
1	9	-23.032600	-3.641300	533.472595
1	10	-19.842400	0.459500	533.711609
1	11	-25.095400	7.670400	533.201721
1	12	-28.856501	-11.940200	530.144104
1	13	-25.144300	-15.203300	530.532104
1	14	-27.854000	-20.445101	530.519897
1	15	12.004400	-98.440598	542.646301
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1	17	5.387700	-99.869202	537.275208
1	18	-2.951500	-104.265900	536.273315
1	19	-8.682100	-108.897903	537.399902
1	20	-20.196600	-90.742104	534.298889
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1	26	-34.639500	-47.487400	528.627502
1	27	-41.214500	-52.625000	527.024292
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1	31	-61.941101	-62.247299	531.087891
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1	34	-69.181602	-47.109798	542.408813
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1	37	-50.525200	-22.403400	531.147583
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1	39	-47.112900	-8.424200	525.501891
1	40	-45.503900	-2.106400	530.011475
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1	42	-41.336800	3.009200	527.769104
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1	51	-49.167198	14.284700	528.677124
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1	57	-42.350300	34.696201	533.736816
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1	59	-39.890701	47.636200	525.202393
1	60	-38.190300	49.448601	525.794128
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1	64	-38.210999	55.476601	526.142883
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1	77	-89.482002	185.028503	517.986328
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1	79	-162.195297	-28.249599	571.318420
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2	6	-13.511783	-17.552860	534.033691
2	7	-15.818811	-13.662982	534.434692
2	8	-16.305651	-8.734028	534.107544
2	9	-22.950747	-3.491637	533.527771
2	10	-19.843826	0.459008	533.711731
2	11	-25.094757	7.667470	533.190674
2	12	-28.855127	-11.965628	529.853516
2	13	-25.162884	-15.187809	530.690125
2	14	-27.953686	-21.793123	529.803589
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2	28	-39.754795	-43.314449	528.222961
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2	39	-47.252625	-8.221005	525.765564
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2	46	-45.581554	8.333778	526.171570
2	47	-42.074848	11.866984	528.901611
2	48	-45.734669	12.111468	526.101990
2	49	-57.627583	8.158144	525.561523
2	50	-56.826107	11.299814	528.458496
2	51	-49.225258	14.308434	528.461121
2	52	-44.939255	15.694787	527.116211
2	53	-43.653400	17.905334	527.134583
2	54	-40.340527	21.018179	529.657104
2	55	-52.056427	24.688354	533.223755
2	56	-41.163052	32.004589	533.772705
2	57	-42.290051	34.725250	533.718079
2	58	-41.057667	37.508007	527.621155
2	59	-39.384276	47.629505	525.216980
2	60	-38.131161	49.450314	525.804504
2	61	-36.286922	51.472683	525.832764
2	62	-38.649265	51.690811	527.416565
2	63	-40.547810	53.560249	525.210632
2	64	-38.177353	55.465374	525.998413
2	65	-40.546017	59.630634	525.978516
2	66	-47.059609	64.146149	524.219299
2	67	-47.931644	66.386757	522.129150
2	68	-47.168388	70.309509	523.031555
2	69	-52.413097	75.288017	520.533691
2	70	-51.643002	79.721428	519.153687
2	71	-80.505592	132.680893	520.507446
2	72	-85.816299	140.604919	520.815308
2	73	-81.471207	147.268600	520.678650
2	74	-88.589592	146.731262	521.104431
2	75	-88.579689	165.431610	520.100708
2	76	-93.591484	179.272583	523.339539
2	77	-89.526643	185.095200	517.963806
2	78	-97.428047	255.984146	529.434143
2	79	-161.531433	-27.223381	570.871948
2	80	-147.028107	-34.043388	570.122192
2	81	-137.479889	-41.399925	569.797791
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2	83	-103.623566	-62.417015	577.401367
3	Origin	0	0	0
3	1	-1.680729	-0.880897	539.084412
3	2	-1.222311	-1.920317	538.769775
3	3	-7.768576	5.880703	534.190491
3	4	-10.598531	-26.247704	534.346130
3	5	-13.224548	-19.302744	534.223877
3	6	-13.501499	-17.569363	534.031860

3	7	-15.834845	-13.663184	534.431396
3	8	-16.324823	-8.727365	534.109558
3	9	-23.036983	-3.636888	533.481506
3	10	-19.856899	0.456090	533.713928
3	11	-25.104172	7.660491	533.200562
3	12	-28.868544	-11.982713	529.975647
3	13	-25.160789	-15.199367	530.843140
3	14	-27.869038	-20.323044	530.999146
3	15	12.032029	-98.427032	541.746948
3	16	4.551939	-108.942329	538.627197
3	17	5.464696	-99.937950	535.939697
3	18	-2.939838	-104.464691	536.627319
3	19	-8.666052	-108.866013	537.377930
3	20	-20.144438	-90.609123	534.441772
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3	25	-35.658810	-52.487118	528.616455
3	26	-34.698685	-46.899574	528.235229
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3	38	-42.576210	-8.922546	526.560974
3	39	-47.324760	-8.087701	525.521423
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3	42	-41.350594	3.005780	527.770081
3	43	-49.228516	1.394070	525.335327
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3	49	-57.731457	8.263397	525.936035
3	50	-56.937168	11.463546	528.044861
3	51	-49.310791	14.343253	528.634277
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3	54	-40.337265	21.018877	529.727600

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3	59	-39.858894	47.629696	525.183960
3	60	-38.192482	49.428604	525.708313
3	61	-36.299736	51.469833	525.832764
3	62	-38.698517	51.676904	527.506470
3	63	-40.534733	53.567745	525.145325
3	64	-38.198391	55.502438	526.587952
3	65	-40.526920	59.634579	526.069458
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3	68	-47.177876	70.312820	522.990723
3	69	-52.386917	75.287727	520.485107
3	70	-51.727085	79.715935	519.233459
3	71	-80.468231	132.669083	521.192261
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3	74	-88.589706	146.741028	521.017578
3	75	-88.608490	165.377106	519.851013
3	76	-93.661301	179.208923	523.113464
3	77	-89.562126	184.980194	518.373779
3	78	-97.467094	255.973114	529.433777
3	79	-161.471771	-26.860616	569.172974
3	80	-147.487869	-33.922363	570.018921
3	81	-137.650589	-41.073452	573.000671
3	82	-139.189987	-33.574707	570.566895
3	83	-103.618011	-61.974770	578.415771
4	Origin	0	0	0
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4	3	-7.767116	5.886126	534.252258
4	4	-10.603708	-26.241089	534.341064
4	5	-13.217548	-19.278339	534.222717
4	6	-13.512814	-17.563492	534.026489
4	7	-15.836823	-13.660987	534.426147
4	8	-16.330671	-8.724605	534.108521
4	9	-23.038292	-3.637665	533.471313
4	10	-19.870613	0.457195	533.712524
4	11	-25.120535	7.644289	533.192383
4	12	-28.949823	-12.068507	529.930420
4	13	-25.133904	-15.213050	530.774414
4	14	-27.865826	-20.307178	530.952942
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4	16	4.581502	-108.931600	538.652161
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4	19	-8.669313	-108.876587	537.262695
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4	22	-42.331192	-96.519859	532.990234
4	23	-52.417664	-94.309822	534.166687
4	24	-53.824287	-93.049988	533.361450
4	25	-35.645081	52.486588	528.577026
4	26	-34.671143	-46.873562	528.153992
4	27	-41.262562	-52.077648	526.774658
4	28	-39.729893	-43.109791	528.176025
4	29	-62.921432	-76.341431	533.001343
4	30	-60.139271	-66.133232	531.389465
4	31	-61.822948	-61.663750	530.897400
4	32	-63.360455	-59.098080	531.095947
4	33	-66.619545	-50.461487	538.998569
4	34	-69.061180	-46.580418	542.284851
4	35	-56.433632	-26.050636	526.964172
4	36	-57.425762	-25.299849	528.095947
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4	38	-42.624619	-8.912014	526.531921
4	39	-49.294491	-8.433905	524.403137
4	40	-45.602085	-1.500940	530.314819
4	41	-41.337746	0.720552	531.828247
4	42	-41.333347	3.018487	527.921448
4	43	-49.785760	1.415405	525.110352
4	44	-49.560959	2.828458	525.361084
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4	46	-45.704697	8.328218	526.737183
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4	48	-45.669426	12.135907	526.439941
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4	50	-56.946907	11.506169	527.858337
4	51	-49.254375	14.450071	529.245300
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4	54	-40.379379	21.000549	529.491577
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4	56	-41.189701	32.016659	533.702148
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4	58	-41.083710	37.504440	527.642761
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4	61	-36.329063	51.468292	525.814270
4	62	-38.713215	51.675133	527.484863
4	63	-40.555313	53.561409	525.125061
4	64	-38.235104	55.487232	526.690063
4	65	-40.557278	59.614727	526.073914
4	66	-47.080627	64.129715	524.057617

4	67	-47.950054	66.359024	522.040833
4	68	-47.204689	70.300919	522.992432
4	69	-52.473701	75.264183	520.483459
4	70	-51.745823	79.706924	519.233887
4	71	-80.504425	132.678909	521.209717
4	72	-85.796486	140.651108	520.449646
4	73	-81.476089	147.281158	520.637634
4	74	-88.657074	146.685226	520.998596
4	75	-88.651352	165.359314	519.776367
4	76	-93.663277	179.246414	523.004822
4	77	-89.472740	185.051712	518.205017
4	78	-97.618401	255.983810	529.525879
4	79	-161.545883	-26.877649	570.879639
4	80	-147.299377	-33.925911	570.002625
4	81	-137.669022	-41.405018	573.024231
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Location 4		Coordinates		
Scan	Point	X coordinate	Y coordinate	Z coordinate
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1	3	-153.922394	-305.785797	538.002075
1	4	-176.120499	-302.130789	533.814575
1	5	-181.894302	-308.138885	532.262878
1	6	-168.271805	-282.017609	534.499512
1	7	-172.168793	-331.659210	533.088074
1	8	-154.296005	-445.932709	545.409180
1	9	-157.336899	-327.425818	537.390320
1	10	-151.770493	-311.431793	538.762817
1	11	-196.273407	-445.380493	533.509705
1	12	-187.360504	-416.138794	527.984497
1	13	-189.628006	-405.312195	526.877502
1	14	-190.286606	-407.152496	527.162170
1	15	-194.389404	-406.647400	530.454407
1	16	-195.982498	-401.669189	528.724670
1	17	-196.627502	-399.675293	525.369873
1	18	-194.904495	-395.870697	524.689575
1	19	-198.420593	-393.628601	524.789795
1	20	-199.077606	-389.975311	524.074219
1	21	-197.928207	-385.782196	524.348328

1	22	-207.207397	-385.813202	526.933105
1	23	-204.701996	-372.678894	524.302979
1	24	-213.234604	-369.787201	525.788513
1	25	-214.692307	-364.959198	526.423889
1	26	-210.804398	-360.441498	524.899902
1	27	-209.576508	-357.519501	529.026794
1	28	-214.785400	-353.781097	525.706177
1	29	-221.290207	-352.889709	529.515076
1	30	-214.425995	-346.446289	525.988281
1	31	-223.065796	-346.057098	525.067871
1	32	-218.886703	-342.008789	525.748474
1	33	-219.475006	-332.259705	525.774109
1	34	-226.864700	-334.918610	523.795227
1	35	-217.608902	-328.645813	525.456421
1	36	-228.528793	-333.284088	524.493225
1	37	-224.398697	-329.416809	523.958008
1	38	-224.512299	-327.640594	525.647705
1	39	-218.844894	-324.093201	528.524292
1	40	-223.831207	-325.379211	527.050903
1	41	-221.582397	-320.414307	525.002197
1	42	-216.153107	-314.517792	525.549988
1	43	-228.908295	-320.089691	522.976196
1	44	-218.641602	-313.687408	524.774109
1	45	-226.096893	-316.480408	523.280884
1	46	-223.159805	-313.784485	523.747498
1	47	-218.803497	-309.996704	524.904114
1	48	-228.087799	-312.849396	526.232788
1	49	-223.515701	-309.389709	524.018188
1	50	-219.852905	-304.433502	523.983704
1	51	-245.399307	-314.769897	519.903992
1	52	-222.236298	-300.537415	523.362488
1	53	-221.207108	298.751587	523.293884
1	54	-220.125198	-295.494690	524.141113
1	55	-219.780594	-291.728088	523.944885
1	56	-222.732895	-287.522308	525.721680
1	57	-222.608398	-281.310486	521.687988
1	58	-225.692001	-281.916992	521.044983
1	59	-218.018799	-275.990601	522.229004
1	60	-223.154495	-264.519989	520.783508
1	61	-215.270004	-260.165497	522.489685
1	62	-217.742706	-256.106689	520.570679
1	63	-229.759796	-253.718506	522.445923
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1	72	-224.719604	-224.370102	518.745178
1	73	-221.814499	-225.454697	519.051575
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1	75	-223.445404	-212.333603	517.851379
1	76	-224.110703	-210.590393	516.176697
1	77	-219.108597	-213.196304	518.648987
1	78	-221.594393	-209.054901	518.003601
1	79	-218.893005	-207.432007	518.229919
1	80	-214.436874	-204.839340	528.153259
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1	85	-212.809006	-184.270798	514.321899
1	86	-214.452805	-177.005203	517.691284
1	87	-215.692200	-162.466003	512.314270
1	88	-215.986893	-157.215607	511.368011
1	89	-214.544006	-152.620804	511.568512
1	90	-214.119797	-149.829102	511.408112
1	91	-221.249298	-114.974800	510.392914
1	92	-228.575195	-61.654499	505.851013
1	93	-221.262497	-56.471901	503.665497
1	94	-216.834198	-45.044601	501.238495
1	95	-203.527206	-12.999100	504.866394
1	96	-199.348206	3.107800	498.824097
1	97	-200.717103	56.827999	490.973602
1	98	-286.047302	-476.671295	591.802795
1	99	-292.202515	-469.210510	571.430298
1	100	-286.831512	-460.809814	568.326172
1	101	-218.379196	-417.191895	565.932129
1	102	-223.005707	-407.110199	559.469788
1	103	-250.124496	-412.943298	564.323120
1	104	-244.521805	-394.749115	563.636780
1	105	-226.828705	-393.832111	560.507019
1	106	-227.589005	-397.476715	561.063416
1	107	-221.848404	-397.776215	561.844788
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1	109	-263.061493	-241.947693	552.699280
1	110	-275.596710	-231.727798	554.633728
1	111	-273.718689	-228.551102	554.214478
1	112	-269.046997	-226.965698	553.472473
1	113	-262.659210	-228.109894	559.086182
1	114	-267.698486	-234.659805	555.950500
1	115	-278.838287	-198.074097	552.677185
1	116	-250.626907	-196.565994	549.682007
1	117	-240.114105	-185.525406	553.618713

1	118	-246.005096	-192.208603	552.660828
1	119	-243.105804	-198.976303	546.855103
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2	2	-157.421570	-311.092560	537.989075
2	3	-153.980209	-305.804230	537.998108
2	4	-176.113251	-302.121429	533.805481
2	5	-181.839966	-308.055969	532.253967
2	6	-168.352890	-281.920441	534.508118
2	7	-172.185760	-331.669067	533.120056
2	8	-154.018005	-445.859314	545.878967
2	9	-157.337555	-327.447052	537.405029
2	10	-151.758987	-311.419708	538.771790
2	11	-196.272934	-445.359863	533.742798
2	12	-187.392227	-416.159271	528.395020
2	13	-189.604477	-405.332367	527.034485
2	14	-190.091522	-407.194305	527.292603
2	15	-194.362732	-406.658569	530.498169
2	16	-196.060745	-401.757660	528.435547
2	17	-196.568497	-399.692780	525.533752
2	18	-194.846329	-395.897888	524.549255
2	19	-197.561783	-393.496246	525.117981
2	20	-199.268906	-390.030426	524.268433
2	21	-197.937119	-385.780273	524.208984
2	22	-207.302368	-385.857025	526.842896
2	23	-204.676300	-372.706543	524.347534
2	24	-213.226852	-369.765472	525.710815
2	25	-214.635773	-364.981659	526.326599
2	26	-210.824738	-360.520416	524.995605
2	27	-209.550491	-357.537964	529.021790
2	28	-214.746780	-353.826752	525.731506
2	29	-221.304703	-352.943298	529.676147
2	30	-214.436111	-346.430847	525.933350
2	31	-222.922455	-346.035706	525.113708
2	32	-218.990875	-342.020935	525.787964
2	33	-219.477051	-332.290344	526.919434
2	34	-226.874863	-334.986633	523.838562
2	35	-217.659546	-328.660919	525.379028
2	36	-228.539948	-333.268768	524.778320
2	37	-224.392120	-329.439514	524.262207
2	38	-224.417496	-327.519096	525.441833
2	39	-218.815033	-324.074005	528.624878
2	40	-223.907120	-325.375885	526.580933
2	41	-221.564636	-320.427643	524.937866
2	42	-216.233337	-314.586304	525.525269
2	43	-228.883560	-320.169403	522.814392
2	44	-218.605438	-313.697021	524.736511
2	45	-226.075516	-316.459656	523.026978

2	46	-223.149246	-313.796490	523.777527
2	47	-218.777954	-309.992126	524.812683
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2	49	-223.548477	-309.384247	523.998840
2	50	-219.822006	-304.412018	523.814697
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2	52	-222.189636	-300.574646	523.300659
2	53	-221.211761	-298.732910	523.246826
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2	56	-222.735199	-287.522919	525.445374
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2	60	-223.180710	-264.652466	520.657288
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2	63	-229.636353	-253.575714	522.301758
2	64	-224.467697	-248.614441	525.001831
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2	71	-227.490204	-224.872208	516.943542
2	72	-224.717255	-224.305237	518.629211
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2	111	-273.462097	-228.355469	554.567383
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3	9	-157.266098	-327.435150	537.460083
3	10	-151.703720	-311.412598	538.818909
3	11	-196.402802	-445.332275	533.682312
3	12	-187.542130	-416.119934	528.631653
3	13	-189.659470	-405.259857	526.780762
3	14	-190.332336	-407.123474	527.749512
3	15	-194.454620	-406.608704	530.408875
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3	18	-194.978516	-395.843353	524.533589
3	19	-198.411438	-393.527313	525.475037
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3	23	-204.737854	-372.627380	524.446045
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4	5	-181.799530	-308.043762	532.258484
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4	7	-172.156387	-331.673004	533.104980
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4	16	-195.947037	-401.788055	528.218323
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NOTE: Coordinates offset by:		-156.137985	-316.023560	542.210144

Location 6		Coordinates		
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1	6	-36.445499	-11.838900	488.888489
1	7	-34.685799	-13.518800	490.647797
1	8	-12.092700	16.038900	476.563995
1	9	-19.795700	24.699600	478.478790
1	10	-58.344398	30.897499	476.446686

1	11	-59.610600	24.924700	476.429108
1	12	-55.755901	18.665800	478.592102
1	13	-58.987499	18.819201	478.062592
1	14	-103.656998	47.473900	477.799591
1	15	-112.564796	49.547901	477.085785
1	16	-68.628601	19.648001	478.584290
1	17	-107.278198	49.336201	476.778412
1	18	-112.445396	49.615898	477.083710
1	19	-55.681499	42.214199	481.279205
1	20	-55.295601	46.076599	481.357788
2	Origin	0.000000	0.000000	0.000000
2	1	-18.707803	16.798746	478.584808
2	2	-40.934357	21.807661	475.953339
2	3	-36.529968	12.738346	477.225555
2	4	-55.198418	12.062726	477.126953
2	5	-39.871986	1.936140	481.448395
2	6	-36.463188	-11.825622	488.891083
2	7	-34.690163	-13.513882	490.665070
2	8	-12.085739	16.039087	476.578186
2	9	-19.798740	24.696777	478.492371
2	10	-58.309387	30.920105	476.447968
2	11	-59.586090	24.956917	476.411011
2	12	-55.719807	18.682962	478.546204
2	13	-58.871258	18.824961	478.112793
2	14	-103.564003	47.484467	477.661896
2	15	-111.513840	49.139465	476.798615
2	16	-68.626953	19.695900	478.677795
2	17	-107.303993	49.357239	476.844269
2	18	-112.349825	49.707317	476.807129
2	19	-55.646679	42.213047	481.347015
2	20			
3	Origin	0.000000	0.000000	0.000000
3	1	-18.727483	16.815266	478.534515
3	2	-40.766415	21.738646	475.970551
3	3	-36.538189	12.748989	477.163544
3	4	-55.246990	12.098129	477.141510
3	5	-39.877148	1.959264	481.422699
3	6	-36.378563	-11.900068	489.025604
3	7	-34.569744	-13.622606	490.744843
3	8	-12.113829	16.107292	476.547852
3	9	-19.822241	24.717264	478.473541
3	10	-58.323727	30.927853	476.432770
3	11	-59.866821	25.093220	476.370300
3	12	-55.770519	18.709457	478.568085
3	13	-58.877419	18.857792	478.041077

3	14	-103.648125	47.462841	477.483307
3	15	-112.316444	49.529552	476.484741
3	16	-68.687782	19.668793	478.798920
3	17			
3	18	-112.573883	49.733093	477.483459
3	19	-55.649841	42.231308	481.299927
3	20	-55.244812	46.063599	481.357819
4	Origin	0.000000	0.000000	0.000000
4	1	-18.722479	16.809145	478.552094
4	2	-40.566570	21.645069	476.000122
4	3	-36.543175	12.735076	477.182831
4	4	-55.186176	12.091323	477.093353
4	5	-39.832176	1.958769	481.465607
4	6	-36.469456	-11.818730	488.864349
4	7	-34.701878	-13.495216	490.622528
4	8	-12.112083	16.037458	476.552612
4	9	-19.827366	24.700323	478.436096
4	10	-58.307011	30.952076	476.402710
4	11	-59.605206	24.984179	476.451263
4	12	-55.774834	18.722832	478.586334
4	13	-58.914818	18.840374	478.003876
4	14	-103.652397	47.553902	477.561371
4	15	-112.609261	49.637913	476.793091
4	16	-68.682594	19.682678	478.715973
4	17	-107.376907	49.446983	476.963715
4	18	-112.390144	49.775646	476.602692
4	19	-55.581142	42.268536	481.221344
4	20	-55.253647	46.066456	581.393921

Appendix B: Final Adjusted UTM Coordinate Values

Location	Scan	Point	EASTING (X Coordinate)	NORTHING (Y Coordinate)
1	1	0	543027.912	4944949.431
1	1	1	543022.8226	4944949.204
1	1	2	543023.6367	4944937.871
1	1	3	543016.563	4944936.625
1	1	4	543018.0993	4944931.613
1	1	5	543026.8326	4944921.356
1	1	6	543024.8683	4944917.569
1	1	7	543011.9585	4944934.468
1	1	8	543005.667	4944941.732
1	1	9	543014.4559	4944951.588
1	1	10	543023.6037	4944937.869
1	1	11	543021.0506	4944944.234
1	1	12	543023.6486	4944946.692
1	1	13	543024.9377	4944917.462
1	1	14	543026.4942	4944920.997
1	1	15	543018.383	4944945.224
1	1	16	543013.0255	4944944.076
1	1	17	543018.0318	4944931.625
1	1	18	543040.3337	4944921.144
1	1	19	542993.0089	4944881.975
1	1	20	542987.8943	4944891.478
1	1	21	542989.8776	4944895.648
1	1	22	542989.5628	4944901.565
1	1	23	542981.4557	4944901.069
1	1	24	542979.3841	4944903.772
1	1	25	542984.9597	4944909.927
1	1	26	542983.4259	4944912.379
1	1	27	542981.803	4944908.992
1	1	28	542977.1816	4944913.853
1	1	29	542973.6128	4944915.59
1	1	30	542972.8169	4944919.816
1	1	31	542975.5756	4944922.544
1	1	32	542968.3693	4944926.76
1	1	33	542968.2634	4944932.696
1	1	34	542967.0147	4944936.416
1	1	35	542966.4064	4944942.489
1	1	36	542963.1428	4944948.924
1	1	37	542960.544	4944949.523

1	1	38	542945.9035	4944964.282
1	1	39	542953.1098	4944965.117
1	1	40	542947.6083	4944966.586
1	1	41	542944.1415	4944967.512
1	1	42	542944.7893	4944971.835
1	1	43	542955.2429	4944969.835
1	1	44	542953.3608	4944970.445
1	1	45	542950.3757	4944980.15
1	1	46	542937.8434	4944991.566
1	1	47	542898.3089	4945015.615
1	1	48	542887.2053	4945010.447
1	1	49	542933.526	4945027.049
1	1	50	542937.7195	4945020.964
1	1	51	542929.7736	4945028.433
1	1	52	542929.3186	4945040.429
1	1	53	542953.1897	4944913.211
1	1	54	542948.4947	4944940.042
1	1	55	542942.6478	4944944.757
1	1	56	542940.9605	4944948.832
1	1	57	542935.5544	4944954.264
1	1	58	542918.5772	4944943.066
1	1	59	542906.5322	4944949.069
1	1	60	542909.3603	4944951.745
1	1	61	542899.0546	4945000.001
1	1	62	542896.9476	4945007.304
1	1	63	542897.9914	4945015.207
1	1	64	542891.4176	4945038.406
1	1	65	542879.2172	4945104.471
1	1	66	542877.7825	4945103.452
1	1	67	542879.655	4945090.558
1	1	68	542882.6153	4945084.165
1	1	69	542868.4963	4945062.495
1	1	70	542865.5184	4945061.029
1	1	71	542862.9617	4945055.081
1	1	72	542861.9741	4945051.151
1	1	73	542863.3473	4945049.749
1	1	74	542864.2861	4945048.089
1	1	75	542867.5982	4945042.305
1	1	76	542868.0668	4945039.655
1	1	77	542867.4128	4945037.082
1	1	78	542866.8618	4945036.721

1	1	79	542865.6887	4945032.104
1	1	80	542857.0372	4945029.3
1	1	81	542866.816	4945015.143
1	1	82	542863.129	4945017.021
1	1	83	542864.7744	4945017.712
1	1	84	542862.589	4945021.997
1	1	85	542887.1822	4945010.352
1	1	86	542863.2987	4945013.824
1	1	87	542859.5055	4945013.162
1	1	88	542860.0852	4945011.598
1	1	89	542858.068	4945011.739
1	1	90	542866.5097	4945005.361
1	1	91	542872.7568	4945000.591
1	1	92	542875.3455	4944995.756
1	1	93	542874.4465	4944995.374
1	1	94	542877.3414	4944991.165
1	1	95	542905.7604	4944972.166
1	1	96	542875.083	4944981.713
1	1	97	542867.3155	4944979.228
1	1	98	542864.0804	4944977.217
1	1	99	542862.7553	4944976.164
1	1	100	542863.8327	4944969.081
1	1	101	542850.8173	4944961.05
1	1	102	542862.2011	4944956.067
1	1	103	542863.685	4944950.948
1	1	104	542862.1084	4944949.84
1	1	105	542863.973	4944948.392
1	1	106	542873.1605	4944941.969
1	1	107	542868.8987	4944940.697
1	1	108	542870.9226	4944937.96
1	1	109	542871.6708	4944936.054
1	1	110	542875.1761	4944933.541
1	1	111	542896.3569	4944927.326
1	1	112	542897.2632	4944925.729
1	1	113	542893.6217	4944918.823
1	1	114	542911.3851	4944919.96
1	1	115	542904.8837	4944912.179
1	1	116	542918.3095	4944911.66
1	1	117	542952.943	4944912.976
1	1	118	542907.542	4944894.874
1	1	119	542914.9851	4944895.306

1	1	120	542910.2515	4944892.479
1	1	121	542916.6097	4944892.111
1	1	122	542915.4514	4944886.106
1	1	123	542928.0171	4944875.536
1	1	124	542981.2355	4944872.735
1	1	125	542989.1155	4944901.225
1	1	126	542988.6128	4944896.226
1	1	127	542989.2522	4944828.153
1	1	128	543026.1352	4944824.505
1	1	129	542986.4378	4944831.468
1	1	130	542781.7204	4944953.909
1	1	131	542772.7228	4944939.387
1	1	132	542772.4914	4944938.219
1	1	133	542796.4585	4944821.613
1	1	134	542806.3611	4944806.789
1	1	135	542805.7708	4944807.472
1	1	137	542796.4878	4944821.614
1	1	138	542794.1409	4944818.316
1	1	139	542804.1157	4944815.996
1	1	141	542824.2373	4944788.961
1	1	142	542833.1478	4944782.08
1	1	143	542824.7681	4944772.561
1	1	144	542836.0098	4944776.791
1	1	145	542837.1478	4944772.515
1	1	147	542842.7212	4944759.23
1	1	148	542848.3453	4944753.65
1	1	149	542862.0324	4944753.491
1	1	150	542868.6776	4944750.924
1	1	151	542868.602	4944746.673
1	1	152	542866.8647	4944737.836
1	1	153	542888.932	4944714.855
1	1	154	542917.5236	4944685.329
1	1	155	543023.6392	4944708.092
1	1	156	543063.9587	4944744.115
1	1	157	543121.3695	4944710.907
1	1	158	543119.095	4944686.76
1	1	159	543149.2911	4944661.373
1	2	0	543027.912	4944949.431
1	2	1	543022.8417	4944949.204
1	2	2	543023.6204	4944937.876
1	2	3	543016.5723	4944936.616

1	2	4	543018.0927	4944931.614
1	2	5	543026.9747	4944921.337
1	2	6	543024.9879	4944917.571
1	2	7	543011.9577	4944934.437
1	2	8	543005.6865	4944941.736
1	2	9	543014.4863	4944951.585
1	2	10	543027.912	4944949.431
1	2	11	543027.912	4944949.431
1	2	12	543027.912	4944949.431
1	2	13	543027.912	4944949.431
1	2	14	543027.912	4944949.431
1	2	15	543027.912	4944949.431
1	2	16	543027.912	4944949.431
1	2	17	543027.912	4944949.431
1	2	18	543027.912	4944949.431
1	2	19	542992.8115	4944882.194
1	2	20	542987.5007	4944891.947
1	2	21	542989.5123	4944896.112
1	2	22	542989.476	4944901.626
1	2	23	542981.1617	4944901.58
1	2	24	542979.0578	4944904.295
1	2	25	542984.9411	4944909.969
1	2	26	542983.3977	4944912.622
1	2	27	542981.4856	4944909.322
1	2	28	542976.9393	4944914.448
1	2	29	542973.4127	4944916.09
1	2	30	542972.5166	4944920.447
1	2	31	542975.3163	4944923.075
1	2	32	542968.2531	4944927.383
1	2	33	542968.09	4944933.291
1	2	34	542966.9512	4944936.909
1	2	35	542966.1873	4944943.035
1	2	36	542963.0416	4944949.511
1	2	37	542960.4332	4944950.122
1	2	38	542946.1389	4944965.019
1	2	39	542953.0188	4944965.782
1	2	40	542947.7871	4944967.224
1	2	41	542944.079	4944968.151
1	2	42	542944.7367	4944972.457
1	2	43	542955.1069	4944970.471
1	2	44	542953.2303	4944971.033

1	2	45	542950.2904	4944980.72
1	2	46	542938.0038	4944992.213
1	2	47	542898.3745	4945016.99
1	2	48	542887.2392	4945011.092
1	2	49	542933.2212	4945027.357
1	2	50	542937.845	4945021.175
1	2	51	542930.108	4945028.548
1	2	52	542929.4604	4945040.574
1	2	53	542952.8907	4944913.769
1	2	54	542948.1878	4944940.67
1	2	55	542942.4458	4944945.343
1	2	56	542940.7986	4944949.451
1	2	57	542935.6657	4944955.287
1	2	58	542918.4105	4944943.634
1	2	59	542906.3832	4944949.61
1	2	60	542909.2217	4944952.264
1	2	61	542899.0136	4945000.522
1	2	62	542896.7367	4945007.845
1	2	63	542897.9557	4945015.809
1	2	64	542891.2264	4945038.9
1	2	65	542879.3861	4945105.25
1	2	66	543027.912	4944949.431
1	2	67	542880.3567	4945090.951
1	2	68	542882.6208	4945084.877
1	2	69	542868.5061	4945063.099
1	2	70	542866.1247	4945061.291
1	2	71	542862.8431	4945055.51
1	2	72	542861.9964	4945051.8
1	2	73	542863.3871	4945050.379
1	2	74	542864.2943	4945048.717
1	2	75	542867.6302	4945043.05
1	2	76	542868.0739	4945040.294
1	2	77	542867.3802	4945037.718
1	2	78	542866.8561	4945037.349
1	2	79	542865.6967	4945032.767
1	2	80	542856.855	4945029.197
1	2	81	542866.7063	4945015.834
1	2	82	542863.112	4945017.68
1	2	83	542864.7186	4945018.369
1	2	84	542862.6502	4945022.645
1	2	85	542887.2333	4945010.986

1	2	86	542863.1966	4945014.472
1	2	87	542859.5058	4945013.992
1	2	88	542860.0831	4945012.323
1	2	89	542857.9425	4945012.39
1	2	90	542866.2244	4945006.032
1	2	91	542872.7701	4945001.261
1	2	92	542875.4322	4944996.124
1	2	93	542874.3508	4944996.009
1	2	94	542877.3034	4944991.773
1	2	95	542905.3783	4944972.631
1	2	96	542874.9585	4944982.347
1	2	97	542867.1294	4944979.907
1	2	98	542864.134	4944977.609
1	2	99	542862.7299	4944976.735
1	2	100	542863.6725	4944969.776
1	2	101	542850.6652	4944961.657
1	2	102	542862.0655	4944956.796
1	2	103	542863.4594	4944951.657
1	2	104	542861.9328	4944950.465
1	2	105	542863.8061	4944949.111
1	2	106	542872.6	4944942.386
1	2	107	542868.7291	4944941.301
1	2	108	542870.8905	4944938.53
1	2	109	542871.2175	4944936.637
1	2	110	542875.0239	4944934.136
1	2	111	542896.454	4944928.002
1	2	112	542897.0031	4944926.356
1	2	113	542893.4447	4944919.411
1	2	114	542911.5972	4944921.057
1	2	115	542904.6438	4944912.709
1	2	116	542918.8624	4944912.49
1	2	117	542952.8379	4944913.564
1	2	118	542907.2027	4944895.421
1	2	119	542914.7188	4944895.868
1	2	120	542910.3222	4944893.245
1	2	121	542916.3013	4944892.719
1	2	122	542915.2059	4944886.793
1	2	123	542927.8287	4944876.081
1	2	124	542980.742	4944873.259
1	2	125	542989.3424	4944901.468
1	2	126	542988.3039	4944896.723

1	2	127	542988.9046	4944828.577
1	2	128	543025.7381	4944824.908
1	2	129	542985.6513	4944831.633
1	2	130	542781.5467	4944954.944
1	2	131	542772.4787	4944940.154
1	2	132	542772.0399	4944938.84
1	2	133	542796.1771	4944822.217
1	2	134	542806.0183	4944807.549
1	2	135	542806.0183	4944807.549
1	2	137	542796.1771	4944822.217
1	2	138	542793.7189	4944819.118
1	2	139	542804.3128	4944816.818
1	2	141	542823.8079	4944789.552
1	2	142	542832.6427	4944782.68
1	2	143	542824.445	4944773.188
1	2	144	542835.6598	4944777.408
1	2	145	542836.7168	4944772.971
1	2	147	542842.2045	4944759.273
1	2	148	542847.9844	4944754.23
1	2	149	542861.3439	4944753.533
1	2	150	542867.7496	4944751.039
1	2	151	542868.1695	4944747.212
1	2	152	542866.5434	4944738.276
1	2	153	542888.6167	4944715.358
1	2	154	542917.307	4944685.858
1	2	155	543023.04	4944708.583
1	3	0	543027.912	4944949.431
1	3	1	543022.8466	4944949.196
1	3	2	543023.6374	4944937.872
1	3	3	543016.5879	4944936.602
1	3	4	543018.1567	4944931.624
1	3	5	543026.9994	4944921.355
1	3	6	543024.9797	4944917.527
1	3	7	543011.9984	4944934.41
1	3	8	543005.7061	4944941.727
1	3	9	543014.4996	4944951.588
1	3	10	543027.912	4944949.431
1	3	11	543027.912	4944949.431
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2	2	30	542971.4736	4945383.73
2	2	31	542964.6483	4945376.514
2	2	32	542957.7583	4945374.997
2	2	33	542949.4946	4945370.332

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2	2	37	542927.8642	4945364.419
2	2	38	542924.6485	4945366.183
2	2	39	542917.9884	4945366.198
2	2	40	542925.7717	4945384.602
2	2	41	542923.943	4945387.817
2	2	42	542932.5699	4945386.432
2	2	43	542913.3238	4945373.586
2	2	44	542910.8529	4945374.052
2	2	45	542908.1804	4945373.843
2	2	46	542910	4945377.401
2	2	47	542900.0327	4945379.133
2	2	48	542899.9713	4945382.082
2	2	49	542889.231	4945396.63
2	2	50	542888.4061	4945401.65
2	2	51	542891.626	4945407.387
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2	2	57	542910.164	4945421.959
2	2	58	542916.6213	4945427.075
2	2	59	542911.8993	4945430.564
2	2	60	542889.7148	4945430.942
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2	2	62	542899.8703	4945445.617
2	2	63	542897.8048	4945447.552
2	2	64	542900.5618	4945451.492
2	2	65	542888.478	4945441.763
2	2	66	542895.0396	4945448.107
2	2	67	542896.2945	4945450.261
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2	2	71	542905.8435	4945482.677
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2	3	28	542978.8146	4945391.583
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2	3	34	542945.6862	4945366.668
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4	3	36	542858.0837	4945600.703
4	3	37	542861.5199	4945605.095
4	3	38	542861.1659	4945606.847
4	3	39	542866.1291	4945611.242
4	3	40	542861.3854	4945609.171
4	3	41	542862.8451	4945614.459
4	3	42	542867.1994	4945621.229
4	3	43	542855.5564	4945613.479
4	3	44	542864.5968	4945621.643
4	3	45	542857.659	4945617.499
4	3	46	542859.5331	4945620.497
4	3	47	542863.8943	4945625.2

4	3	48	542855.1456	4945620.819
4	3	49	542859.1086	4945625.003
4	3	50	542861.9304	4945630.49
4	3	51	542837.7819	4945616.654
4	3	52	542858.8952	4945633.928
4	3	53	542859.6142	4945635.892
4	3	54	542860.15	4945639.29
4	3	55	542859.6552	4945643.191
4	3	56	542856.2715	4945646.679
4	3	57	542855.3346	4945652.819
4	3	58	542852.3382	4945651.657
4	3	59	542858.857	4945658.717
4	3	60	542852.3381	4945669.372
4	3	61	542859.1524	4945674.882
4	3	62	542856.0476	4945678.417
4	3	63	542843.7903	4945679.066
4	3	64	542848.2076	4945684.753
4	3	65	542850.2411	4945691.136
4	3	66	542851.814	4945693.605
4	3	67	542846.4545	4945700.499
4	3	68	542843.9263	4945701.547
4	3	69	542845.9272	4945701.023
4	3	70	542842.0785	4945705.83
4	3	71	542841.2383	4945707.507
4	3	73	542845.6218	4945708.717
4	3	74	542839.8002	4945717.061
4	3	75	542843.2586	4945720.773
4	3	76	542842.2641	4945722.386
4	3	77	542847.7305	4945720.584
4	3	78	542844.6129	4945724.275
4	3	79	542846.9166	4945726.219
4	3	80	542851.1452	4945729.715
4	3	81	542847.7395	4945737.468
4	3	82	542850.6624	4945737.536
4	3	83	542850.8662	4945744.321
4	3	84	542845.2873	4945749.949
4	3	85	542849.0447	4945750.189
4	3	86	542846.4994	4945756.888
4	3	87	542842.6354	4945771.203
4	3	88	542841.6002	4945776.336
4	3	89	542842.2677	4945781.086

4	3	90	542842.2214	4945783.877
4	3	91	542829.4476	4945817.091
4	3	92	542813.4672	4945868.489
4	3	93	542819.873	4945874.82
4	3	94	542822.3466	4945886.796
4	3	95	542830.1786	4945920.595
4	3	96	542831.6978	4945937.156
4	3	97	542821.4782	4945989.996
4	3	98	542824.6337	4945450.697
4	3	99	542817.4099	4945457.341
4	3	100	542821.5183	4945465.813
4	3	101	542881.9708	4945519.543
4	3	102	542875.5362	4945528.732
4	3	103	542849.7617	4945518.82
4	3	104	542852.3535	4945537.504
4	3	105	542869.8067	4945541.69
4	3	106	542869.7376	4945537.54
4	3	107	542875.6639	4945538.048
4	3	108	542805.5281	4945685.61
4	3	109	542809.0924	4945685.325
4	3	110	542795.3583	4945693.592
4	3	111	542796.8231	4945696.745
4	3	112	542800.9975	4945699.277
4	3	113	542806.0767	4945698.42
4	3	114	542802.9406	4945692.098
4	3	115	542786.5661	4945726.614
4	3	116	542814.0403	4945731.814
4	3	117	542822.4149	4945744.478
4	3	118	542817.6087	4945736.323
4	3	119	542822.0216	4945730.557
4	4	0	542926.623	4945629.5
4	4	1	542926.2967	4945633.498
4	4	2	542924.5224	4945634.176
4	4	3	542927.0422	4945640.004
4	4	4	542904.5513	4945639.844
4	4	5	542899.9959	4945633.132
4	4	6	542908.8237	4945661.176
4	4	7	542913.4094	4945611.42
4	4	8	542950.2066	4945501.788
4	4	9	542927.3018	4945618.015
4	4	10	542930.1373	4945634.777

4	4	11	542908.5878	4945495.348
4	4	12	542912.4941	4945525.598
4	4	13	542908.4787	4945535.884
4	4	14	542908.216	4945534.031
4	4	15	542904.0069	4945533.778
4	4	16	542901.5262	4945538.339
4	4	17	542900.7076	4945540.327
4	4	18	542901.6866	4945544.32
4	4	19	542897.8402	4945545.971
4	4	20	542896.606	4945549.488
4	4	21	542896.9553	4945553.791
4	4	22	542887.9226	4945552.245
4	4	23	542888.1466	4945565.546
4	4	24	542879.2233	4945567.013
4	4	25	542877.1571	4945571.488
4	4	26	542880.0941	4945576.584
4	4	27	542880.8306	4945579.672
4	4	28	542875.059	4945582.485
4	4	29	542868.452	4945582.192
4	4	30	542874.0958	4945589.792
4	4	31	542865.8489	4945588.852
4	4	32	542868.8912	4945593.403
4	4	33	542866.7615	4945602.872
4	4	34	542859.9814	4945599.053
4	4	35	542868.0556	4945606.82
4	4	36	542858.098	4945600.442
4	4	37	542861.4571	4945604.952
4	4	38	542861.1556	4945606.662
4	4	39	542866.1244	4945611.118
4	4	40	542861.3723	4945609.007
4	4	41	542862.7888	4945614.282
4	4	42	542867.1592	4945620.958
4	4	43	542855.4844	4945613.359
4	4	44	542864.5665	4945621.436
4	4	45	542857.6774	4945617.522
4	4	46	542859.415	4945620.454
4	4	47	542863.6587	4945624.914
4	4	48	542855.0826	4945620.633
4	4	49	542858.926	4945624.863
4	4	50	542861.8882	4945630.34
4	4	51	542838.4945	4945616.518

4	4	52	542858.8197	4945633.762
4	4	53	542859.5539	4945635.723
4	4	54	542860.131	4945639.184
4	4	55	542859.6975	4945642.805
4	4	56	542856.1994	4945646.54
4	4	57	542855.1454	4945652.617
4	4	58	542852.1578	4945651.411
4	4	59	542858.9189	4945658.802
4	4	60	542858.9467	4945674.27
4	4	61	542858.9085	4945674.661
4	4	62	542855.7542	4945677.961
4	4	63	542843.6829	4945678.728
4	4	64	542848.0013	4945684.612
4	4	65	542849.9794	4945690.952
4	4	66	542851.7351	4945693.472
4	4	67	542846.2711	4945700.835
4	4	68	542843.5511	4945701.498
4	4	69	542846.6596	4945700.178
4	4	70	542841.8573	4945705.59
4	4	71	542841.0544	4945707.531
4	4	72	542843.7108	4945708.463
4	4	73	542846.7831	4945707.845
4	4	74	542839.3395	4945716.866
4	4	75	542842.9058	4945720.628
4	4	76	542841.9151	4945722.252
4	4	77	542847.3366	4945720.505
4	4	78	542844.2476	4945724.062
4	4	79	542846.5939	4945726.355
4	4	80	542850.7609	4945729.529
4	4	81	542847.3426	4945737.257
4	4	82	542850.2199	4945737.28
4	4	83	542850.5741	4945744.125
4	4	84	542843.9645	4945750.46
4	4	85	542848.6707	4945749.943
4	4	86	542846.0887	4945756.584
4	4	87	542842.0679	4945771.024
4	4	88	542841.0726	4945776.246
4	4	89	542841.7818	4945780.926
4	4	90	542841.5566	4945783.703
4	4	91	542828.8918	4945816.848
4	4	92	542812.5478	4945868.233

4	4	93	542818.9983	4945874.496
4	4	94	542821.4726	4945886.536
4	4	95	542828.808	4945920.564
4	4	96	542830.6588	4945936.919
4	4	97	542820.2667	4945989.754
4	4	98	542825.1569	4945450.367
4	4	99	542817.7523	4945456.622
4	4	100	542821.8599	4945465.277
4	4	101	542882.1399	4945519.355
4	4	102	542875.9354	4945528.691
4	4	103	542850.0324	4945518.364
4	4	104	542852.3255	4945537.378
4	4	105	542869.881	4945541.376
4	4	106	542869.8286	4945537.269
4	4	107	542875.4353	4945538.041
4	4	108	542805.4713	4945685.319
4	4	109	542808.8024	4945685.321
4	4	110	542794.8543	4945693.284
4	4	111	542796.3767	4945696.557
4	4	112	542800.6561	4945698.928
4	4	113	542805.928	4945697.901
4	4	114	542802.546	4945691.289
4	4	115	542786.24	4945726.097
4	4	116	542813.4318	4945731.622
4	4	117	542822.0721	4945744.394
4	4	118	542817.4175	4945736.425
4	4	119	542821.5587	4945730.317
6	1	0	543065.5667	4946480.5
6	1	1	543070.4736	4946505.166
6	1	2	543063.4542	4946526.838
6	1	3	543057.9008	4946518.427
6	1	4	543047.7862	4946534.041
6	1	5	543046.8877	4946515.795
6	1	6	543036.8	4946505.816
6	1	7	543036.252	4946503.446
6	1	8	543073.1986	4946499.08
6	1	9	543076.7215	4946510.123
6	1	10	543062.3986	4946546.444
6	1	11	543056.6149	4946544.488
6	1	12	543053.196	4946537.981
6	1	13	543051.6803	4946540.839

6	1	14	543053.5552	4946593.876
6	1	15	543050.7976	4946602.597
6	1	16	543047.4776	4946549.556
6	1	17	543053.3109	4946597.941
6	1	18	543050.9169	4946602.529
6	1	19	543073.4916	4946549.924
6	1	20	543077.011	4946551.561
6	2	0	543065.5667	4946480.5
6	2	1	543070.4794	4946505.158
6	2	2	543063.4558	4946526.833
6	2	3	543057.8996	4946518.42
6	2	4	543047.8	4946534.135
6	2	5	543046.9029	4946515.787
6	2	6	543036.8024	4946505.838
6	2	7	543036.254	4946503.452
6	2	8	543073.2023	4946499.074
6	2	9	543076.7175	4946510.124
6	2	10	543062.4359	4946546.426
6	2	11	543056.6551	4946544.484
6	2	12	543053.2292	4946537.959
6	2	13	543051.7445	4946540.742
6	2	14	543053.6117	4946593.802
6	2	15	543050.8163	4946602.549
6	2	16	543047.5197	4946549.579
6	2	17	543053.3159	4946597.974
6	2	18	543051.0443	4946602.493
6	2	19	543073.5083	4946549.893
6	2	20	543065.5667	4946480.5
6	3	0	543065.5667	4946480.5
6	3	1	543070.4836	4946505.184
6	3	2	543063.4821	4946526.653
6	3	3	543057.9045	4946518.432
6	3	4	543047.8056	4946534.195
6	3	5	543046.9202	4946515.803
6	3	6	543036.7815	4946505.727
6	3	7	543036.2219	4946503.293
6	3	8	543073.2467	4946499.133
6	3	9	543076.7232	4946510.154
6	3	10	543062.4353	4946546.442
6	3	11	543056.7822	4946544.537
6	3	12	543053.2261	4946538.016

6	3	13	543051.7696	4946540.764
6	3	14	543053.5502	4946593.863
6	3	15	543050.8064	4946602.546
6	3	16	543047.4653	4946549.617
6	3	17	543065.5667	4946480.5
6	3	18	543051.0542	4946602.527
6	3	19	543073.5224	4946549.905
6	3	20	543077.0257	4946551.511
6	4	0	543065.5667	4946480.5
6	4	1	543070.4809	4946505.176
6	4	2	543063.5035	4946526.433
6	4	3	543057.89	4946518.429
6	4	4	543047.8308	4946534.139
6	4	5	543046.9427	4946515.764
6	4	6	543036.8051	4946505.847
6	4	7	543036.2641	4946503.471
6	4	8	543073.1875	4946499.096
6	4	9	543076.706	4946510.15
6	4	10	543062.4646	4946546.44
6	4	11	543056.6688	4946544.514
6	4	12	543053.2354	4946538.026
6	4	13	543051.7356	4946540.788
6	4	14	543053.6264	4946593.913
6	4	15	543050.8523	4946602.681
6	4	16	543047.4799	4946549.62
6	4	17	543053.3559	4946598.083
6	4	18	543051.0825	4946602.563
6	4	19	543073.5895	4946549.865
6	4	20	543077.0236	4946551.52

Appendix C: Hydrologic Conductivity Measurements

Vernier Format 2			Location 1: 8/21/2016 17:18:2		
Sensor 1		Sensor 2		Sensor 3	
Time	Conductivity	Time	Conductivity	Time	Conductivity
T	C	T	C	T	C
s	μS/cm	s	μS/cm	s	μS/cm
0	193	0	197	0	143
1	193	1	196	1	133
2	194	2	198	2	181
3	193	3	197	3	162
4	193	4	196	4	162
5	193	5	197	5	181
6	192	6	197	6	162
7	193	7	196	7	162
8	194	8	197	8	162
9	192	9	198	9	172
10	193	10	197	10	191
11	192	11	198	11	162
12	193	12	197	12	162
13	192	13	197	13	172
14	194	14	197	14	152
15	192	15	196	15	152
16	193	16	197	16	172
17	190	17	196	17	162
18	193	18	197	18	162
19	193	19	197	19	172
20	193	20	197	20	172
21	192	21	197	21	162
22	194	22	196	22	172
23	193	23	197	23	181
24	193	24	198	24	162
25	193	25	198	25	172
26	188	26	198	26	181
27	192	27	196	27	181
28	193	28	198	28	162
29	193	29	197	29	172
30	194	30	197	30	133
31	194	31	196	31	133
32	194	32	197	32	143

33	194	33	198	33	152
34	192	34	196	34	152
35	193	35	197	35	162
36	194	36	196	36	172
37	192	37	197	37	181
38	194	38	197	38	172
39	192	39	197	39	172
40	193	40	197	40	172
41	193	41	198	41	152
42	193	42	196	42	172
43	194	43	198	43	143
44	193	44	198	44	162
45	194	45	197	45	152
46	193	46	196	46	162
47	192	47	197	47	162
48	193	48	197	48	172
49	193	49	199	49	143
50	194	50	197	50	162
51	194	51	197	51	133
52	191	52	198	52	152
53	193	53	198	53	162
54	194	54	198	54	143
55	192	55	199	55	181
56	194	56	198	56	143
57	193	57	205	57	133
58	192	58	201	58	143
59	194	59	206	59	162
60	192	60	208	60	152
61	168	61	209	61	172
62	192	62	209	62	152
63	193	63	214	63	133
64	193	64	218	64	181
65	194	65	222	65	162
66	193	66	222	66	143
67	193	67	230	67	162
68	194	68	243	68	162
69	193	69	248	69	152
70	192	70	241	70	133
71	192	71	245	71	152
72	192	72	255	72	162
73	193	73	256	73	133

74	193	74	260	74	162
75	193	75	273	75	162
76	190	76	272	76	162
77	193	77	272	77	162
78	192	78	275	78	143
79	194	79	282	79	152
80	192	80	281	80	133
81	193	81	277	81	162
82	193	82	281	82	133
83	193	83	277	83	162
84	193	84	277	84	133
85	194	85	277	85	162
86	193	86	277	86	172
87	193	87	275	87	162
88	194	88	274	88	143
89	194	89	273	89	152
90	193	90	269	90	143
91	194	91	270	91	133
92	194	92	269	92	162
93	194	93	268	93	172
94	194	94	262	94	133
95	194	95	258	95	162
96	194	96	261	96	162
97	194	97	254	97	162
98	194	98	254	98	133
99	194	99	251	99	133
100	196	100	250	100	162
101	195	101	247	101	133
102	199	102	248	102	172
103	199	103	246	103	133
104	203	104	241	104	143
105	206	105	239	105	162
106	208	106	237	106	152
107	216	107	235	107	143
108	215	108	234	108	133
109	224	109	233	109	162
110	227	110	228	110	162
111	236	111	229	111	152
112	237	112	228	112	152
113	261	113	227	113	172
114	253	114	223	114	143

115	254	115	223	115	133
116	262	116	222	116	133
117	267	117	218	117	133
118	266	118	220	118	162
119	262	119	218	119	133
120	278	120	215	120	172
121	274	121	214	121	143
122	278	122	215	122	162
123	277	123	213	123	133
		124	212	124	133
		125	212	125	162
		126	210	126	133
		127	210	127	133
		128	211	128	133
		129	209	129	152
		130	210	130	162
		131	209	131	133
		132	208	132	143
		133	207	133	152
		134	206	134	133
		135	207	135	162
		136	206	136	133
		137	206	137	133
		138	205	138	133
		139	203	139	162
		140	204	140	143
		141	203	141	162
		142	204	142	162
		143	204	143	162
		144	203	144	162
		145	201	145	152
		146	203	146	133
		147	200	147	152
		148	203	148	152
		149	201	149	133
		150	201	150	162
		151	201	151	133
		152	200	152	162
		153	201	153	133
		154	200	154	143
		155	199	155	133

	156	201	156	162
	157	200	157	133
	158	200	158	162
	159	199	159	143
	160	198	160	143
	161	198	161	191
	162	200	162	152
	163	199	163	133
	164	200	164	143
	165	200	165	172
	166	198	166	162
	167	199	167	191
	168	198	168	162
	169	198	169	143
	170	199	170	133
	171	197	171	133
	172	198	172	133
	173	198	173	162
	174	197	174	162
	175	198	175	143
	176	197	176	133
	177	198	177	162
	178	198	178	152
	179	199	179	152
	180	197	180	162
			304	162
			305	191
			306	201
			307	191
			308	143
			309	172
			310	181
			311	201
			312	172
			313	143
			314	191
			315	181
			316	191
			317	152
			318	162
			319	143

	320	143
	321	143
	322	201
	323	191
	324	133
	325	152
	326	191
	327	133
	328	133
	329	133
	330	133
	331	191
	332	133
	333	133
	334	133
	335	133
	336	133
	337	181
	338	162
	339	162
	340	162
	341	152
	342	162
	343	162
	344	162
	345	172
	346	162
	347	143
	348	162
	349	162
	350	152
	351	152
	352	133
	353	162
	354	143
	355	172
	356	162
	357	143
	358	172
	359	162
	360	181

	361	172
	362	162
	363	162
	364	162
	365	152
	366	162
	367	152
	368	143
	369	162
	370	143
	371	133
	372	143
	373	162
	374	172
	375	143
	376	143
	377	152
	378	162
	379	143
	380	143
	381	152
	382	162
	383	143
	384	152
	385	162
	386	143
	387	152
	388	172
	389	162
	390	162
	391	143
	392	172
	393	143
	394	152
	395	162
	396	143
	397	143
	398	152
	399	162
	400	162
	401	143

	402	143
	403	143
	404	133
	405	143
	406	143
	407	143
	408	143
	409	162
	410	152
	411	162
	412	152
	413	143
	414	152
	415	152
	416	143
	417	143
	418	143
	419	133
	420	133
	421	162
	422	133
	423	152
	424	172
	425	133
	426	133
	427	143
	428	152
	429	143
	430	133
	431	143
	432	152
	433	143
	434	152
	435	133
	436	143
	437	143
	438	162
	439	152
	440	143
	441	133
	442	143

	443	143
	444	143
	445	143
	446	162
	447	133
	448	133
	449	133
	450	133
	451	133
	452	133
	453	14912
	454	16000
	455	15456
	456	16360
	457	16224
	458	13113
	459	15981
	460	16215
	461	13901
	462	16516
	463	15622
	464	12626
	465	15437
	466	15796
	467	10614
	468	16856
	469	13541
	470	12705
	471	13307
	472	13366
	473	16059
	474	14659
	475	11859
	476	15330
	477	16516
	478	16681
	479	15145
	480	13852
	481	16156
	482	15505
	483	16263

		484	14688
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Vernier Format 2				location 2: 8/21/2016 17:18:34			
Sensor 1		Sensor 2		Sensor 3			
Time	Conductivity	Time	Conductivity	Time	Conductivity		
s	μS/cm	s	μS/cm	s	μS/cm		
0	42	0	214	0	230		
1	139	1	191	1	238		
2	93	2	212	2	235		
3	205	3	199	3	238		
4	139	4	211	4	236		
5	93	5	215	5	238		
6	142	6	217	6	237		
7	55	7	212	7	236		
8	204	8	219	8	240		
9	156	9	196	9	240		
10	189	10	212	10	230		
11	207	11	220	11	231		
12	73	12	205	12	235		
13	213	13	214	13	240		
14	191	14	185	14	241		
15	184	15	212	15	237		
16	213	16	199	16	236		
17	199	17	203	17	236		
18	196	18	205	18	240		
19	184	19	32	19	237		
20	183	20	220	20	241		
21	198	21	217	21	238		
22	175	22	220	22	240		
23	210	23	176	23	238		
24	196	24	115	24	235		
25	212	25	97	25	218		
26	107	26	212	26	237		
27	213	27	148	27	229		
28	214	28	218	28	240		
29	164	29	218	29	240		
30	170	30	222	30	240		
31	203	31	218	31	237		
32	204	32	213	32	240		
33	170	33	213	33	240		
34	186	34	218	34	237		

35	199	35	222	35	236
36	204	36	212	36	237
37	194	37	214	37	241
38	173	38	218	38	237
39	212	39	220	39	236
40	156	40	220	40	238
41	206	41	222	41	238
42	193	42	219	42	241
43	175	43	223	43	241
44	198	44	222	44	237
45	198	45	222	45	237
46	184	46	222	46	234
47	209	47	220	47	238
48	209	48	219	48	240
49	206	49	220	49	238
50	199	50	220	50	237
51	177	51	220	51	237
52	182	52	220	52	240
53	151	53	222	53	238
54	202	54	215	54	240
55	183	55	222	55	240
56	178	56	218	56	238
57	197	57	220	57	236
58	177	58	222	58	240
59	198	59	220	59	225
60	187	60	220	60	238
61	186	61	222	61	241
62	114	62	222	62	240
63	120	63	220	63	236
64	209	64	220	64	241
65	166	65	220	65	236
66	247	66	220	66	238
67	271	67	220	67	236
68	262	68	220	68	236
69	315	69	222	69	236
70	317	70	222	70	237
71	340	71	223	71	237
72	350	72	220	72	238
73	375	73	222	73	212
74	368	74	223	74	240
75	404	75	220	75	234

76	405	76	222	76	240
77	385	77	216	77	237
78	424	78	222	78	238
79	421	79	220	79	237
80	393	80	222	80	240
81	393	81	222	81	240
82	364	82	222	82	236
83	362	83	223	83	238
84	343	84	222	84	238
85	280	85	220	85	238
86	317	86	220	86	240
87	314	87	220	87	240
88	301	88	222	88	226
89	279	89	222	89	236
90	198	90	220	90	238
91	251	91	220	91	240
92	262	92	223	92	236
93	237	93	222	93	237
94	255	94	222	94	240
95	242	95	220	95	236
96	235	96	220	96	235
97	237	97	220	97	240
98	230	98	223	98	236
99	233	99	222	99	237
100	233	100	223	100	231
101	229	101	223	101	238
102	228	102	223	102	241
103	196	103	220	103	238
104	183	104	216	104	240
105	216	105	220	105	240
106	225	106	222	106	240
107	212	107	222	107	236
108	217	108	219	108	241
109	202	109	222	109	237
110	190	110	223	110	240
111	203	111	222	111	241
112	215	112	222	112	242
113	221	113	178	113	243
114	218	114	220	114	240
115	129	115	220	115	246
116	180	116	222	116	246

117	217	117	220	117	247
118	220	118	222	118	248
119	218	119	206	119	250
120	80	120	223	120	254
121	213	121	222	121	253
122	217	122	220	122	260
123	218	123	220	123	261
124	216	124	222	124	266
125	210	125	222	125	269
126	216	126	220	126	274
127	215	127	220	127	274
128	216	128	220	128	275
129	209	129	220	129	273
130	213	130	220	130	281
131	216	131	219	131	294
132	216	132	223	132	292
133	217	133	220	133	297
134	205	134	222	134	298
135	216	135	223	135	303
136	215	136	223	136	308
137	216	137	223	137	310
138	215	138	223	138	306
139	217	139	222	139	317
140	216	140	222	140	302
141	212	141	223	141	317
142	217	142	223	142	312
143	215	143	222	143	325
144	216	144	220	144	325
145	216	145	220	145	327
146	216	146	220	146	325
147	215	147	223	147	325
148	216	148	222	148	308
149	215	149	222	149	325
150	216	150	222	150	323
151	216	151	222	151	300
152	215	152	218	152	322
153	216	153	222	153	324
154	216	154	222	154	322
155	212	155	220	155	317
156	216	156	223	156	317
157	215	157	223	157	315

158	215	158	220	158	293
159	215	159	220	159	304
160	215	160	205	160	303
161	215	161	223	161	309
162	216	162	223	162	299
163	215	163	222	163	303
164	216	164	220	164	302
165	215	165	222	165	305
166	18	166	220	166	298
167	18	167	220	167	299
168	18	168	220	168	298
169	18	169	223	169	293
170	215	170	223	170	290
171	215	171	223	171	287
172	214	172	224	172	287
173	214	173	226	173	285
174	215	174	224	174	287
175	214	175	229	175	284
176	214	176	232	176	284
177	215	177	229	177	281
178	215	178	234	178	279
179	215	179	244	179	281
180	214	180	252	180	275
181	214	181	261	181	274
182	215	182	263	182	273
183	215	183	267	183	257
184	215	184	273	184	268
185	215	185	274	185	271
186	214	186	299	186	266
187	215	187	300	187	267
188	215	188	308	188	265
189	216	189	315	189	267
190	215	190	322	190	266
191	215	191	325	191	263
192	215	192	329	192	262
193	215	193	335	193	262
194	216	194	341	194	257
195	215	195	341	195	262
196	215	196	341	196	259
197	215	197	340	197	254
198	216	198	340	198	256

199	214	199	341	199	250
200	214	200	340	200	255
201	214	201	323	201	249
202	214	202	333	202	254
203	215	203	327	203	254
204	214	204	327	204	250
205	213	205	324	205	249
206	214	206	320	206	250
207	215	207	315	207	249
208	215	208	313	208	253
209	215	209	308	209	248
210	215	210	306	210	246
211	214	211	300	211	247
212	215	212	222	212	247
213	214	213	291	213	248
214	215	214	286	214	246
215	216	215	283	215	246
216	214	216	281	216	230
217	216	217	276	217	246
218	215	218	275	218	238
219	215	219	269	219	244
220	216	220	266	220	244
221	214	221	264	221	244
222	214	222	264	222	241
223	215	223	261	223	246
224	214	224	256	224	246
225	215	225	255	225	247
226	215	226	249	226	241
227	215	227	249	227	243
228	215	228	248	228	244
229	215	229	247	229	246
230	215	230	244	230	243
231	215	231	244	231	243
232	215	232	233	232	241
233	214	233	243	233	243
234	215	234	241	234	243
235	215	235	238	235	246
236	216	236	238	236	242
237	215	237	236	237	242
238	215	238	235	238	241
239	214	239	231	239	242

240	216	240	234	240	241
241	215	241	233	241	237
242	216	242	230	242	237
243	214	243	230	243	243
244	214	244	230	244	243
		245	230	245	243
		246	230	246	243
		247	230	247	241
		248	229	248	242
		249	228	249	240
		250	227	250	241
		251	229	251	241
		252	228		
		253	227		
		254	226		
		255	226		
		256	226		
		257	224		
		258	226		
		259	216		
		260	226		
		261	222		
		262	225		
		263	223		
		264	225		
		265	225		
		266	226		
		267	223		
		268	224		
		269	224		
		270	223		
		271	223		
		272	223		
		273	222		
		274	223		
		275	223		
		276	223		
		277	222		
		278	223		
		279	223		
		280	223		

	281	222	
	282	223	
	283	223	
	284	222	
	285	222	
	286	223	
	287	222	
	288	219	
	289	223	
	290	223	
	291	222	
	292	223	
	293	222	
	294	223	
	295	223	
	296	223	
	297	223	
	298	222	
	299	222	
	300	219	
	301	198	
	302	223	
	303	222	
	304	222	
	305	222	
	306	222	
	307	222	
	308	222	
	309	223	
	310	220	
	311	223	
	312	222	
	313	222	
	314	222	
	315	222	
	316	222	
	317	222	
	318	222	
	319	222	
	320	223	
	321	222	

	322	222	
	323	223	
	324	218	
	325	223	
	326	222	
	327	222	

Vernier Format 2				location 3: 8/21/2016 17:19:21			
Sensor 1		Sensor 2		Sensor 3			
Time	Conductivity	Time	Conductivity	Time	Conductivity		
s	μS/cm	s	μS/cm	s	μS/cm		
0	201.4	0	226	0	242		
1	201.3	1	224	1	242		
2	201.4	2	224	2	243		
3	201.5	3	224	3	241		
4	201.3	4	223	4	241		
5	201.5	5	223	5	242		
6	201.5	6	224	6	242		
7	201.5	7	223	7	243		
8	201.4	8	223	8	241		
9	201.6	9	224	9	242		
10	201.5	10	223	10	242		
11	201.5	11	224	11	241		
12	201.6	12	223	12	242		
13	201.5	13	224	13	242		
14	201.5	14	224	14	241		
15	201.5	15	224	15	241		
16	201.5	16	225	16	241		
17	201.5	17	223	17	241		
18	201.4	18	223	18	243		
19	201.6	19	223	19	241		
20	201.5	20	224	20	241		
21	201.5	21	224	21	243		
22	201.4	22	224	22	242		
23	201.6	23	224	23	242		
24	201.5	24	223	24	241		
25	201.3	25	223	25	241		
26	201.5	26	225	26	242		
27	201.4	27	223	27	241		
28	201.5	28	224	28	241		
29	201.5	29	223	29	241		

30	201.4	30	224	30	241
31	201.4	31	224	31	241
32	201.4	32	223	32	243
33	201.4	33	224	33	243
34	201.5	34	223	34	241
35	201.4	35	224	35	241
36	201.6	36	224	36	241
37	201.3	37	224	37	241
38	201.3	38	224	38	243
39	201.3	39	224	39	241
40	201.5	40	224	40	242
41	201.4	41	223	41	241
42	201.4	42	223	42	241
43	201.4	43	224	43	241
44	201.3	44	224	44	243
45	201.3	45	224	45	243
46	201.5	46	224	46	241
47	201.4	47	225	47	241
48	201.4	48	223	48	246
49	201.3	49	225	49	241
50	201.4	50	223	50	241
51	201.3	51	223	51	243
52	201.3	52	224	52	243
53	201.3	53	224	53	242
54	201.5	54	223	54	242
55	201.4	55	224	55	241
56	201.3	56	223	56	241
57	201.5	57	223	57	241
58	201.3	58	224	58	242
59	201.5	59	224	59	241
60	201.5	60	225	60	241
61	201.5	61	223	61	241
62	201.4	62	223	62	242
63	201.4	63	224	63	246
64	201.3	64	223	64	241
65	201.5	65	224	65	243
66	201.6	66	223	66	243
67	201.4	67	224	67	241
68	201.6	68	225	68	241
69	201.4	69	223	69	241
70	201.5	70	224	70	241

71	201.6	71	223	71	242
72	201.5	72	224	72	241
73	201.6	73	224	73	243
74	201.6	74	223	74	241
75	201.7	75	224	75	241
76	201.4	76	224	76	242
77	201.4	77	225	77	241
78	201.6	78	225	78	243
79	201.8	79	224	79	243
80	201.9	80	224	80	243
81	203.6	81	224	81	241
82	208.6	82	224	82	242
83	219.5	83	224	83	243
84	235.2	84	223	84	243
85	252.3	85	224	85	242
86	258.4	86	224	86	241
87	263.2	87	224	87	241
88	266.5	88	224	88	241
89	272.2	89	224	89	243
90	276.1	90	224	90	243
91	278.1	91	225	91	241
92	279.5	92	224	92	241
93	281	93	225	93	244
94	281.7	94	224	94	243
95	281.9	95	224	95	246
96	282.8	96	224	96	241
97	281.7	97	223	97	241
98	281.8	98	224	98	242
99	277.7	99	225	99	244
100	277.7	100	223	100	241
101	273.3	101	225	101	243
102	266.6	102	224	102	241
103	266	103	224	103	241
104	264.4	104	224	104	241
105	260.5	105	223	105	243
106	256.5	106	224	106	248
107	251.7	107	223	107	241
108	246.4	108	224	108	243
109	241.9	109	223	109	241
110	240.3	110	225	110	242
111	237.3	111	224	111	241

112	230.3	112	224	112	242
113	232.5	113	224	113	242
114	224.7	114	223	114	243
115	223.3	115	225	115	241
116	218.2	116	223	116	243
117	216.4	117	224	117	243
118	214.2	118	224	118	244
119	212.2	119	224	119	242
120	212.3	120	223	120	243
121	209.5	121	224	121	243
122	208.1	122	225	122	243
123	209	123	225	123	241
124	206.4	124	224	124	242
125	206.3	125	224	125	242
126	205.9	126	224	126	242
127	205.2	127	224	127	241
128	205.1	128	224	128	243
129	205	129	226	129	243
130	204	130	225	130	242
131	204.5	131	224	131	244
132	203.9	132	224	132	241
133	203.8	133	224	133	242
134	203.2	134	224	134	244
135	203.3	135	223	135	242
136	203.4	136	224	136	243
137	203.1	137	224	137	241
138	203	138	226	138	243
139	203	139	225	139	244
140	202.8	140	224	140	242
141	202.6	141	224	141	243
142	202.6	142	223	142	243
143	202.2	143	224	143	243
144	202.5	144	223	144	243
145	202.5	145	224	145	243
146	202.5	146	224	146	244
147	202.3	147	224	147	242
148	202.2	148	224	148	243
149	202.3	149	223	149	242
150	202.2	150	224	150	243
151	202.2	151	224	151	241
152	202.2	152	224	152	242

153	202.2	153	224	153	243
154	202.1	154	223	154	241
155	202.2	155	224	155	242
156	202.2	156	223	156	241
157	202.1	157	224	157	242
158	202.1	158	225	158	242
159	202	159	229	159	243
160	202.1	160	234	160	243
161	202.1	161	238	161	242
162	202.1	162	250	162	243
163	202.1	163	261	163	241
164	202.1	164	271	164	241
165	202.2	165	290	165	242
166	202.1	166	303	166	241
167	201.9	167	323	167	243
168	201.9	168	341	168	241
169	202.1	169	362	169	244
170	202.1	170	373	170	242
171	201.9	171	395	171	241
172	201.9	172	402	172	243
173	202	173	414	173	242
174	202.1	174	418	174	243
175	202.1	175	423	175	244
176	202.1	176	425	176	243
177	202.1	177	423	177	243
178	202.1	178	417	178	242
179	202	179	408	179	241
180	202.2	180	398	180	243
181	201.9	181	390	181	242
182	201.9	182	381	182	242
183	202.1	183	368	183	243
184	202.2	184	353	184	244
185	201.9	185	349	185	242
186	202.3	186	334	186	241
187	201.8	187	322	187	243
188	201.9	188	313	188	242
189	202.1	189	305	189	241
190	202.1	190	296	190	243
191	202.1	191	285	191	243
192	202	192	281	192	243
193	202.1	193	274	193	244

194	201.9	194	270	194	243
195	202	195	265	195	243
196	202	196	260	196	243
197	201.9	197	255	197	241
198	202.1	198	253	198	242
199	202.2	199	249	199	244
200	202.1	200	248	200	241
201	202.2	201	246	201	242
202	202.1	202	241	202	243
203	202.2	203	242	203	243
204	201.8	204	239	204	243
205	202.2	205	237	205	241
206	202.1	206	235	206	246
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5	241	5	424

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