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# **I-82, MP 36 to 44 Rattlesnake Hills Landslide Evaluation**

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Prepared for:  
Mr. Todd Trepanier, PE  
Regional Administrator, South Central Region  
Washington State Department of Transportation

Mr. James R. Struthers, LEG  
Chief Engineering Geologist, Geotechnical Office  
Washington State Department of Transportation

Mr. Dave Norman, LG, LEG, LHG  
State Geologist, Department of Natural Resources  
Washington Geologic Survey

Prepared by:  
Norman I. Norrish, PE  
Principal  
Wyllie & Norrish Rock Engineers Inc.

# TABLE OF CONTENTS

	<u>Page</u>
QUALIFICATIONS STATEMENT .....	1
EXECUTIVE SUMMARY .....	2
1 INTRODUCTION.....	5
2 TECHNICAL PARTICIPANTS.....	5
3 SCOPE-OF-WORK .....	5
4 EVALUATION APPROACH .....	6
5 ASSUMPTIONS AND CONSTRAINTS.....	7
6 LANDSLIDE MORPHOLOGY .....	7
6.1 Geologic Setting .....	7
6.2 Landslide Movement Mechanism.....	8
6.3 Landslide Geometry .....	9
6.4 Movement Characterization .....	9
6.4.1 Automated Motorized Total Stations (AMTS) - Prism.....	9
6.4.2 GPS Hubs .....	11
6.4.3 LiDAR .....	11
6.4.4 Radar.....	11
6.4.5 Hillshade Imaging.....	11
6.4.6 Seismic.....	12
6.4.7 Implications of Inferred Toe Buttresses.....	12
6.4.8 Summary .....	12
7 POTENTIAL FAILURE MODES .....	13
7.1 Terminology .....	13
7.2 Rate of Failure.....	13
7.2.1 Decision Analysis Approach.....	13
7.2.2 Engineering Approach.....	14
7.2.3 Conclusions with Respect to Rate of Failure.....	15
7.3 Large-Scale Westward Failure .....	16
7.4 Scarp-Proximal Failures .....	16
7.5 Toe-Proximal Failures .....	17
7.6 Potential for Slide Expansion .....	17
7.7 Slide Activation / Reactivation.....	17
8 RUNOUT SCENARIOS.....	18
8.1 Empirical Estimate.....	18

8.2	Risk to Proximal Infrastructure .....	19
9	MONITORING .....	20
9.1	Monitoring Requirements .....	20
9.2	Methods Employed.....	20
9.3	Areal Coverage .....	20
9.4	Data Integrity .....	21
9.5	Monitoring Recommendations.....	21
10	GEOTECHNICAL RECOMMENDATIONS .....	22
10.1	Three-Dimensional Slope Model .....	22
10.2	Geotechnical Properties .....	23
10.3	Groundwater .....	23
11	REFERENCES CITED .....	23

## **FIGURES**

Figure 1 – Geologic Plan

Figure 2 – Site Plan

Figure 3 – Profile along Azimuth 195

Figure 4 – Profile along Azimuth 205

Figure 5 – Comparison of Prism 4 with Target RS4

Figure 6 – Comparison of Prism 4 with Target RS4

Figure 7 – Comparison of West Prisms vs GPS Hub Velocity

Figure 8 – Long Duration LiDAR Change Analysis

Figure 9 – Short Duration LiDAR Change Analysis

Figure 10 – Radar Analysis

Figure 11 – Slide Mechanics

Figure 12 – Section N2 - N2' Location

Figure 13 – Stability Analyses of West-Facing Slope

Figure 14 – Runout Analysis for Idealized Slope

Figure 15 – Empirical Runout Analyses

Figure 16 – Risk to Infrastructure

## **APPENDICES**

Appendix A – Decision tree Analysis of Post-Failure Velocity

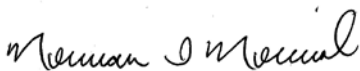
## QUALIFICATIONS STATEMENT

Norman I. Norrish, P.E., is an independent consulting engineer practicing as an employee of Wyllie & Norrish Rock Engineers Inc. He has been a registered professional in Washington State since 2001 and in other jurisdictions since 1974. His 44-year technical career has included four years employment as a mining engineer at an open pit operation and the balance as a consultant with experience throughout North America and Internationally. His relevant technical expertise relates to geotechnical site characterization, analysis, design, construction and monitoring of slopes for civil infrastructure projects and mining projects. Selected landslide projects from his career resume that are similar in nature and scope to the Rattlesnake Ridge Landslide include:

- **Valdez Creek Mine, AK:** Successful monitoring of an unstable 300-foot highwall slope to enable gold recovery after suspension of mining by regulatory agency.
- **SR 20, Newhalem, WA:** Slope monitoring after a 1 million cy rock avalanche to determine state of mountainside stability, timing of road reopening, and design of long term rockfall mitigation catchment.
- **Semirara Coal Mine, Philippines:** Slope monitoring to facilitate ongoing coal mining beneath a failing footwall (dip slope), along with eventual stabilization through dissipation of groundwater pressures.
- **Steep Rock Iron Mine, Ontario:** Slope monitoring using total station and prisms to ensure safety of mining operations.
- **Coal Mountain Mine, BC:** Independent review of monitoring data derived from AMTS / prism, ground-based radar, and GPS sources to predict footwall stability and runout estimates in the event of slope failure.
- **Twin Buttes Mine, Arizona:** Slope monitoring using prism measurement techniques to ensure safety of mining operations.
- **I-90 Hyak to Kechelus Dam, WA:** Responsible professional for the investigation, design and construction monitoring of approximately two-miles of steep cut slopes in volcanic bedrock to facilitate the widening of freeway. Slope monitoring included automated total stations / prisms and subsurface load measurement, both with real-time reporting to a project web site, as well as ground-surface change analyses derived from terrestrial LiDAR.

The forgoing statement is provided as evidence of my credentials to perform the independent evaluation of the Rattlesnake Ridge Landslide transmitted herewith.

Respectfully submitted,



Norman I. Norrish, P.E.  
Wyllie & Norrish Rock Engineers Inc.

## **EXECUTIVE SUMMARY**

The Rattlesnake Ridge Landslide<sup>1</sup>, located at Union Gap south of Yakima, WA, is a large, translational slide controlled by movement along a weak, inclined, sedimentary interbed within a basalt flow sequence. The slide was first observed in early October 2017, and subsequent monitoring measurements from multiple direct and remote sensing methodologies, report ongoing movement in a south to south-westerly direction, toward I-82. The inclination of movement is shallow (less than 15°), approximately parallel to the ground surface, and is inferred to be coincident with the inclination of the controlling interbed. The failure mass is estimated at 4 million cubic yards with a measured total displacement of approximately 12 feet to date.

During November and December 2017, the landslide movement exhibited acceleration typical of slide masses that are becoming less stable with time and trending to “failure”, commonly interpreted as rapid evacuation from the hillside. As a precaution, and lacking alternative predictive tools, the acceleration behavior of the slide mass was used to estimate a range of calendar dates for failure. Subsequent to these predictions, the slide has virtually stopped accelerating and is now exhibiting a constant velocity of approximately 2½ to 3 inches per day. Constant velocity cannot be extrapolated to a failure date.

The Rattlesnake Landslide has the positive benefit of its location in plain view, without the complications of vegetative or forest cover, steep-terrain, or heavy precipitation. These attributes, combined with the multi-agency participation of cooperating technical experts, makes this one of the best-documented landslides of which the author is aware. However, even with this comprehensive investigative effort, there are no absolutes when it comes to the prediction of future landslide behavior. Accordingly, the opinions that follow are qualified as appropriate.

### ***Opinion with respect to rapid failure:***

1. It cannot be stated, unequivocally, that the landslide will not fail as a rapid translation. However, the likelihood of rapid translation is considered very improbable (less than 5 percent).
2. It can be stated categorically that the landslide will demonstrate an increasing rate of movement (termed “antecedent acceleration signature”), prior to rapid failure.
3. It can be stated categorically that the acceleration signature will be measurable with currently deployed instrumentation systems, subject to minor refinements.
4. Assuming continued diligence, it can be stated categorically that the acceleration signature will provide adequate time for evacuation and detours of highway lifelines prior to rapid failure.
5. In order for slide debris to reach the Yakima River, two very improbable events must occur; a rapid translational failure of the hillside AND fluidization of the debris, through air or

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<sup>1</sup> The Rattlesnake Hills Landslide has colloquially become known as the Rattlesnake Ridge Landslide. The latter terminology is used herein.

water entrainment, to increase mobility. This combination of events is considered highly remote.

***Opinion with respect to most probable slide behavior:***

1. The geometric relationship between the failure mass and the topography causes the slide to be free to move in two directions; southerly toward the quarry and southwesterly toward I-82. The 12-feet of movement to date means that the slide is detached at its head scarp and eastern lateral scarp, and that available buttressing at the toe or on its flanks, is nominal and decreasing. The movement magnitude also means that the slip surface is at a state of residual (lowest) shear strength. These two conditions combine to limit the possibility of significant changes to the forces currently acting on the slide, with the result that movement rates should not change radically. Thus, the most probable scenario for future movement is for slowing to a rate commonly referred to as “creep” (probably in the range of a few inches per week).
2. The duration of creep movement could be years to decades. During such, material will be “bulldozed” to the unconstrained south and west margins of the slide, and then be liberated to move down the proximal slopes as either discrete rockfalls or small failure events (tens to a few thousands of cubic yards). This will result in talus development along the quarry wall and periodic rockfall and small slide impacts to Thorp Road. Rockfall barriers should be maintained to protect I-82 northbound.
3. Long-term stability is contingent on whether a self-arresting talus buttress can accumulate in the quarry bowl.
4. Earthquake loading could conceivably affect long-term stability, and an analysis of such should be performed at a future date when subsurface geotechnical data is available.

***Opinion with respect to large-scale westward slope failures:***

1. Stability analyses indicate that no credible failure mechanisms are present for a large-scale slope failure directly to the west. (10 to 25 percent of current slide volume).

In summary, the Rattlesnake Ridge landslide should be treated as a serious threat to public safety, but one that is both predictable and manageable. The conclusion herein, and the consensus opinion of geo-professionals who were informally canvassed, is that this slide, in common with water-deprived translational slides, will continue to displace for an indefinite period at a slow and deliberate rate. While the probability of rapid displacement is not zero, it is considered to be very improbable.

Recommendations to improve efficiency and effectiveness of the investigative efforts and to refine the interpretation of the landslide mechanics include:

- Implementation of fully-deployed, automated data reporting and warning systems, with a vetting protocol to minimize false alarms.

- Establishment of a graduated landslide status alert system (e.g. extreme, high, continuing) based on slide behavior and with level-specific actions with respect to monitoring frequency, visual observation intensity, and messaging to the public.
- Further integration and streamlining of the monitoring / remote sensing / site characterization / mitigation activities for the common interest and under the technical direction of a designated lead entity or group.
- Geotechnical investigations to sample and test slip surface materials and to confirm the groundwater regime, and 3D modelling and analysis of the slide.

## **1 INTRODUCTION**

A large landslide developed upslope of the Columbia Asphalt & Ready-Mix, Anderson Quarry, located south of the city of Yakima. Surface fissures associated with landslide movement were observable in early October 2017. Due to public safety concerns, the serviceability of Interstate I-82, and risks to proximal infrastructure, investigative and monitoring efforts were initiated. In mid to late December, accelerating landslide movement indicated the potential for rapid failure. The consequences of such a failure promised to affect many stakeholders, State agencies and property owners, and consequently several public and private entities initiated quasi-independent technical analyses and risk assessments, leading to dissenting opinions as to future slide behavior.

Wyllie & Norrish Rock Engineers Inc. (W&N) was retained by the State of Washington to perform an independent evaluation of the landslide for the primary purposes of assessing the adequacy of the technical works underway and to make recommendations for modifications as appropriate. It was not the intent of this evaluation to replicate geotechnical analyses being performed by members of the involved technical groups, but rather to review and comment on the adequacy of these efforts. As a by-product of this review, opinions were also to be provided on probable landslide behavior and the level-of-risk to adjacent facilities.

The works herein were authorized under a Professional Services Agreement Number Y-12143 administered by the Washington State Department of Transportation.

## **2 TECHNICAL PARTICIPANTS**

The author has relied on data and analyses developed or reported by others, referred to collectively hereafter as the “Technical Participants”:

- Washington State Department of Transportation (WSDOT)
- Washington State Department of Natural Resources (DNR)
- Yakama Nation
- Columbia Asphalt & Ready-Mix (Columbia)
- Cornforth Consultants, Inc. (Cornforth)
- Pacific Northwest Seismic Network (PNSN)
- Crustal Deformation Group, University of Washington (UW)

## **3 SCOPE-OF-WORK**

The following narrative is excerpted directly from the professional services agreement for the evaluation herein:



*The CONSULTANT will conduct a thorough review of available geologic mapping, geotechnical data, and landslide monitoring data pertinent to the subject landslide. This data includes, but is not limited to:*

*Published and unpublished, site-specific geologic mapping developed in response to this landslide activity,*

*Landslide monitoring data currently being collected by Cornforth Consultants Inc. (GPS data, UAV structure from motion, AMTS data*

*Landslide monitoring data currently being collected by the Washington State Department of Transportation (terrestrial lidar scans and traditional survey of targets on west slope),*

*Seismic data currently being collected by PNSN (Pacific Northwest Seismic Network).*

*Radar data collected by the University of Washington*

*The CONSULTANT will identify additional data that is needed in order to make a complete analysis.*

*The CONSULTANT will provide an opinion on the mode of failure of the subject landslide with an emphasis on assessing the risk of and timing of a catastrophic failure, direction and runout length of landslide debris, including associated risk to downslope residences, Thorp Road, I-82, and the Yakima River, as well as other significant features within the study area.*

*The CONSULTANT will provide an opinion if the potential slide activity is fully contained within the area currently being monitored, or if a larger area should be monitored.*

*The CONSULTANT will provide an opinion on the adequacy of current landslide monitoring and provide recommendations, if applicable, for additional landslide monitoring.*

*The CONSULTANT will provide an opinion as to whether or not this slide area may be part of a larger geological feature or process and if so the evidence for and details on that larger process or feature, to the extent possible.*

*The CONSULTANT will provide an opinion if this landslide may create, impact or be responsible for or trigger a larger scale geological event.*

*The CONSULTANT will conduct a reconnaissance of the site as part of their review.*

*The CONSULTANT will summarize the above in a letter report including an executive summary highlighting all relevant conclusions. A draft of this report will be available to the STATE within 10 days of execution of the Contract.*

*The CONSULTANT will be available to participate in 2 status briefings, by phone, as their work effort progresses and summarize these status briefings in a brief written document to the STATE.*

*The STATE will be responsible for providing all of the above-referenced data that is not otherwise publically available.*

*The STATE will be responsible for coordinating access to the site through the property owner and the Yakama Nation.*

## **4 EVALUATION APPROACH**

A review of available geologic mapping, geotechnical data, and landslide monitoring data pertinent to the subject landslide was reviewed. This data included:

- Published and unpublished, site-specific geologic mapping developed in response to this landslide activity,
- Landslide monitoring data currently being collected by Cornforth Consultants Inc. (GPS data, imaging from unmanned aerial vehicle (UAV) surveys and surveying data)
- Landslide monitoring data currently being collected by the Washington State Department of Transportation (terrestrial lidar scans and traditional survey of targets on west slope),
- Seismic data currently being collected by PNSN (Pacific Northwest Seismic Network) and DNR.
- Radar data collected by the University of Washington, Crustal Deformation Group.

Discussions were held with professional geologists familiar with the volcanic geology of eastern Washington, most notably, Dr. Steve Reidel of Washington State University.

A one-day site reconnaissance was performed on January 16, 2018, accompanied by personnel from the Yakama Nation, WSDOT, DNR, Cornforth Consultants and Columbia Asphalt & Ready-Mix.

## **5 ASSUMPTIONS AND CONSTRAINTS**

The assumptions and constraints of this review include the following:

- Evaluation of temporal information, such as landslide monitoring data, represents a “snapshot” in time. Conclusions and opinions with respect to landslide character and behavior based on such short duration intervals may need to be revised as future information becomes available.
- Data supplied by the Technical Participants has generally been relied upon without verification, except in specific instances where independent verification was mandated by the Scope of Services.
- The short duration of the evaluation, the extensive database of information, and the lack of subsurface information, combined to require that assumptions be made. Consequently, the conclusions reached herein should be regarded as informed opinions supported by engineering judgement and selective analyses, rather than rigorous engineering design. Instances where assumptions were used are so highlighted.

## **6 LANDSLIDE MORPHOLOGY**

### **6.1 Geologic Setting**

As shown in Figure 1, the Rattlesnake Ridge landslide site is geologically-located within the Miocene age Saddle Mountains BASALT of the Columbia River Basalt GROUP (Reidel, et al., 2013). Specifically, the basal shear surface of the slide mass has recently been re-interpreted as coinciding with the Selah sedimentary interbed that separates two basalt flows, the overlying

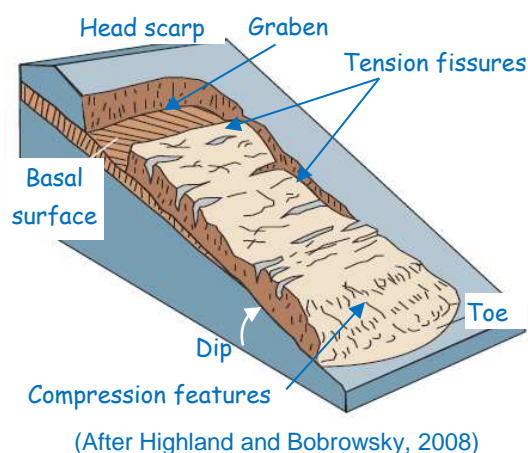
Pomona MEMBER from the underlying Umatilla MEMBER at this location (Reidel and Campbell, 2018). The Rattlesnake Hills are formed by an east-west trending asymmetrical anticline. (Myers, et al., 1979). The hills have steeper north-facing slopes, often with thrust faulting, and shallow dipping, south-facing, “dip-slopes” coincident with bedding. During folding, inter-flow strain was accommodated in the weaker and less brittle interbeds such as the Selah interbed.

The Selah interbed represents an inter-flow period of approximately one million years during which time sediments were deposited by fluvial processes on the topographic surface formed by the Umatilla basalt (Reidel, 2018). During this period, the ridges were subject to uplift with the consequence that interbeds, such as the Selah, thin with elevation, ranging from tens of feet thick at basin locations to zero thickness at ridge-tops. The Selah interbed is described as a tuffaceous sandstone with the parent sediments comprised of over-bank deposits consisting of clays, silts and sands with varying concentrations of ash (Reidel, 2018). Weathering and thermal alteration of the ash was favorable for the development of authigenic (secondary) clays such as illite (Aden and Johnston, 1982). Illite clays are usually considered alteration products of muscovite and are regarded as the mechanism where muscovite may be eventually altered to montmorillonite (mindat.org, 2011).

Regional geologic mapping of the Rattlesnake Hills north anticline reports the proximal volcanic flows to have inclinations from 12° to 20° toward the south (Figure 1 and Bentley, et al., 1993).

## 6.2 Landslide Movement Mechanism

The slide mass appears to be defined by a south-dipping basal surface (or zone) coincident with the Selah interbed between volcanic flows (Pomona and Umatilla MEMBERS) and is thus classified as a **translational landslide**. Such slides are characterized by movement along a relatively planar surface with little or no rotation. Ongoing movement of a detached translational slide block generally does not alter stability factors; hence these slides tend not to be self-arresting and can translate for considerable distance and for indefinite time. Zones of tension and compression are present in the head and toe regions, respectively, providing diagnostic surface expressions (margin graphic). Slumps (referred to as grabens) can develop along the lateral margins and head scarp as



the *in situ* materials fail into the void abandoned by the displacing landslide. The most important factors controlling the stability of translational landslides are the frictional shear strength along the basal surface, the dip (inclination below horizontal) of the basal surface and the presence/absence of groundwater pressures.

For the Rattlesnake Ridge landslide, the eastern limit is probably defined by a high-angle structural feature (or fracture zone) that has developed into the eastern lateral scarp. The north

(or upslope) limit of the slide may be influenced by geologic structure sympathetic to the mapped graben / normal faults along the ridgeline (Figure 1), to thinning or disappearance of the interbed (Reidel, 2018) or to natural arching. The south and west sides of the slide mass are unconstrained because the interbed is exposed (i.e. “daylights”) in the quarry highwall and on the west-facing topographic slope above I-82, respectively. Although not confirmed by subsurface measurement, pore water pressures along the basal sliding surface do not appear to be a factor in this slide. This conclusion is based on the lack of observed seepage from the quarry walls and from the natural slopes, the semi-arid location, and to the topographic shape of the ridge that is not conducive to infiltration. Although groundwater may not be sufficient to generate pore pressures at the elevation of the slip surface, downward infiltration within high angle fracture zones could eventually reach the basal surfaces decreasing the mechanical shear strength of clay minerals, if present.

Analogue translational landslides similar to, but much older than Rattlesnake Ridge, are reported in eastern Washington; examples include Horse Heaven Hills east of Prosser, Corfu slide on Saddle Mountain south of Othello, and Rattlesnake Mountain in the Hanford Reach National Monument (Reidel, 2018). In all cases the slides involve basalt sliding over underlying sediment and in all cases the slides did not, or have not, evacuated the slopes. The triggering event for these older Pleistocene slides is interpreted as loss of toe support during the Missoula Floods, 15,000 to 13,000 B.P. (Reidel, 2018).

### **6.3 Landslide Geometry**

The Rattlesnake Ridge landslide is shown in plan and profile views in Figures 2, 3 and 4. As noted, the length of the slide from head scarp to toe measures 1400 feet with an estimated depth of between 100 and 200 feet. This yields a depth to length ratio in the range 0.07 to 0.14, typical of translational slides that have a slab-like aspect. At mid-height, the width of the slide is approximately 750 feet. The volume of the slide has been estimated by the Technical Participants at 4,000,000 cy but this quantity is yet to be refined with the development of a 3-dimensional digital model.

### **6.4 Movement Characterization**

The Rattlesnake Landslide is being monitored with a wide array of conventional surveying and remote imaging techniques. Some of the methods provide quantitative measurement of displacement allowing movement rates (velocity and acceleration) to be calculated; while others provide the sense or mechanism of movement and/or surrogates for rate of movement. An important consideration to the accurate interpretation of slide behavior, is the consistency between the various monitoring methods being employed. A high degree of consistency increases confidence. The following sections address this issue.

#### **6.4.1 Automated Motorized Total Stations (AMTS) - Prism**

This methodology is a standard surveying technique, sometimes referred to as electronic distance measurement (EDM), in which an infrared signal is used to accurately measure distance to reflector prisms. The total station source can be motorized and programmed to scan a designated

group of prisms on a set polling frequency, hence the term robotic or AMTS. Output from the AMTS is sent by telemetry for reporting on a project web site. Currently, Columbia is utilizing an AMTS system while WSDOT is employing manual total station surveying of the RS target series.

Figures 3 and 4 represent profiles along two azimuth directions; azimuth 195° proximal to the axis of the slide mass, and azimuth 205° along the west-facing side slope above Thorp Road and I-82. These figures depict slide movement over a twelve-day period from 2018/01/05 to 2018/01/17. This period was selected only for the convenience of analysis and not because it represents a unique period in the history of the slide. The important characteristics:

**Profile 195°** (Figure 3):

- Azimuth direction of movement is southerly (195° to 202°) and is consistent over the selected slide length. (refer to red arrows upper plan image).
- The average rate of 3D movement ranges from 0.20 to 0.25 ft/day.
- The inclination of the movement ranges from -11° to -14° and is parallel to the ground surface (refer to red arrows lower profile view).

**Profile 205°** (Figure 4):

- Azimuth direction of movement for targets RS1, RS2, RS4, RS5, and RS6 ranges from 200° to 210° with an average of 207° and is consistent over the selected slide length. (refer to red arrows upper plan image). Note that targets RS3, RS7 and RS10 are not moving and are inferred to be located below the basal slip surface.
- Targets RS8 and RS9 report atypical southwesterly azimuth directions of 241° and 235°, respectively. This may indicate that the south west slide mass is being buttressed by the residual prism of bedrock on the southwest quarry wall (see Section 6.4.7 for further discussion).
- The average rate of 3D movement ranges from 0.15 to 0.23 ft/day.
- The inclination of the movement flattens in the downslope direction from -15° (RS1) to -7° (RS9) and is generally parallel to the ground surface except at the lower reach (refer to red arrows lower profile view).

Figures 5 and 6 compare the monitoring results from prism 4 with those of target RS4 over the identical time interval (01/05/2018 to 01/21/2018). These monitoring points are located approximately 190 feet apart in the upper half of the slide (Figure 2). The former is installed and managed by Columbia while the latter is surveyed by WSDOT. Horizontal velocities from both systems are about 0.19 feet per day (Figure 5) while elevation change is similar at -0.8 feet (Figure 6). The movement azimuths from the two methods differ by 14° which may be ascribed to locations relative to major fissure development. On balance, the correspondence of measurements between the two measurement programs is excellent. This lends credence to the data integrity and to the reliability of interpretations made therefrom.

### **6.4.2 GPS Hubs**

GPS refers to a geolocation service based on satellite tracking. This initial monitoring system was deployed by Columbia personnel and required traversing across the slide to each of some 60 GPS hubs. Due to safety concerns for access, this network is to be abandoned in the immediate future and replaced with 3 to 5 remote reading GPS hubs.

An example of monitoring data from a GPS hub is shown in Figure 7. Good consistency with AMTS / prism data is noted.

### **6.4.3 LiDAR**

LiDAR is a high resolution, laser scanning technique that can be deployed from either terrestrial or airborne platforms. Post-processing of successive LiDAR scans (“change analyses”) enables movement magnitude, areal extent and direction to be derived. LiDAR is being performed by WSDOT.

Figures 8 and 9 show change analyses derived from LiDAR scans between various dates. Figure 8 is a long duration change analysis that compares a 2015 aerial LiDAR scan to a January 15<sup>th</sup>, 2018 terrestrial scan. The limits of the slide are clearly visible, as are zones of depression (cool colors) and dilation (hot colors). Magnitudes of movement are generally consistent with direct measurement methods. Note that over a 3-year period, excavation activity in the quarry is also represented as ground loss. Figure 9 shows examples of short duration change analyses in which bona fide movements as small as 0.16 feet are detected. The benefit of LiDAR imaging is the presentation of areal movement patterns of varying velocity along with identification of slower moving or stationary areas acting as passive buttresses.

### **6.4.4 Radar**

Ground-based radar has been used by the UW to map displacement patterns and associated rates of ground movement. Figure 10 is an example of such an analysis for a 2¼ hour period on January 6, 2018. Zones on maximum velocity (hot colors) in the southeast landslide mass are consistent with LiDAR imaging. Slower moving lateral scarp slumping is evident along the west margin and upper east margin. The measured velocity rate for the main body of the slide is reported at 0.16 to 0.24 feet / day, in the exact range being reported by AMTS, target surveying and GPS methods.

### **6.4.5 Hillshade Imaging**

Hillshade imaging is a grayscale representation of the topographic surface. The images are obtained from high resolution drone (UAV) mapping. Creation of successive hillshades for Rattlesnake at time intervals of multiple weeks from common virtual viewpoints, enables the “slow-motion” movement of the slide to be viewed. These presentations are being developed by Columbia and Cornforth and are an excellent adjunct for the interpretation of slide behavior.

#### **6.4.6 Seismic**

In January 2018, PNSN deployed four temporary seismic stations and DNR deployed one seismograph, designated UG4, near the landslide. Data is transmitted by telemetry for post-processing into seismograms and spectrograms. Unfortunately, the site is “seismically-noisy” due to the plethora of cultural activity in the area (trucks, trains, helicopters etc.). Effort to date have concentrated on calibration of the seismic signatures to events that can be correlated to slide activity. To assist this effort, 38 short-period, seismic appliances have been deployed by PNSN and University of Oregon. Though non-telemetered, the appliances have collected over a week of data (deployed 2018-01-16, removed 2018-01-26) and are intended to refine PNSNs data interpretation of seismic signals from the landslide. Rockfalls have been positively identified based on documented occurrences in the quarry, and signatures inferred to be related to landslide “creaking” have been detected. If an algorithm to discriminate cultural from landslide events can be developed, seismic monitoring could demonstrate increasing rates of seismic activity as a surrogate for slide acceleration.

#### **6.4.7 Implications of Inferred Toe Buttresses**

From the LiDAR imaging (Figures 8 and 9), RS target monitoring and hillshade presentations, it is inferred that a degree of buttressing is being applied to the slide mass, particularly at the southwest corner, and to a lesser extent at the southeast corner. Only two monitoring points, RS8 and RS9, report movement vectors with a strong southwesterly component. Of note, the azimuth directions for these two targets mimic the orientation of the movement boundary between the buttress and the slide mass (Figures 8 and 9). This boundary is quite possibly a geologic structure. In the southeast quarry, a similar passive buttress may be present. Cornforth personnel report a distinct change in fissure development in this area in early December 2017. It is concluded that the landslide is experiencing some degree of toe buttressing as the slide arches around the north quarry wall, and that this effect is decreasing as the buttresses deform and disaggregate.

#### **6.4.8 Summary**

The multiple monitoring methods being employed at the Rattlesnake Ridge site are portraying a very consistent picture of landslide areal extent, bounding features, and movement rates, direction and inclination. Qualitative methods (hillshade, seismic) substantiate information from direct measurement techniques (AMTS, GPS). Areal imaging techniques (LiDAR, radar) are extremely consistent with point measurement methods (AMTS, GPS). This network of mutually confirmatory monitoring approaches is highly desirable for vetting potentially anomalous results from one method, or to temporarily fill-in for a system that is offline for technical or environmental reasons. The author has no reservations concerning the comprehensiveness and reliability of the monitoring network that is in place. Minor recommendations for deployment are made in Section 9.3.

## 7 POTENTIAL FAILURE MODES

### 7.1 Terminology

For the purposes of this landslide evaluation, the following terminology is used:

**Rapid Failure:** This mechanism refers to a slide that evacuates the hillside in a very short period of time (minutes to hours) and with high runout velocity (miles per day to miles per hour). The 2014 Oso Landslide is such an example. Runout from such slides is a primary public-safety issue.

**Creep Failure:** As the name implies, creep failures proceed at low displacement rates that can continue for years. Runout is not an issue with this mode of failure and the slides may or may not be self-arresting, depending on the geometric freedom to displace (i.e. lack of constraint, particularly in toe region).

With respect to qualitative probability terminology, the usage herein is in general accordance with the following table (after Glastonbury and Fell, 2008):

Expression	Probability Equivalent
Almost impossible	2
Very improbable	5
Very unlikely	10
Improbable	15
Low chance	20
Possible	40
Even chance	50
Probable	70
Very probable	80
High chance	80
Very likely	85
Very high chance	90

### 7.2 Rate of Failure

#### 7.2.1 Decision Analysis Approach

Glastonbury and Fell (2008) published a decision-analysis framework in which to determine probability classes for post-failure runout velocity of translational slides. The approach assigns relative weighting factors to the parameters that determine post-failure velocity; strength condition on slip surface, frictional strength compared to slip surface inclination, presence of lateral or toe buttresses and potential for rapid external loading. The more reliable the decision factors, the narrower will be the range of predicted velocities. Appendix A contains their decision analysis



approach applied to the Rattlesnake Ridge Slide. The results of the analysis are summarized in the table below (modified after Table 1 from Glastonbury and Fell (2008)).

Velocity Limits	Velocity Description	Rattlesnake Slide Probability	General Consequence Category
>11.2 mph	Extremely rapid	0%	Life threatening
2.7 mi/day to 11.2 mph	Very rapid		Life threatening in certain circumstances
142 ft/day to 2.7 mi/day	Rapid	5%	Destruction of structures, possible landslide damming <sup>see Note 4</sup>
1.4 ft/day to 142 ft/day	Moderate	10%	Damage to structures, possible landslide damming <sup>see Note 4</sup>
0.14 ft/day to 1.4 ft/day	Slow	85%	Limited threat to structures and low energy rivers
0.63 in/yr to 0.14 ft/day	Very Slow		Limited damage to structures
< 0.63 in/yr	Extremely Slow		No damage to suitably built structures

The salient observations are:

1. There is an 85% probability that this translational slide will move at velocities less than 1.4 feet/day. The current movement rate is 0.15 to 0.25 feet/day (1.05 to 1.75 feet/week).
2. Referring to Appendix A, Table 6, the primary uncertainty is the degree of buttressing the slide will encounter. This uncertainty provides a focus for ongoing displacement monitoring. As the slide displaces, the degree of buttressing will be more apparent.
3. The decision-analysis approach predicts a 0% probability of “life threatening” post-failure velocities.
4. The reference to “damage to structures” and “possible landslide damming” is interpreted to refer to the presence of such features at the immediate toe of the slide and in the direction of slide movement. This is not the case for the Rattlesnake Slide wherein the nearest private structure (other than quarry infrastructure) is some 1000 feet distant, and the Yakima River some 1200 to 1500 feet distant, in the azimuth direction 195° that the slide is moving along.

### 7.2.2 Engineering Approach

The slide mass is subject to two categories of forces, those tending to drive failure and those tending to resist failure (Figure 11). For the Rattlesnake Ridge slide, the driving force consists solely of the weight component that acts in the direction of slip surface inclination.

(Note: The term “component of weight” is used to indicate that the vector representing the vertical weight is resolved into components parallel and perpendicular to the slip surface. The flatter the slip surface, the less the weight component available as a driving force).

The shear resistance is the force available as the shear strength along the interbed. The first important aspect of shear strength is that it is dependent on the size and mineralogy of particles

along the slip surface. In general, the shear strength progression is: clay < silt < sand < gravel < bedrock. A second important aspect is that for almost all natural materials the available shear strength is dependent on the magnitude of prior shear displacement, thereby exhibiting peak strength at small displacement decreasing to residual strength at extended displacement (Figure 11 upper graphic). This progressive loss of shear strength is referred to as “strain-softening”. The 12-feet of displacement for Rattlesnake, and the probable ancestral tectonic deformation during folding, mean that the current shear strength along the slip surface is at its residual or lowest value.

The ratio of the weight component ( $F_w$ ) to the shear resistance ( $F_s$ ), determines the behavior of the slide mass (see table on Figure 11). When  $F_w$  exceeds  $F_s$  there is a net unbalanced force acting on the slide mass and it exhibits acceleration. Recent displacement monitoring indicates that the slide has transitioned from an acceleration phase to one of constant velocity, suggesting that the resisting and driving forces are approaching parity.

Future changes in movement rate require change to the net unbalanced force acting on the slide mass. This could develop through either increased driving force (e.g. lateral scarp failure, seismic loading) or through decreased resisting force (passive toe block failure, rock mass disaggregation). In order to trigger a rapid translation (i.e. potentially catastrophic), a very rapid increase in the unbalanced force would likewise be required. With the possible exception of seismic loading, all reasonably foreseeable processes that could materially increase driving forces on this 4 million cubic yard slide will be gradual. Although yet to be confirmed, the impact of an earthquake on a landslide at yield is of limited concern, at least within the timeframe of a few years due to the improbability of a proximal high magnitude event. For the resisting force consideration, the slip surface is inferred to be at residual strength so there is not a mechanism for further strength loss. Future investigation and testing will confirm this inference. As the slide moves, resistance is provided by the process of slide dilation and rock mass disaggregation. This will be an ongoing but gradual process. Lateral buttressing is inferred to be limited due to the movement away from the head scarp and east lateral scarp, and to the exposure of the slip surface along most of the west and south margins. The southwest and southeast corners suggest that passive blocks are providing some buttressing. However, based on monitoring, these are interpreted to be in the process of yielding.

### **7.2.3 Conclusions with Respect to Rate of Failure**

Based on the decision analysis and engineering approaches, it is concluded that the potential for rapid failure, defined as greater than 142 feet/day, is very improbable (less than 5%). All the reasonably foreseeable, force-altering, processes will be gradual or of limited magnitude and will result in transient irregularities in the rate of movement. Even in the improbable event of a rapid failure, it will definitely have an antecedent acceleration signature that can be measured, thereby enabling mitigative / protective measures to be implemented in a timely fashion.

As shown in Section 7.2.1, it is estimated that there is an 85% probability that the Rattlesnake slide will continue to “creep” at rates nominally similar to current rates (0.15 to 0.25 feet/day). The duration of such movement cannot be predicted but could range from years to decades. Natural cessation of movement will depend on an increase in resisting force, most probably developed

from the slow accumulation of a talus buttress in the toe region and primarily within the quarry limits. At a conceptual level, engineered cessation of movement would require a combination of material removal at the head of the slide and buttress placement at the toe, contingent on resolution of safety, aesthetic and land ownership issues.

Prediction of “failure” dates is highly uncertain and is predicated on uniform acceleration trends. This slide is demonstrating slowing acceleration thus making date predictions recede to the future. The emphasis should be that pending slide movement is highly predictable but is not quantifiable to a calendar date.

### **7.3 Large-Scale Westward Failure**

It has been posited that a large-scale failure toward the west could endanger Thorp Road, I-82 and the Yakima River. In theory, this failure mechanism would be facilitated by the fact that the basalt flow above the interbed will continue to disaggregate and weaken as the main slide mass moves southerly.

A two-dimensional, limit equilibrium, slope stability model was developed along a cross section corresponding to the maximum 35° inclination of the west-facing slope (Section N2-N2', Figure 12). The model incorporated a 6-foot thick interbed separating disturbed basalt (slide mass) above the bed from *in situ* basalt below (Figure 13). The interbed was conservatively assumed to have a component of dip out of the slope face equivalent to 3°. Presumptive material properties for the *in situ* and disturbed basalt were assigned in accordance with the Hoek-Brown Failure Criterion (Hoek, 2007, Hoek, 2012). The interbed was assumed to behave as a Mohr-Coulomb material with a friction angle of 10° and zero cohesion, for its entire thickness. This is a conservative assumption, contrary to site observations that suggest only the lower portion of the interbed is exhibiting low shear strength values in this range. All slopes were assumed to be fully drained.

Despite the conservatism incorporated into the stability model, the analyses indicate stability margins well in excess of minimums for slope engineering design practice. As noted, reported Factor of Safety values for the disturbed slide mass range from 1.8 (block failure along interbed) to 3.4 for circular failure. For context, typical design practice for a critical slope is to achieve an FoS value of 1.5 while normal WSDOT highway cuts target a minimum value of 1.25.

The viability of a transverse block failure across the interbed while the concurrent movement is strongly southward toward the quarry in the direction of maximum inclination, is highly questionable. This assertion, and the elevated FoS results, lead to the conclusion that large-scale westward failure is almost impossible, in absence of groundwater pressure and seismic loading.

### **7.4 Scarp-Proximal Failures**

Localized failures (tens to hundreds of cy) could develop along the trace of the slip surface as slope areas become over-steepened due to slide movement. Progressive small-scale, circular-type failures, toppling failures and discrete rockfalls are probable as the slide mass is “bull-dozed” with a westerly component. Slope deformation prior to localized failures will probably not be

detected by AMTS/prism monitoring or by GPS monitoring unless the installation is fortuitously located. However, incipient small-scale failures should be detectable by LiDAR imaging. The natural slope is inclined at  $\sim 35^\circ$  and failures should be significantly self-arresting. Rockfall boulders will have the greatest potential to reach Thorp Road but should be constrained by the Conex barrier installations.

## **7.5 Toe-Proximal Failures**

The toe area of the slide, in the direction of movement, will have the greatest potential for collateral slope failures. These could potentially range in size from rockfalls to perhaps thousands of cubic yards and will be contained by the quarry bowl. Left to accumulate, these failures should coalesce into a talus apron against the quarry walls. Prediction of toe-proximal failures should be evident from LiDAR scans and high-resolution drone imaging.

## **7.6 Potential for Slide Expansion**

Potential directions for areal expansion of the Rattlesnake Slide are primarily to the east and to the north (upslope). Expansion to the east is considered almost impossible given that the natural slope has not been altered and that the current lateral scarp is probably structurally-controlled. Expansion to the north is improbable because the slide geometry has evolved to a small radius of curvature at the head scarp thereby facilitating arching of downslope stresses, if there is a tendency to move.

A limited interval of the upper western portion of the slide scarp does not follow the extrapolated interbed trace (see Figure 8 upper). The slide mass is relatively narrow at this location and the lateral scarp failures on the adjacent eastern side could exert a transverse loading that is transmitted to the west and ultimately against the intact prism of rock on the west-facing slope. Limited monitoring data shows some displacement in this direction. Stability analyses and volumetric analyses should be performed to assess the stability and potential size of a transverse slide in this area.

Potential expansion of the slide with depth is also considered very improbable because it would require the presence of an as yet undetected weak interbed below the current slip surface.

## **7.7 Slide Activation / Reactivation**

With regard to the question of whether the Rattlesnake Ridge Landslide may either trigger a larger scale event or represent reactivation of a prior large-scale event, the following opinions are offered:

1. Review of DNR air photographs KY-72-486 41A-1, dated 5-25-72, did not indicate scarps or landforms indicative of a pre-existing mass wasting event.
2. Visual examination during the site reconnaissance of material within the interbed, but above the slip surface, revealed polished / slickensided rock fragments. While not definitive, this may indicate tectonic shearing within the interbed, and thus the landslide may represent the activation of a previously weakened surface.

3. There is no evidence on which to opine as to whether the “landslide may create, impact, or be responsible for or trigger a larger scale geologic event”. The potential for landslide expansion has been addressed in Section 7.6.

## 8 RUNOUT SCENARIOS

### 8.1 Empirical Estimate

Prediction of runout from landslides or pit slope walls is inherently uncertain.

Methods for runout prediction can be divided into empirical (statistical) and dynamic. The former relies on the similarity of conditions at a subject project site to the database of sites on which the empirical relationships are based. Numerical (dynamic) methods consider momentum or energy conservation for the slide debris (Rickenmann, 2005). Empirical methods are deemed to be repeatable and are useful for sensitivity analyses in cases where geologic information is limited and/or uncertain. Numerical methods are appropriate to derive engineering parameters necessary for design, for example structure vulnerability or protection works (Whittall, et al., 2016). The drawback of numerical models is the requirement to assign material properties that are not directly, or easily measurable, such as rheological (viscosity dependence) behavior. Consequently, many investigators have relied on empirical relationships, including Whittall, et al., 2016, whose empirical study was based on a data base of 105 documented slope failures at open pit mines.

For the Rattlesnake Ridge landslide an empirical approach based on mine slopes rather than natural slopes was used because of the commonality of the quarry wall and floor (flat configuration and rock composition) to those in mines. In spite of this similarity, the author is reticent to report on an empirical runout analysis because of the difference in failure mechanism between typical pit slope failures (steep, high slopes in brittle rock) and the subject slide (relatively shallow, low slope experiencing ductile failure). **Consequently, the runout estimates herein are presented with a disclaimer as to accuracy.**

Runout distance is defined in terms of the reach angle,  $\alpha$ , also termed the “Fahrböschung angle” shown in the margin sketch. This angle (or the proxy ratio,  $H/L$ ) have been related to several slide source parameters including failure mass volume, pre-failure slope angle, and fall height,  $H$ . Of these parameters, the strongest correlation is between runout and slope angle. To accomplish the empirical analysis, an idealized and very conservative slope profile was created along the slide axis (Figure 14). It consists of a 450-foot high slope (defined by the nominal vertical height of the slide mass) and a 40° slope angle.

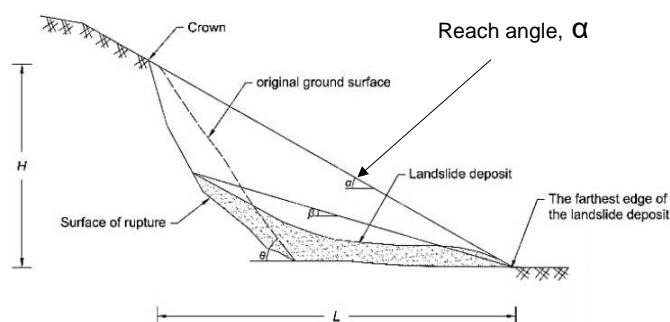


Figure 15 shows a compilation of three predictions for runout distance based on empirical relationships with: A. Slope angle, B. Failure mass volume, C. Fall height

For each relationship, the runouts corresponding to the most probable case (trend line or center of data scatter) and to the “worst” case, represented by the greatest runout at the conservative margin of the appropriate data set. The results are tabulated below:

		Maximum Runout from Toe of Slope (feet) <sup>1</sup>	
Figure	Empirical Relationship	Probable	Worst case
15 - A	Slope Angle	315	680
15 - B	Failure Mass Volume	400	790
15 - C	Fall Height	260	750
	<b>Mean</b>	<b>325</b>	<b>740</b>

1. Runout measured from toe of idealized slope within the quarry bowl (Figure 14 – lower).

The mean values are plotted as shadows from the crest of the idealized slope (Figure 14). The most probable result indicates retention of the runout within the quarry bowl while the worst-case estimate encroaches on I-82 northbound.

The estimates are considered conservative because the actual quarry highwall is much lower than the idealized profile resulting in less kinetic energy in a potential failure mass, and because there is negligible opportunity for entrainment of air or water to fluidize the failure debris and thereby stimulate runout.

## 8.2 Risk to Proximal Infrastructure

Based on the most probable landslide behavior, dominant and subsidiary directions of slide movement, runout assessment and locations of proximal public and private infrastructure (excluding the quarry), Figure 16 summarizes by location designation, the types of hazard and a subjective assessment of probability or occurrence.

Two general risk areas are designated; one within the estimated limits for a rapid slide runout, and a second along the west slope that is judged to be susceptible to hazards related to subsidiary slope movement. Within the rapid runout zone, I-82, the residential area and the Yakima River are at risk. As shown in Figure 16, the probability of impacts due to rapid runout are classed as **Very Improbable** with mitigation strategies as shown.

For the west slope, areas at risk are Thorp Road (subdivided into north and south sections) and I-82 Northbound. The hazards for these three areas are described as rockfalls and small-scale failures, with the probability of occurrence rated from very probable to improbable, depending on location. Mitigation strategies are shown in Figure 16.

## 9 MONITORING

### 9.1 Monitoring Requirements

Monitoring provides data for the interpretation of slide mechanics and for prediction (warning) purposes. Ideally, monitoring should incorporate the following:

- Provide “real” time quantitative data on which to implement public safety response plans (polling frequency of one to three hours).
- Include independent systems for corroboration of slope behavior and to provide redundancy in the event of instrumentation failure or environmental interruption (e.g. fog / snow).
- Provide data that is useful for both the warning function and the mechanism of movement interpretation.

### 9.2 Methods Employed

The current monitoring programs consists of:

- Visual monitoring of west slope on a 24 hour / 7 day per week regiment.
- Web camera to installed from within the Anderson Quarry to view the south toe of the slide.
- GPS hubs - manually read by Columbia personnel on a multi-day cycle. Soon to be discontinued due to safety concerns about accessing the slide mass.
- Prisms / robotic total station – a series of 22 prisms read, five of which read on a 5-minute polling frequency and the remainder on a 30-minute polling frequency. The post-processed data is reported to the web portal <https://geomosnow.leica-geosystems.com/GeoMoSNow/>.
- Reflector targets (RS series) along the west slide margin manually-surveyed by WSDOT on a daily basis. Data reporting by email summary or posted to web site.
- Terrestrial LiDAR / change analyses performed by WSDOT and a twice per week frequency. Recently expanded to include both the west-facing slope above I-82 as well as the quarry face.
- Columbia plan to install three to five GPS hubs with remote reading capability within the next week. Planned polling frequency is not determined.

### 9.3 Areal Coverage

Two areas for additional RS targets (or prisms) are recommended as shown in Figure 4. These are intended to characterize the upper northwest portion of the slide where a data gap exists and the southwest corner where resistance to movement is being detected by LiDAR imaging. With the addition of targets (or prisms) at the designated locations, the monitoring systems are considered adequate to constrain the current movement area. Image analyses, specifically LiDAR change analyses, will determine the requirement for future expanded areal coverage.

## **9.4 Data Integrity**

Based on direct comparison of monitoring data from multiple sources and using varying measurement methods, there is no reason to doubt the integrity of the data. The data is consistent across source platforms and therefore has a high degree of reliability.

## **9.5 Monitoring Recommendations**

The slide has been intensely monitored for approximately 3 ½ months. As the duration extends, it will be increasingly difficult for the individual Technical Participants to justify the ongoing expenditures being incurred. Accordingly, it is advisable to establish a framework within which monitoring intensity is scaled to slide behavior. The following is offered as an example to be refined by the Technical Participants:

### **Extreme Alert Level**

#### *Diagnosis:*

Documented increasing velocity of several, proximal data points (prisms or GPS hubs) over a multi-day period with confirmation from an imaging methodology.

#### *Monitoring Response:*

- Visual observation 24 hr x 7 days, to record timing and nature of slope face failure events (rockfalls, raveling etc.)
- AMTS – 5-minute and 30-minute polling frequency with automated messaging if triggering thresholds are reached.
- West slope RS targets – daily survey.
- LiDAR – twice per week.
- Radar / hillshade – as available.

### **High Alert Level**

#### *Diagnosis:*

Documented decreasing velocity, or elevated uniform velocity with respect to 10-day rolling average, over the majority of the slide mass (80% of measurement points) and with confirmation from an imaging methodology.

#### *Monitoring Response:*

- Visual observation – daily inspections to photo document rockfalls, crack propagation, slope face dilation.
- AMTS – maximum 30-minute polling frequency with automated messaging if triggering thresholds are reached.
- West slope RS targets – three times per week.
- LiDAR – bi-weekly.
- Radar / hillshade – as available.



**Maintenance Alert Level***Diagnosis:*

Decreasing velocity, or uniform velocity less than 0.5 feet/week, over the majority of the slide mass (80% of measurement points) and with confirmation from an imaging methodology.

*Monitoring Response:*

- Visual observation – weekly inspections to photo document rockfalls, crack propagation, slope dilation.
- AMTS – maximum 60-minute polling frequency with automated messaging if triggering thresholds are reached.
- West slope RS targets – weekly.
- LiDAR – monthly.
- Radar / hillshade – as available.

The alert levels should be communicated to agencies required to plan for emergency response.

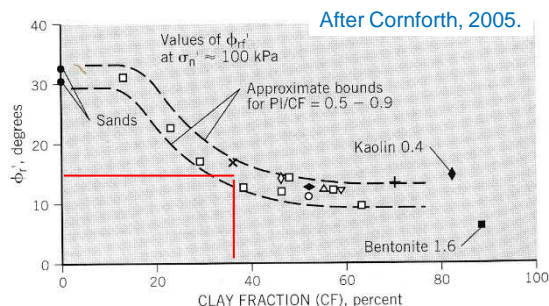
Inherent in the above landslide status framework is the necessity of **automated warning** in which threshold values of velocity (or displacement) are set to trigger voice mail / text messaging to a designated group. This group must comprise several geotechnical professionals who agree to be on-call at all hours, 7-days per week. The group is charged with vetting incoming warning messages, confirming their validity, and informing emergency response personnel as appropriate. False alarms are to be expected due to instrumentation issues or inappropriate trigger levels, and therefore the vetting process prior to public dissemination is important.

**10 GEOTECHNICAL RECOMMENDATIONS****10.1 Three-Dimensional Slope Model**

The inclination of the slip surface and the inclination of the movement vectors should be consistent. That is, it is not geometrically-feasible for movement vectors to be consistently reporting inclinations steeper than the slip surface. A three-dimensional model that includes a digital terrain model (DTM) combined with a digital model of the slip surface would be beneficial to the engineering interpretation, particularly with regard to the shear strength acting on the slip surface.

## 10.2 Geotechnical Properties

In the absence of water pressure, the frictional shear strength along the sliding surface must be less than the dip, probably in the 10° to 14° range. Friction values this low are associated with



significant clay fraction content, often bentonitic (see margin graphic). Visual inspection of the exposed upper portion of the interbed did not reveal such material. The entirety of the interbed should be excavated in a test pit to inspect, sample and test the material on the actual sliding surface (base of interbed). Grain size distribution, Atterberg Limits and ring shear tests will provide design data that will confirm that the slip surface shear strength is consistent

with its geometry. Such data will also be valuable for analyses to investigate long-term stability and / or stabilization options.

## 10.3 Groundwater

Second only to structural geology, the pore pressure distribution within the slopes is critical to stability. To date, the working hypothesis has been that groundwater pore pressure is not present at the slip surface. If the site evolves to become a candidate for an engineered stabilization, boreholes should be drilled above the head scarp and beyond the east lateral scarp for geotechnical sampling and for installation of piezometers at the critical sliding horizon. This assumes that drilling on the slide mass itself will not be viable.

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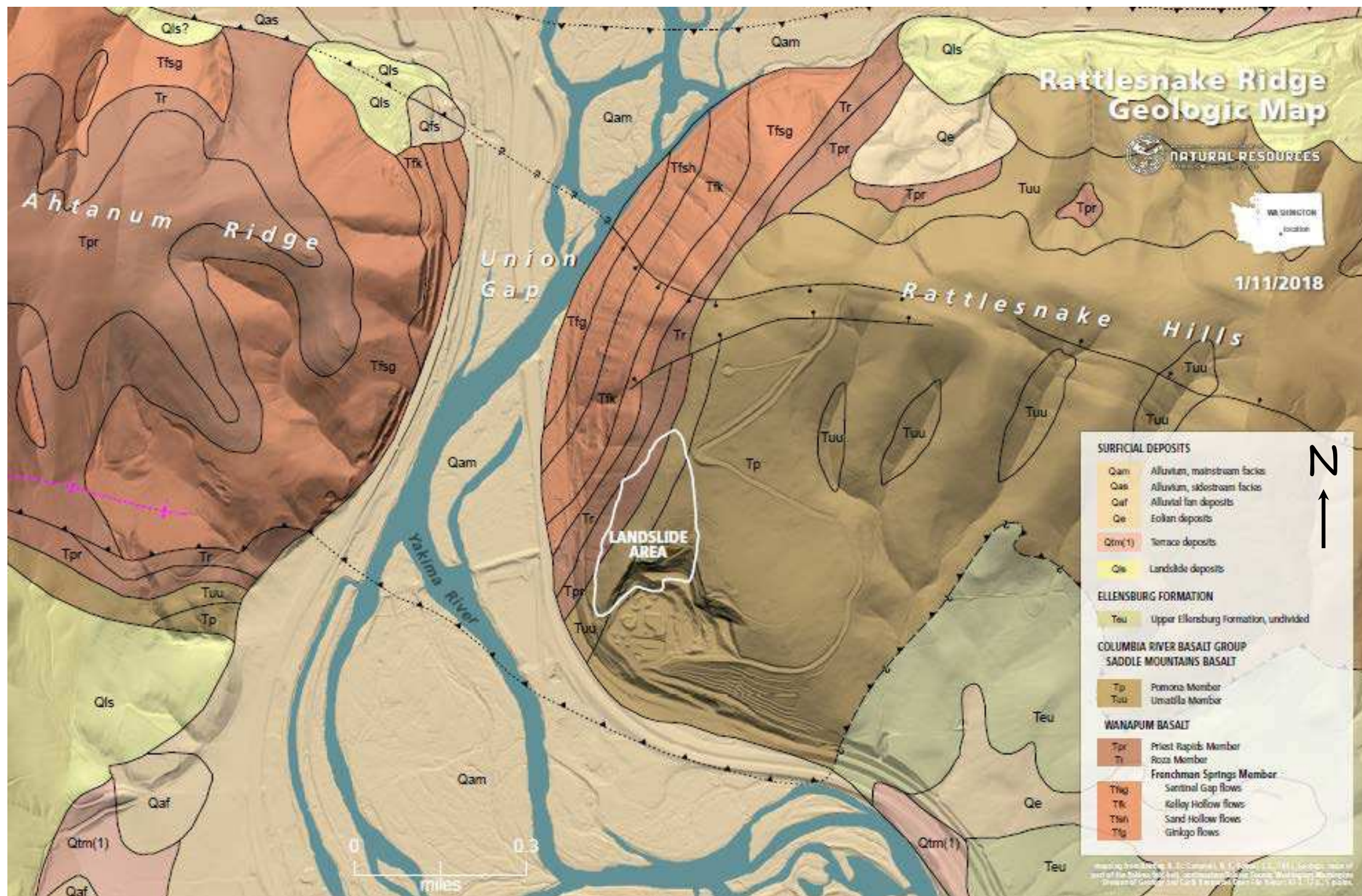
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Source: Washington State Department of Natural Resources

Figure 1  
Geologic Plan



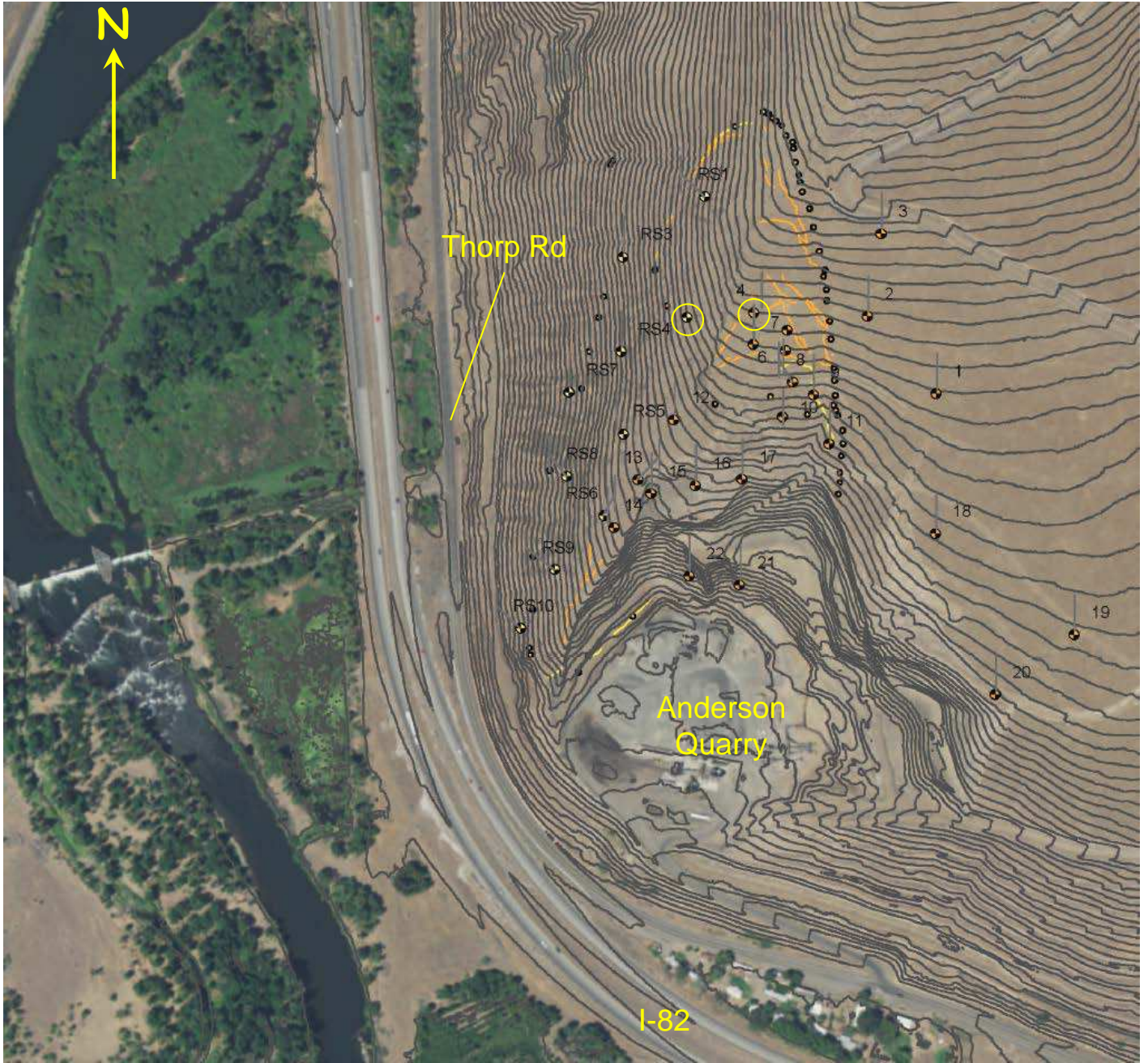
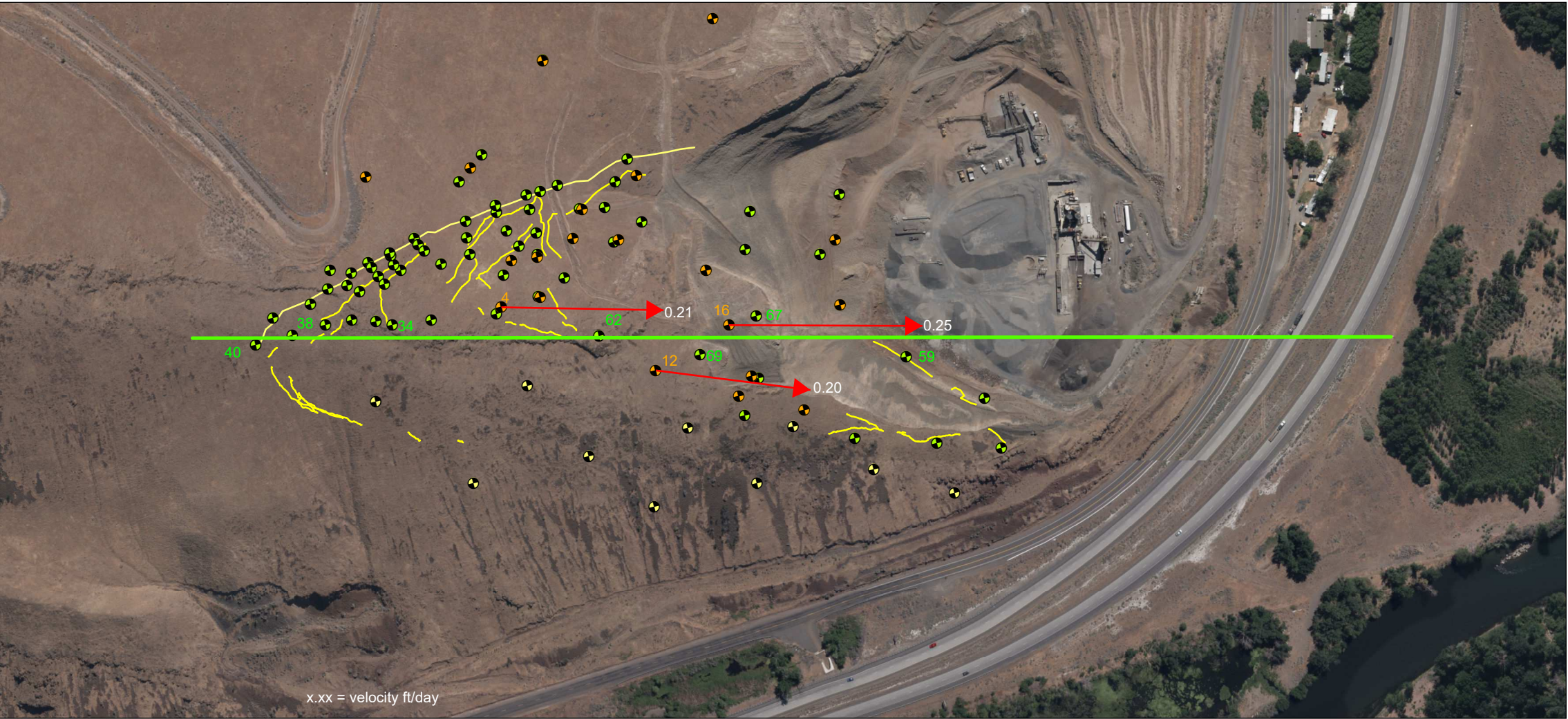


Figure 2  
Site Plan





Legend

Profile Azimuth 195

Columbia Total Station Prisms

Columbia GPS Monitoring

WSDOT Total Station Prism

Cracks

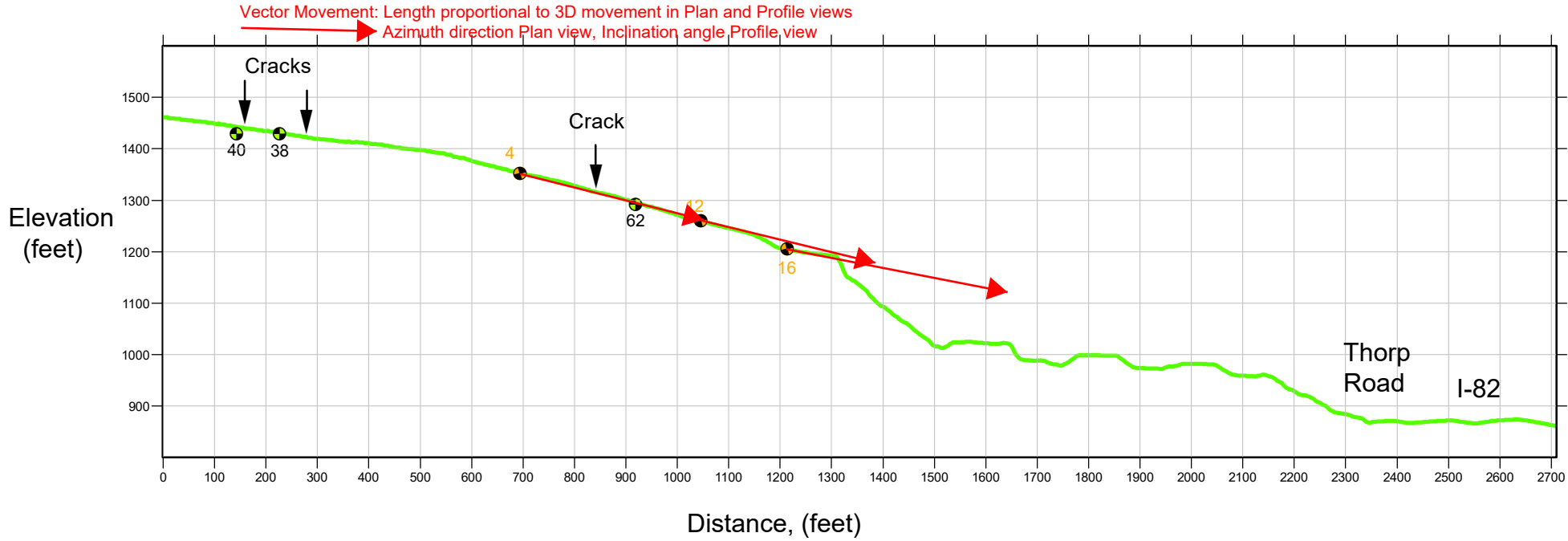
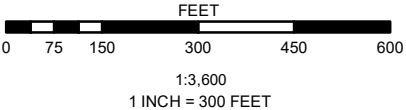
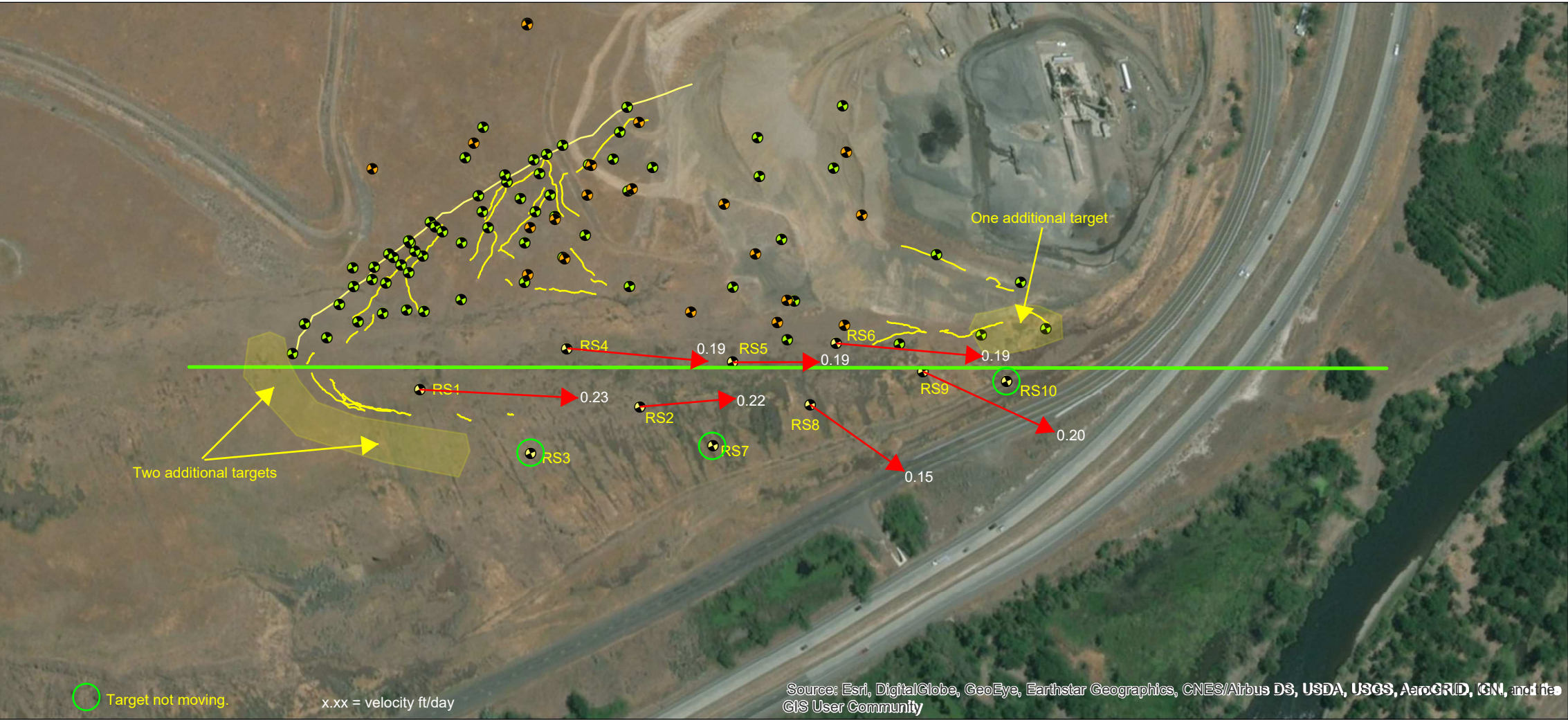


Figure 3  
Profile along Azimuth 195



JOB # STATE ROUTE 082 MILEPOST(S)





Vector Movement: Length proportional to 3D movement in plan and profile view  
Azimuth direction plan view, Inclination angle profile view

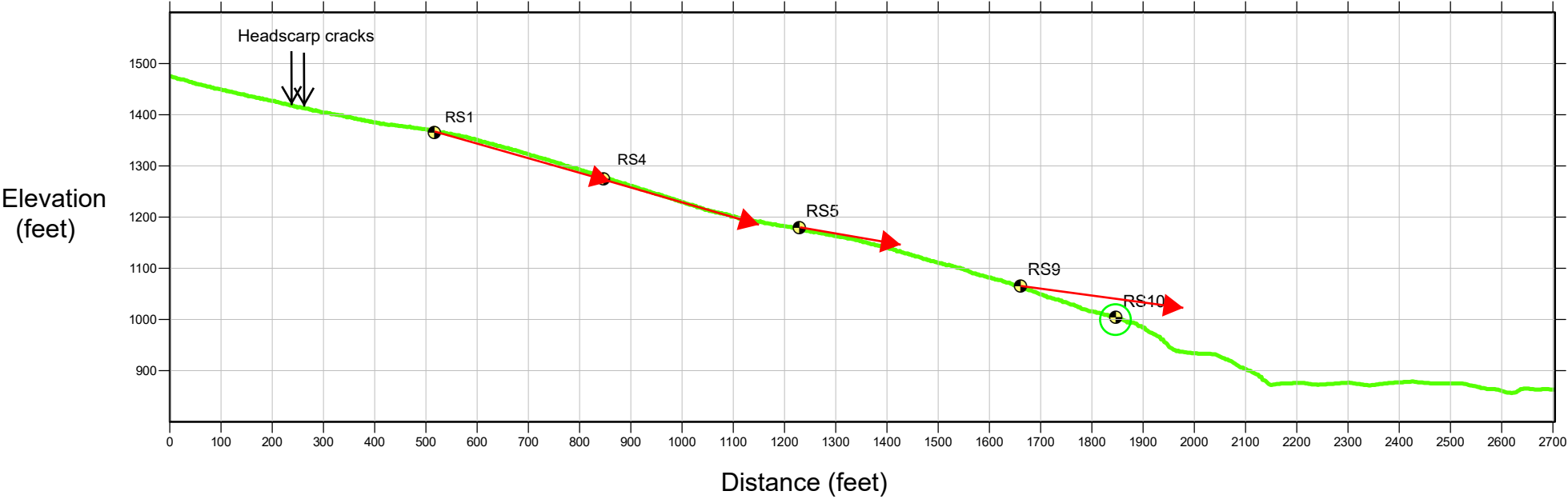
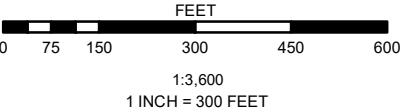


Figure 4  
Profile along Azimuth 205

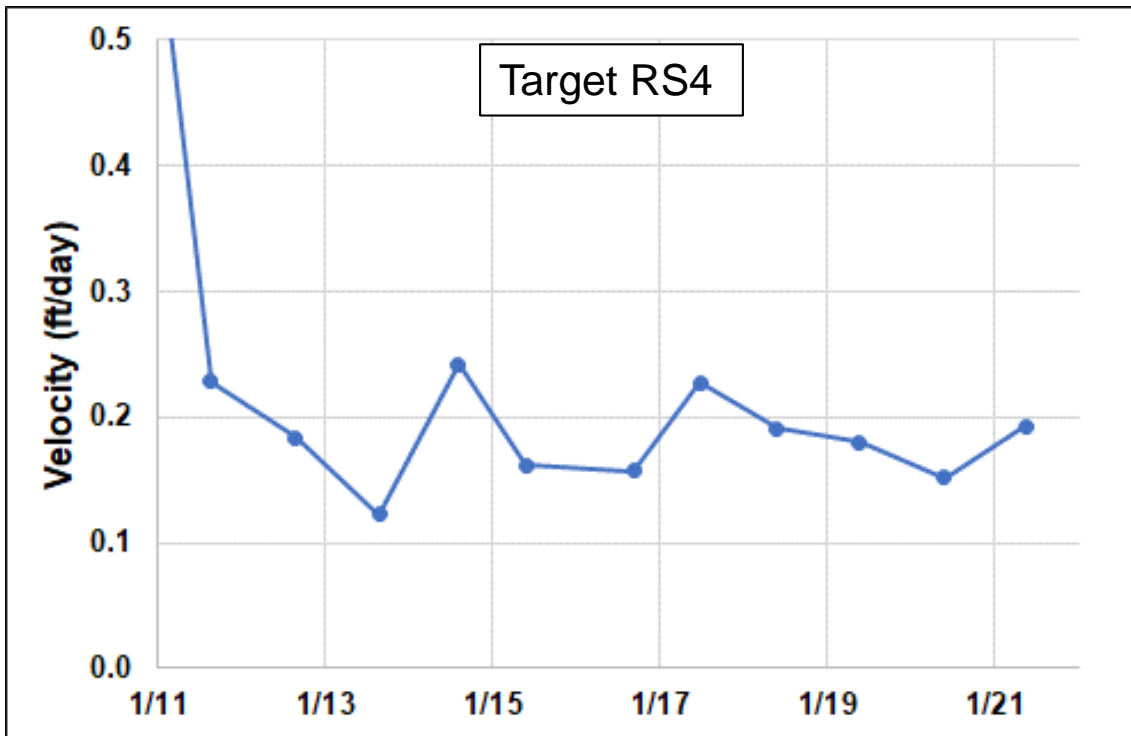


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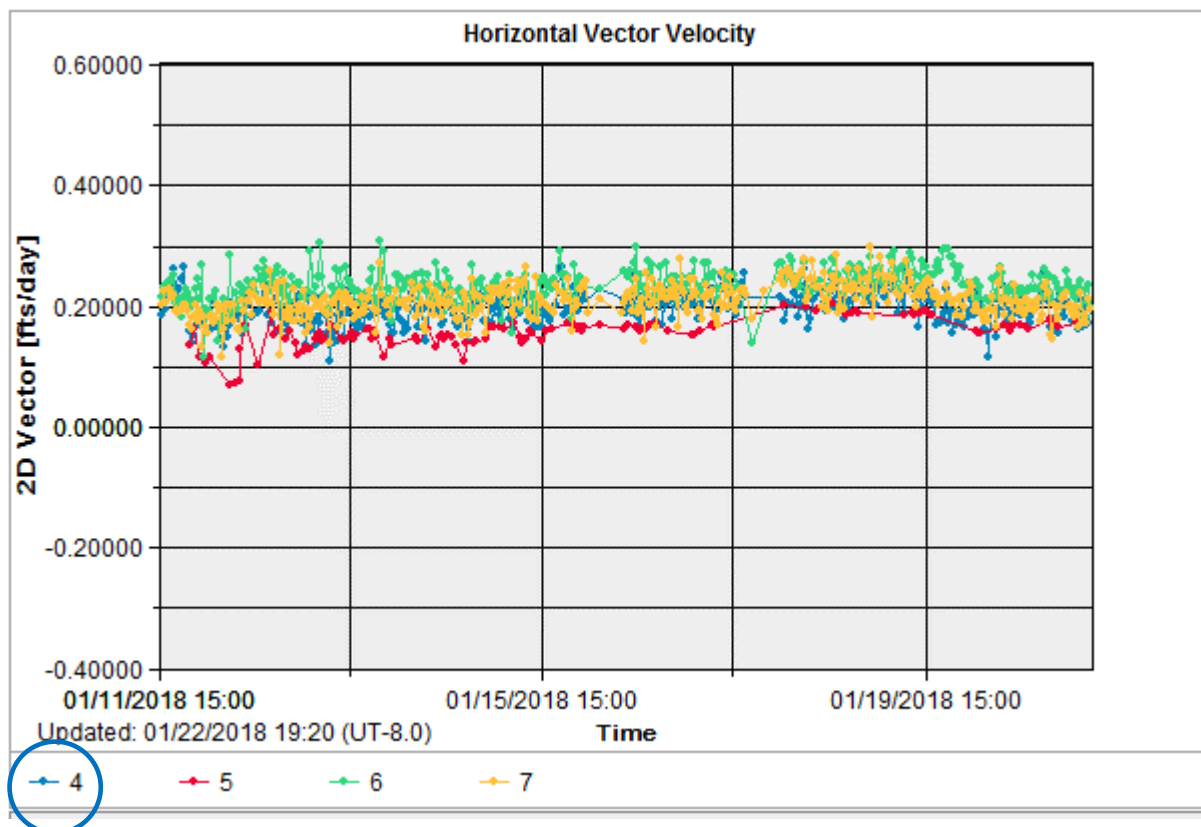
**WSDOT** GEOTECHNICAL OFFICE

PREPARED BY TropleT

Date: January 17, 2018

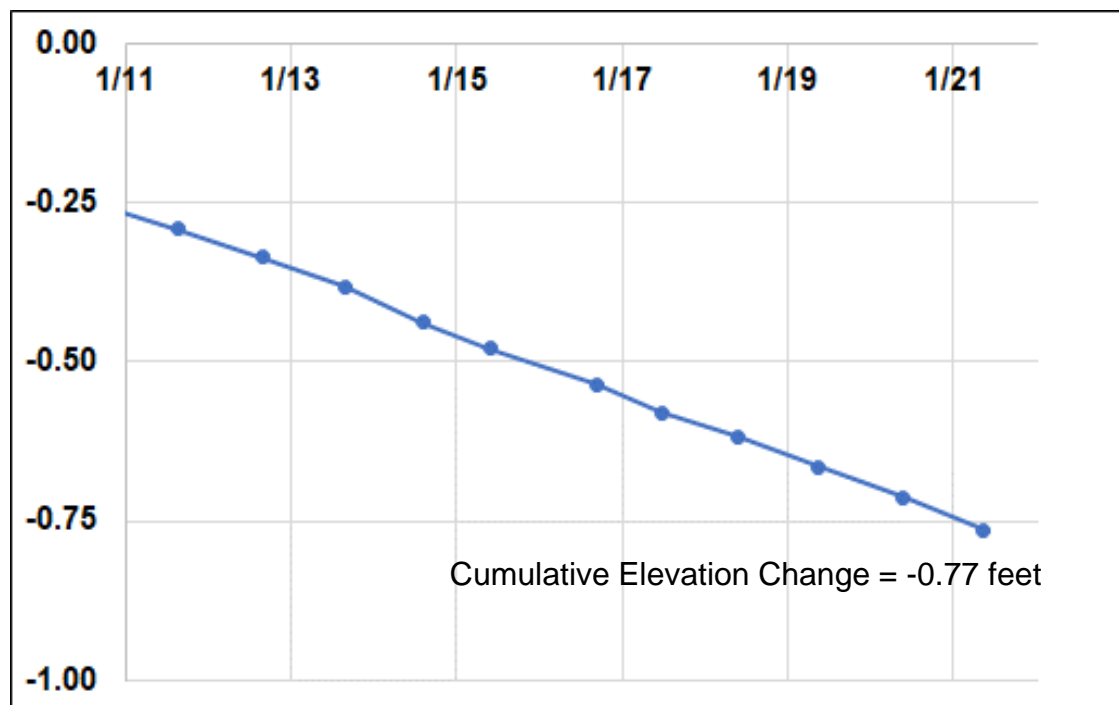


**Note:** For locations of Prism 4 and Target RS4, see Figure 2.

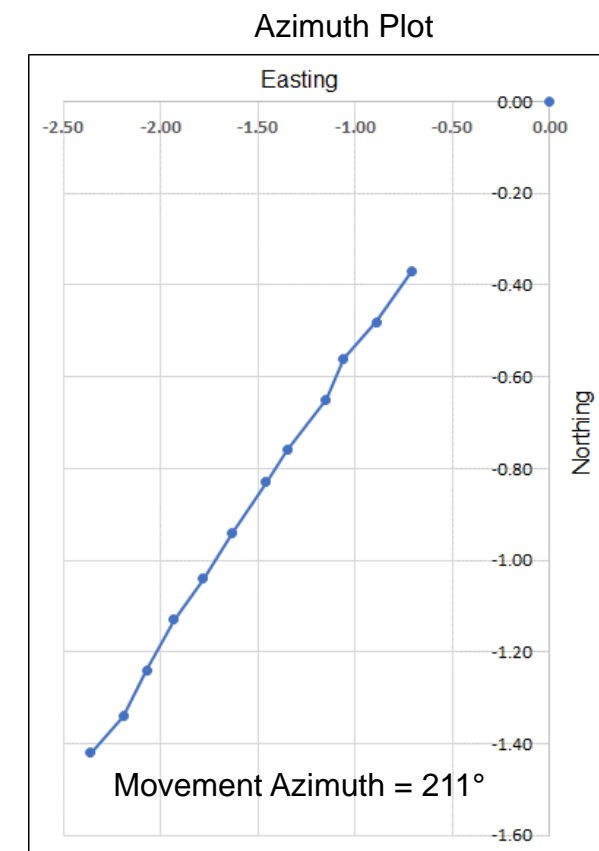


**Figure 5**  
**Comparison of Prism 4 with Target RS4**

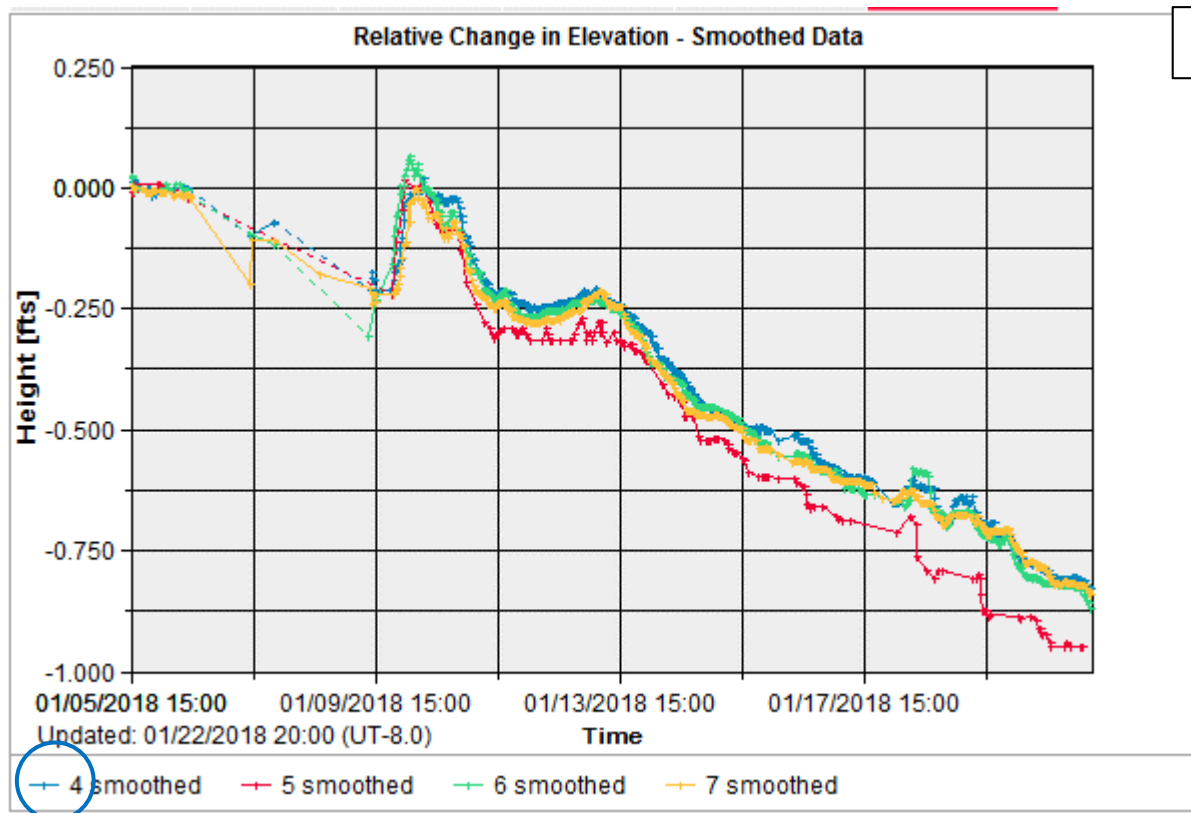




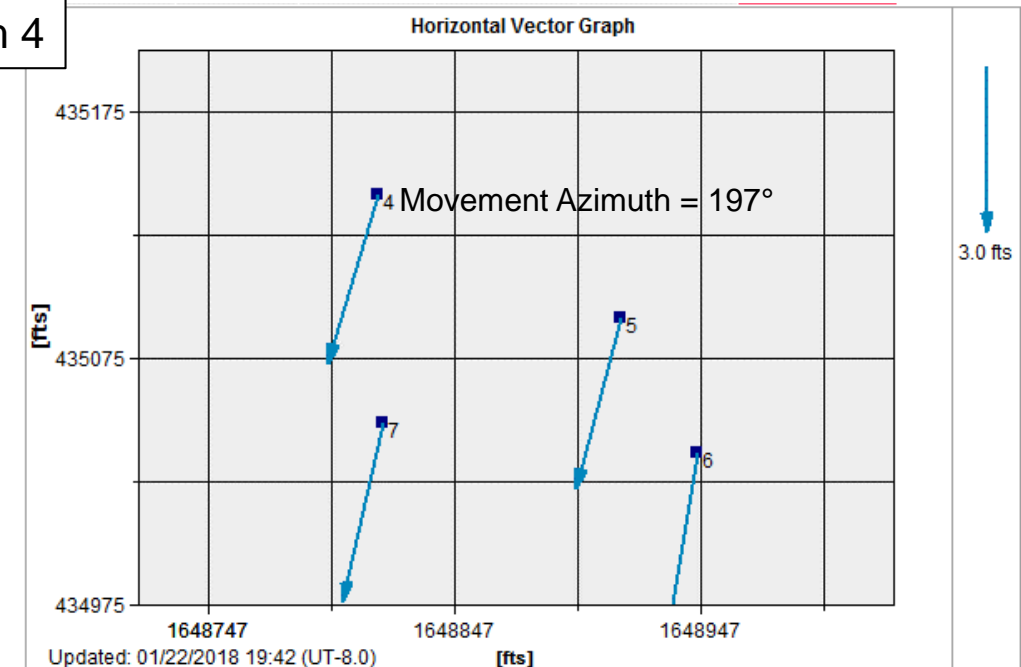
Target RS4



**Note:** For locations of Prism 4 and Target RS4, see Figure 2.



Prism 4



**Figure 6**  
**Comparison of Prism 4 with Target 4**

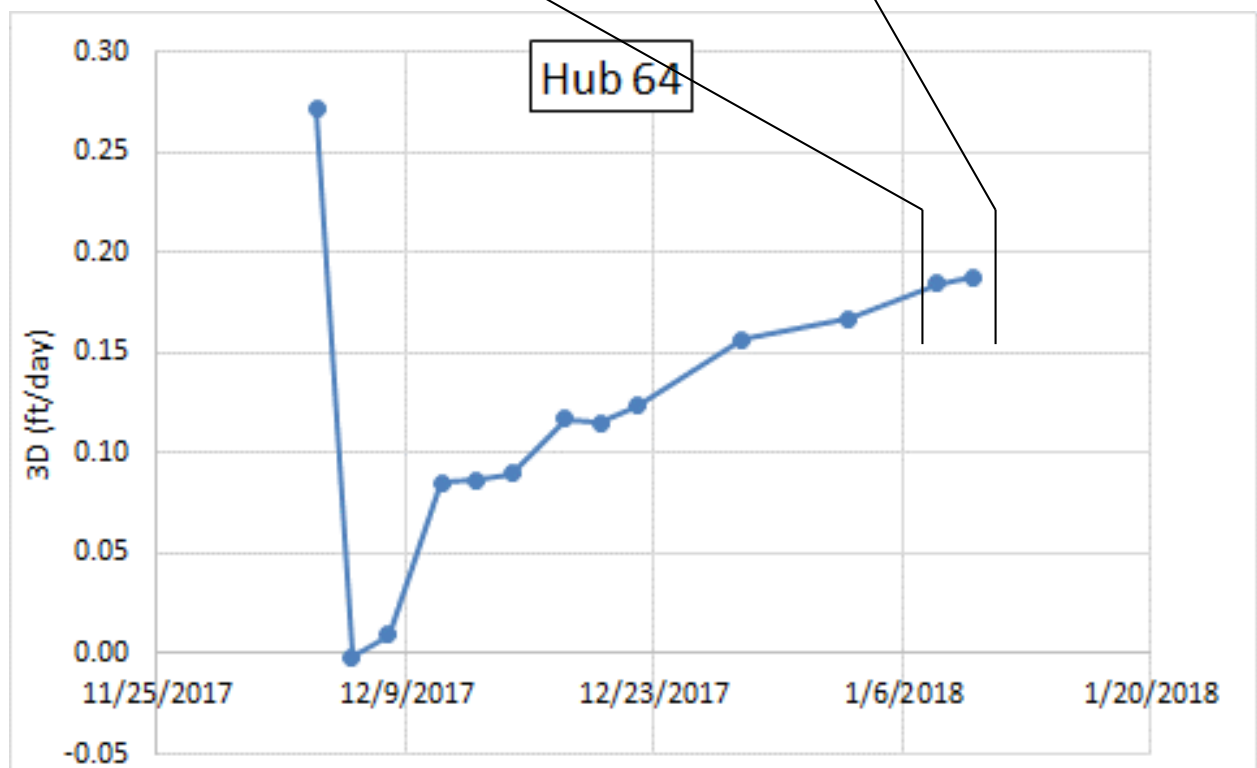
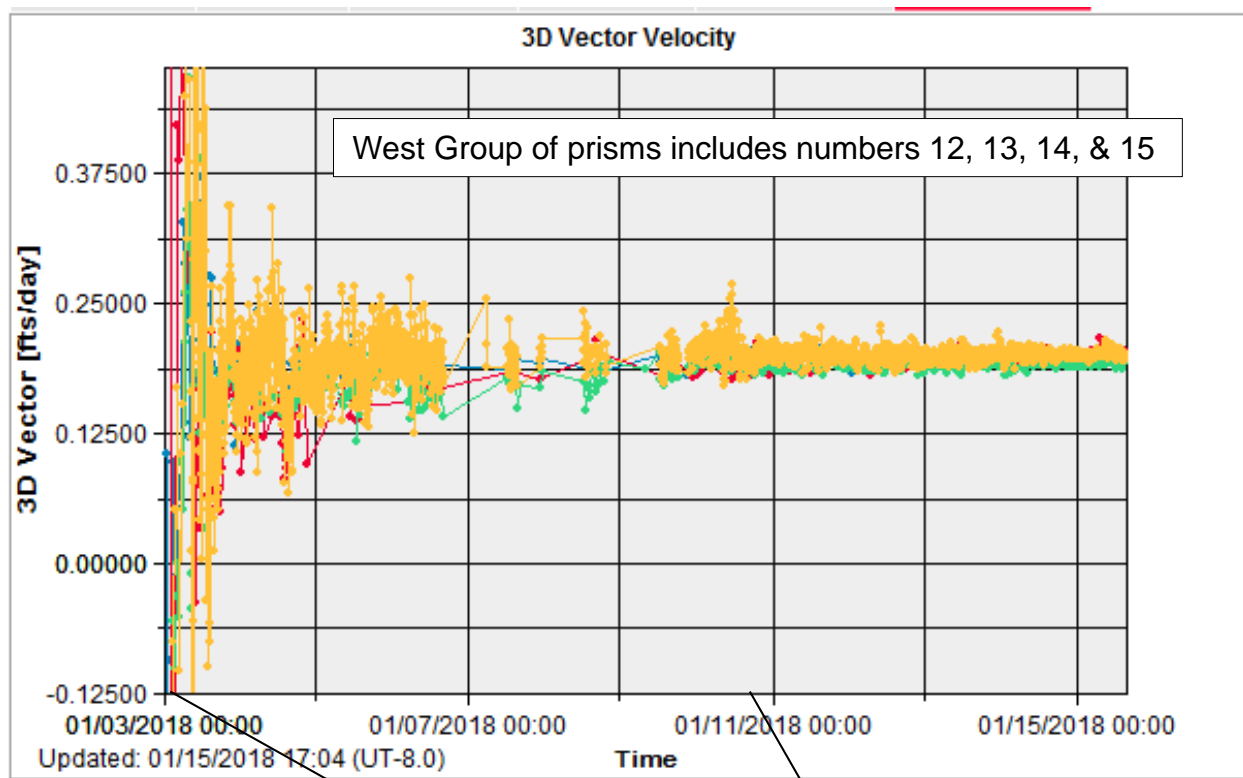


Figure 7  
West Prisms vs GPS Hub- Velocity

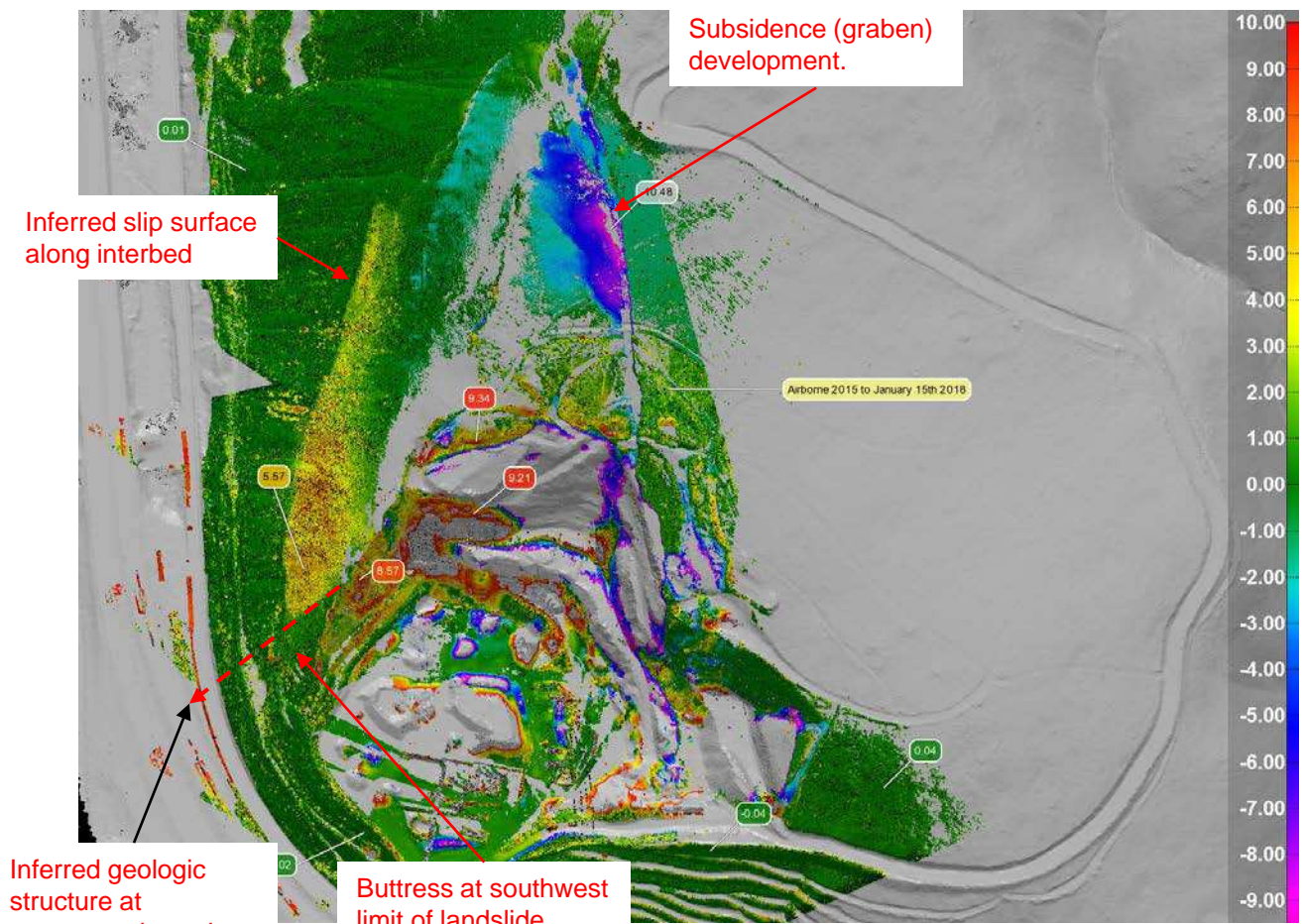
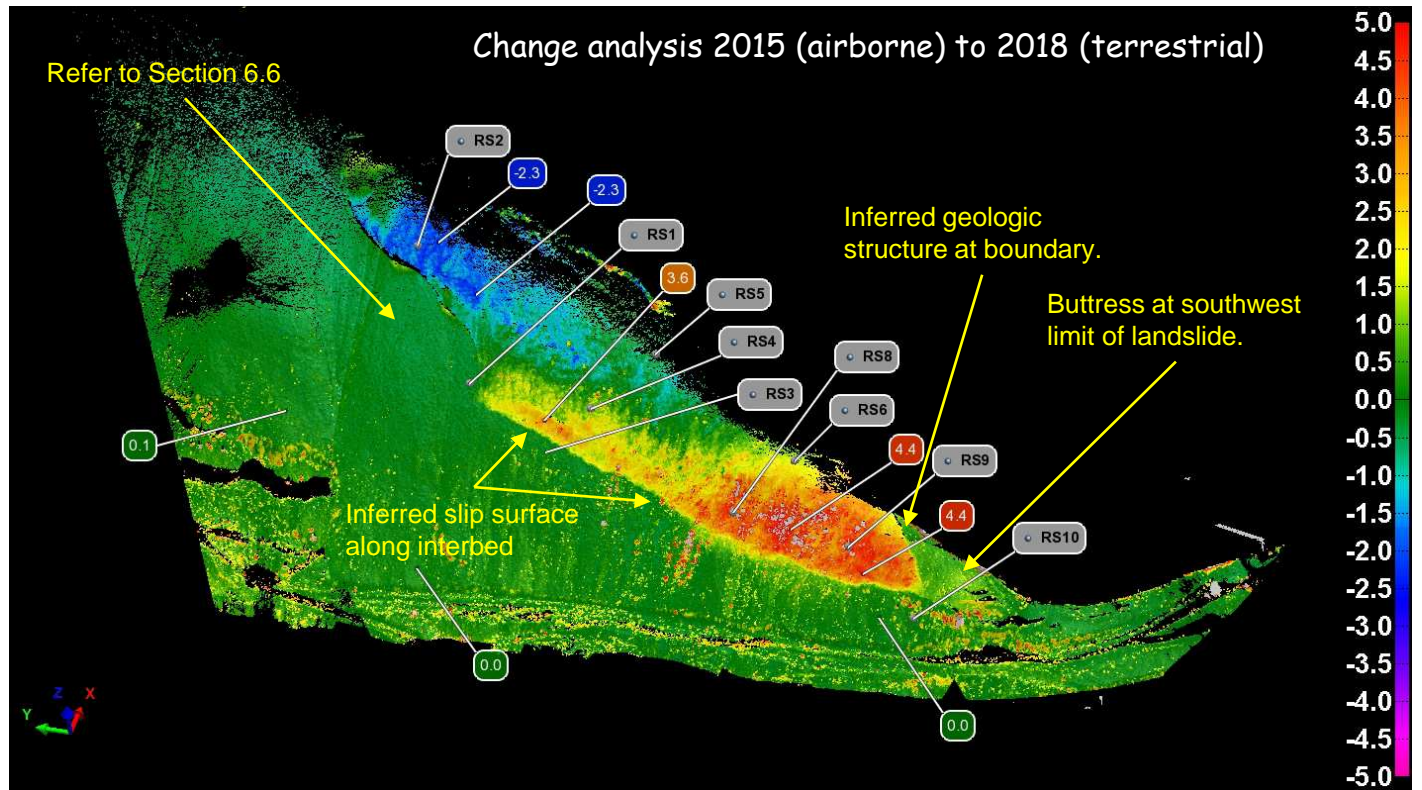


Figure 8  
Long Duration LiDAR Change Analysis



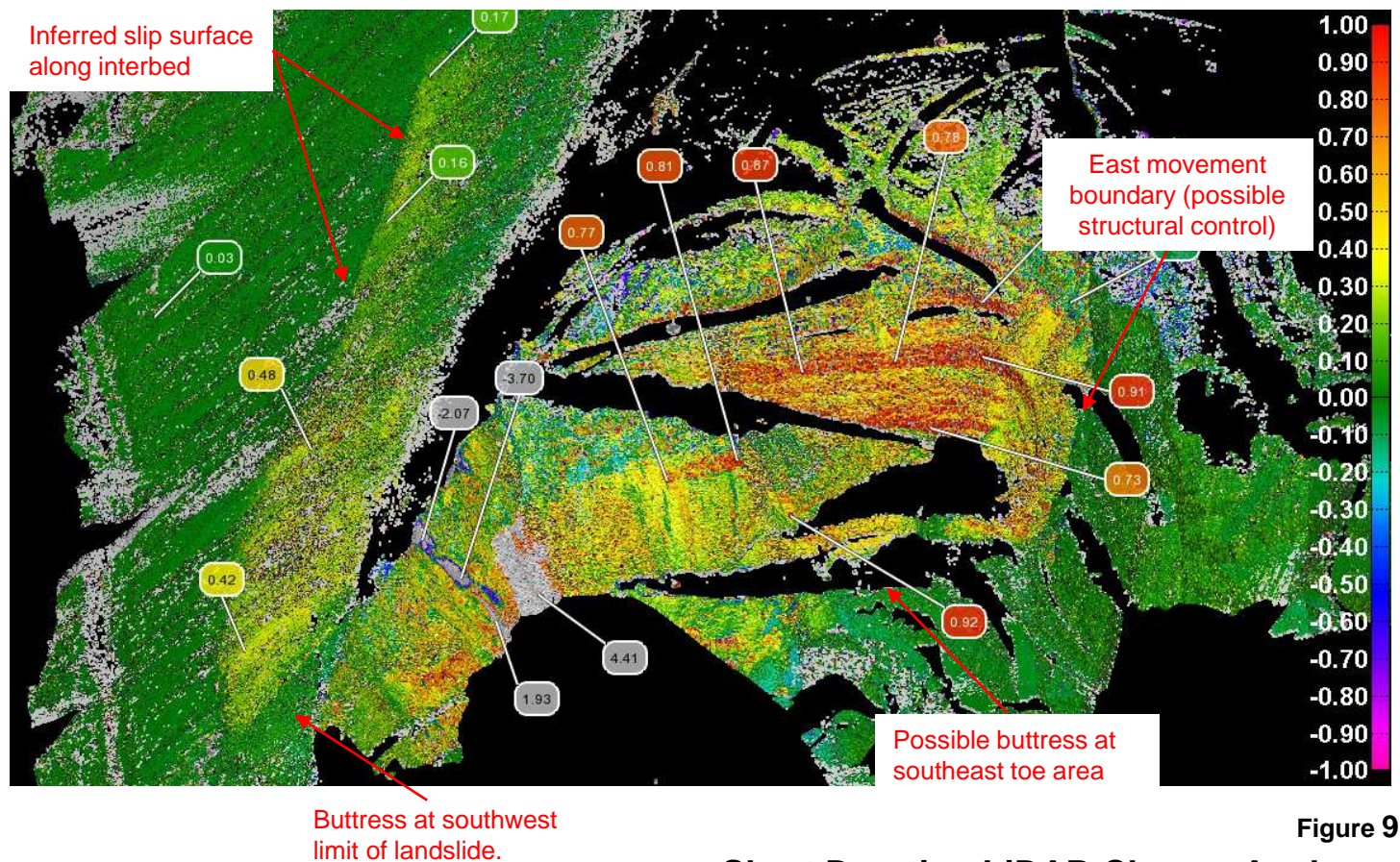
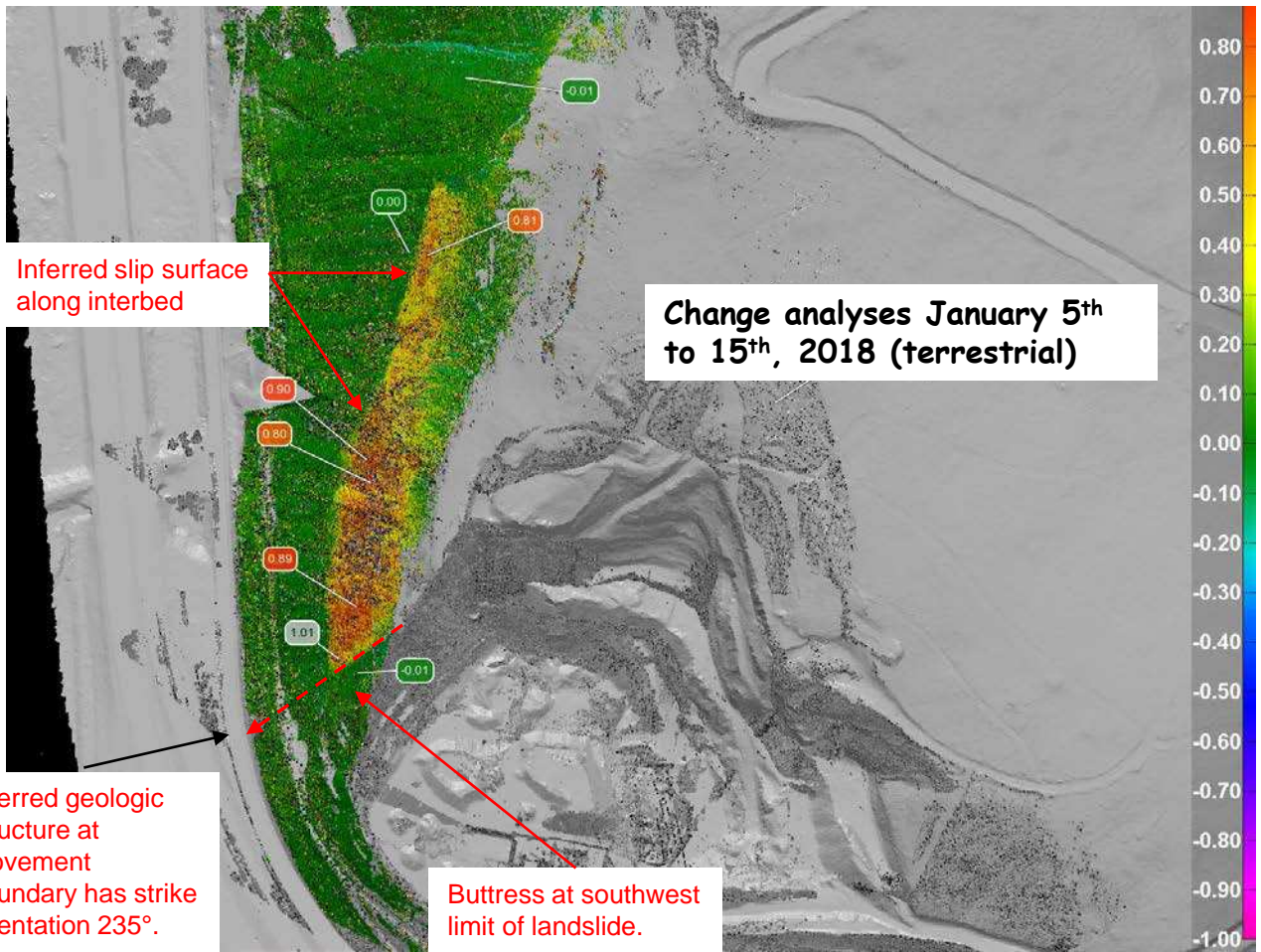


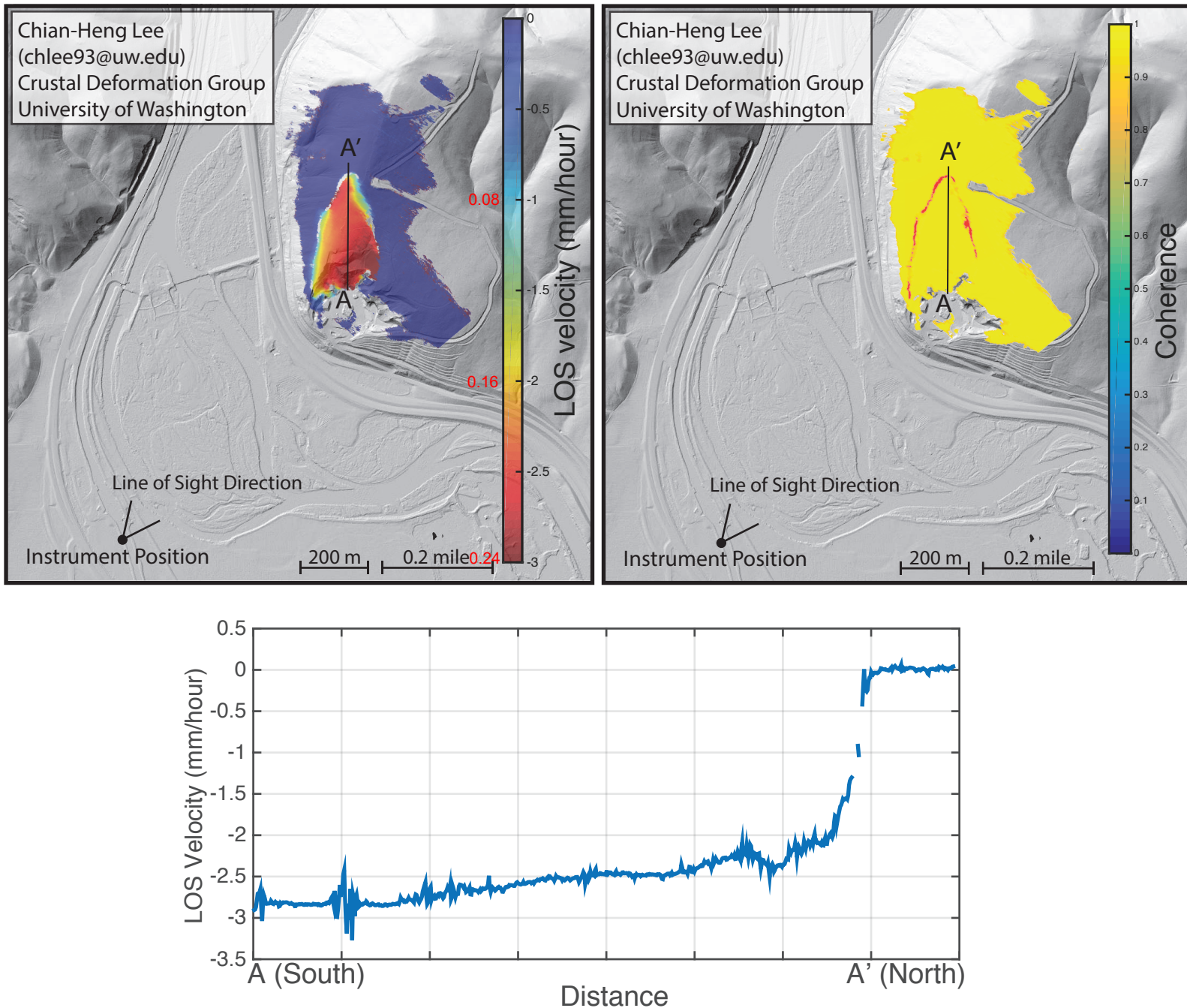
Figure 9  
Short Duration LiDAR Change Analyses



# GPRI preliminary results

GPRI Interferogram, 2018/01/06

Radar Coherence, 2018/01/06

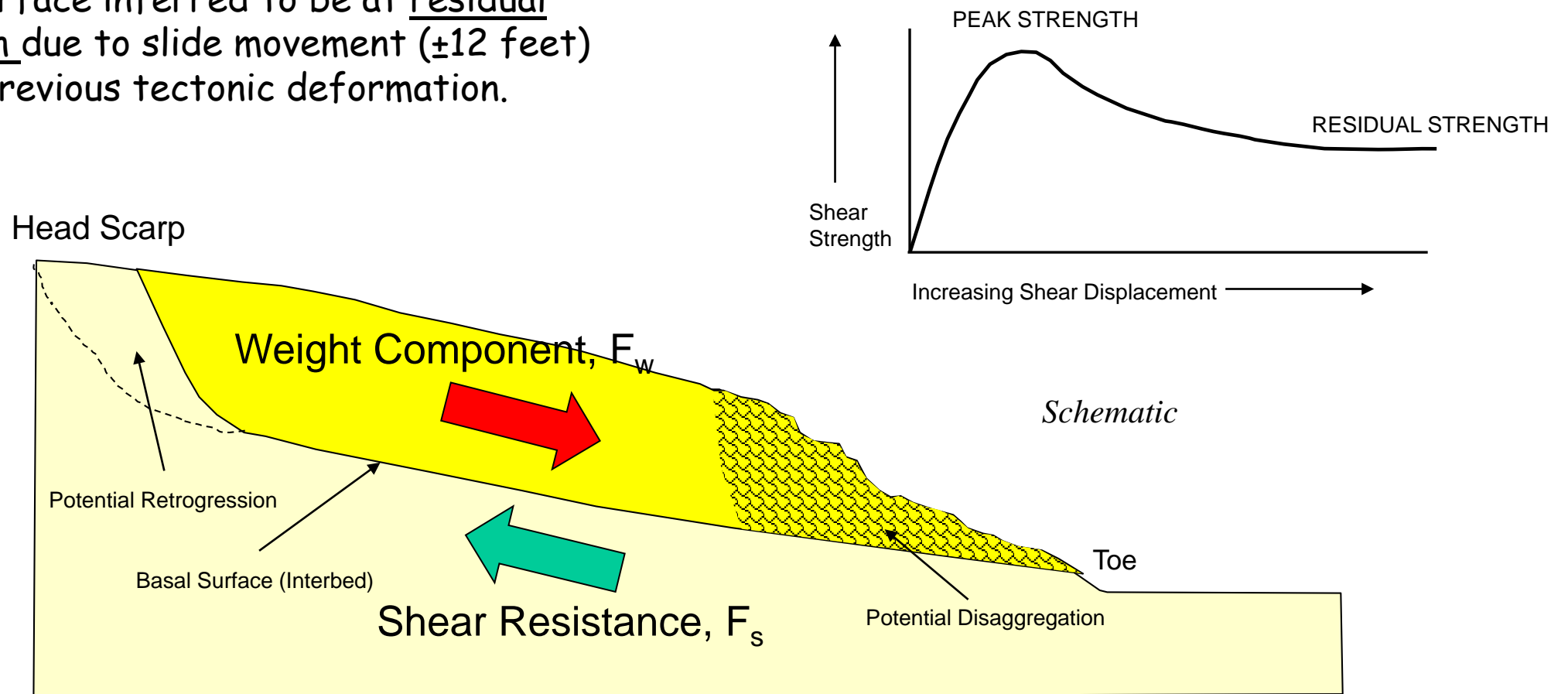


## Caption

Summary of ground-based radar data collected between 4:15pm and 6:30pm (PST) on January 6th, 2018 from a scan location along the WIP canal. The black dot and lines indicates the approximate location and line-of-sight (LOS) of the instrument. **Upper Left:** An interferogram showing the average LOS velocity over the data acquisition period (2.25 hours). A decrease in velocity indicates relative ground movement towards the instrument. **Upper Right:** A coherence image that indicates the correlation of the radar returns over the acquisition period. Coherence lower than 0.8 is not plotted. The inner band of low coherence (~0.3, shown in red) maps the deforming margins of the slide. **Bottom:** A LOS velocity profile along the line A-A' from the quarry to the upslope fissure. The background DEM is from the EarthScope Yakima Lidar Project with a resolution of 0.5 meter.

Figure 10  
Radar Analysis

Basal surface inferred to be at residual strength due to slide movement ( $\pm 12$  feet) and to previous tectonic deformation.

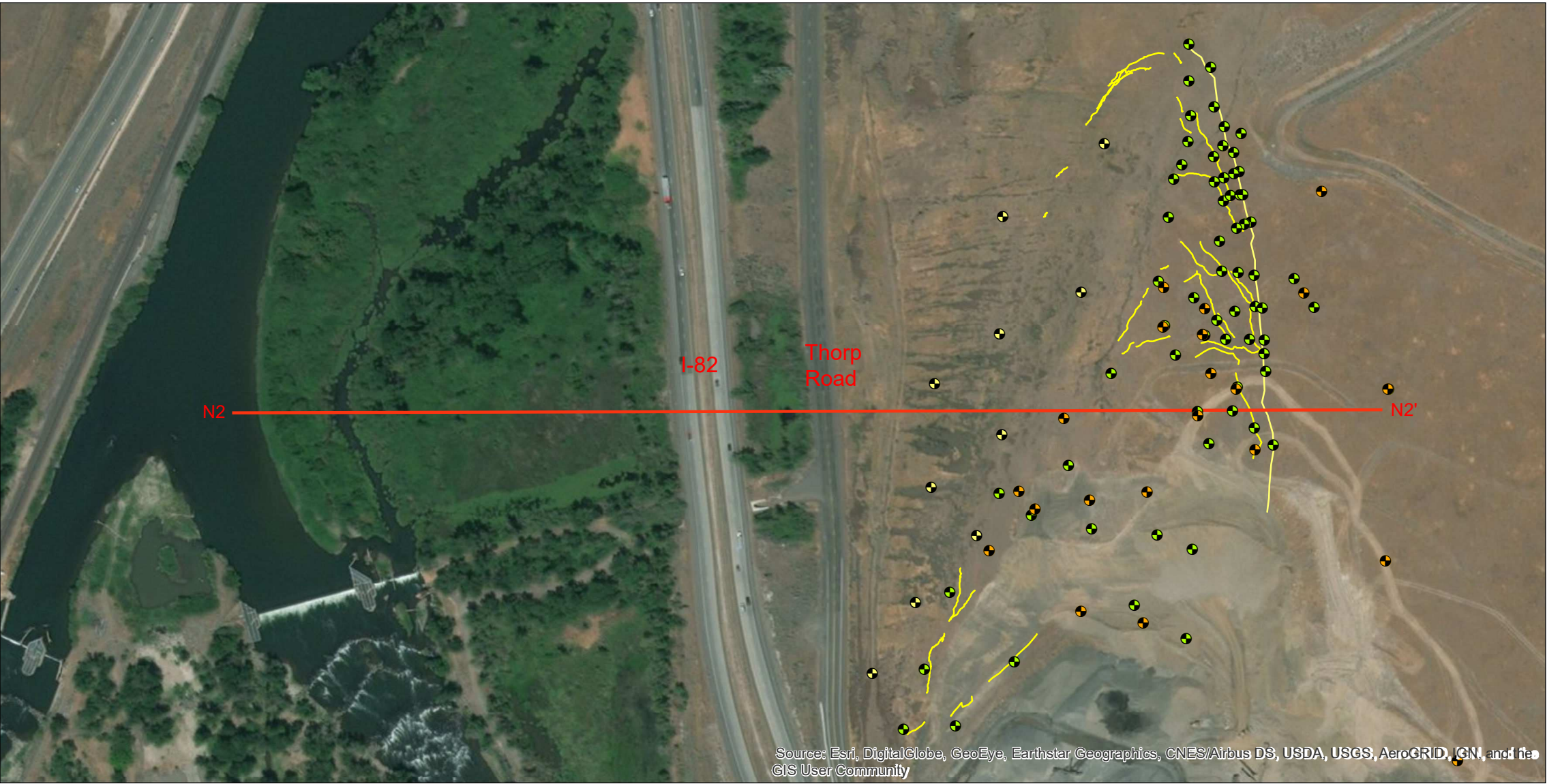


Force Condition		Slide Movement Character
$F_w$ much greater than $F_s$	$F_w \gg F_s$	Acceleration to rapid failure
$F_w$ slightly greater than $F_s$	$F_w > F_s$	Deceleration to constant low velocity
$F_w$ approximately equal to $F_s$	$F_w \sim F_s$	Intermittent or creep movement
$F_w$ slightly less than $F_s$	$F_w < F_s$	Movement stops, short-term stability
$F_w$ much less than $F_s$	$F_w \ll F_s$	No movement, long-term stability

Current Condition

Figure 11  
Slide Mechanics



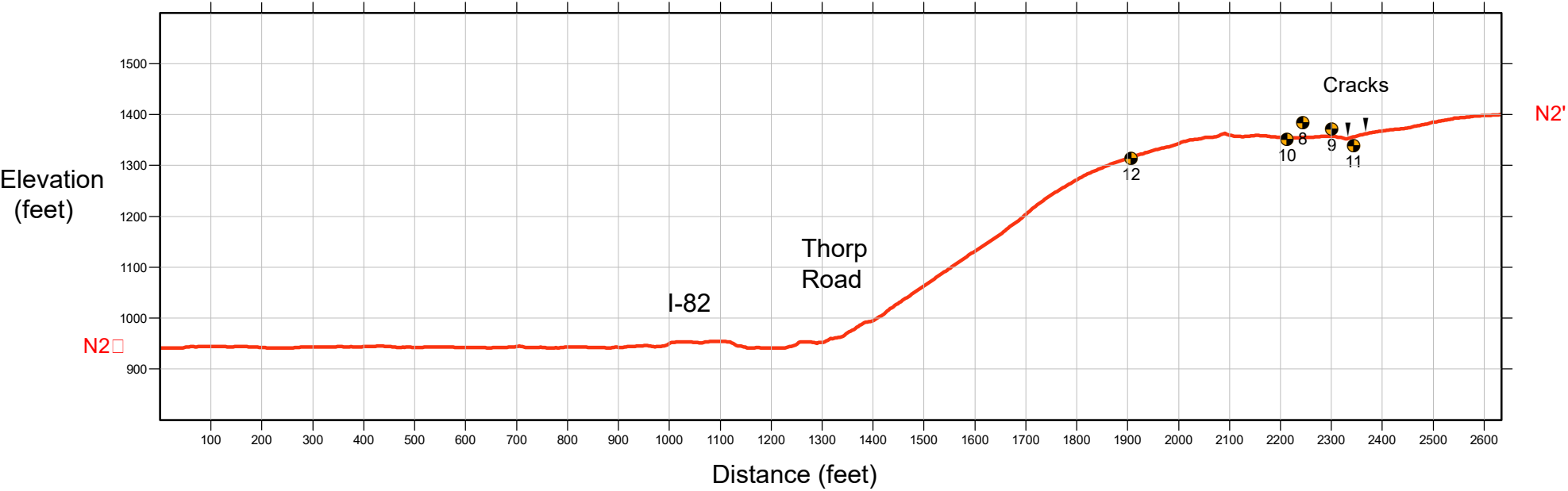
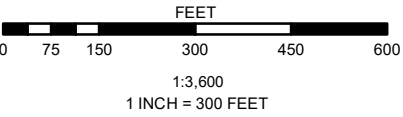


Legend

- Columbia Total Station Prisms
- Columbia GPS Monitoring
- WSDOT Total Station Prism
- Profile N2 - N2'
- Cracks



Figure 12  
Section N2 - N2' Location



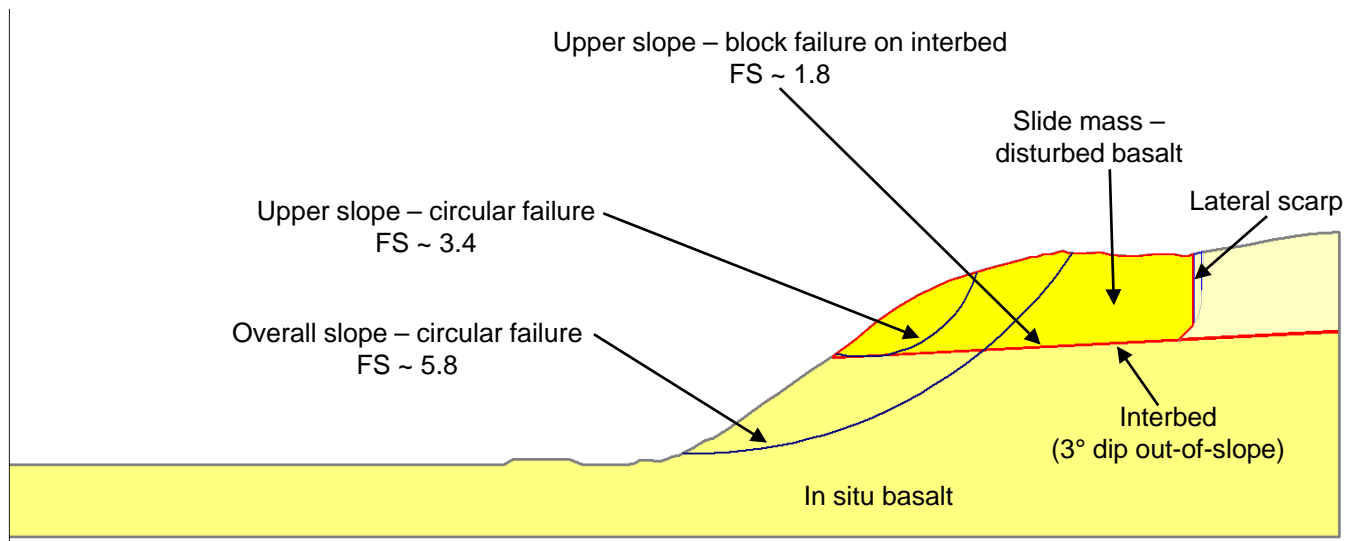
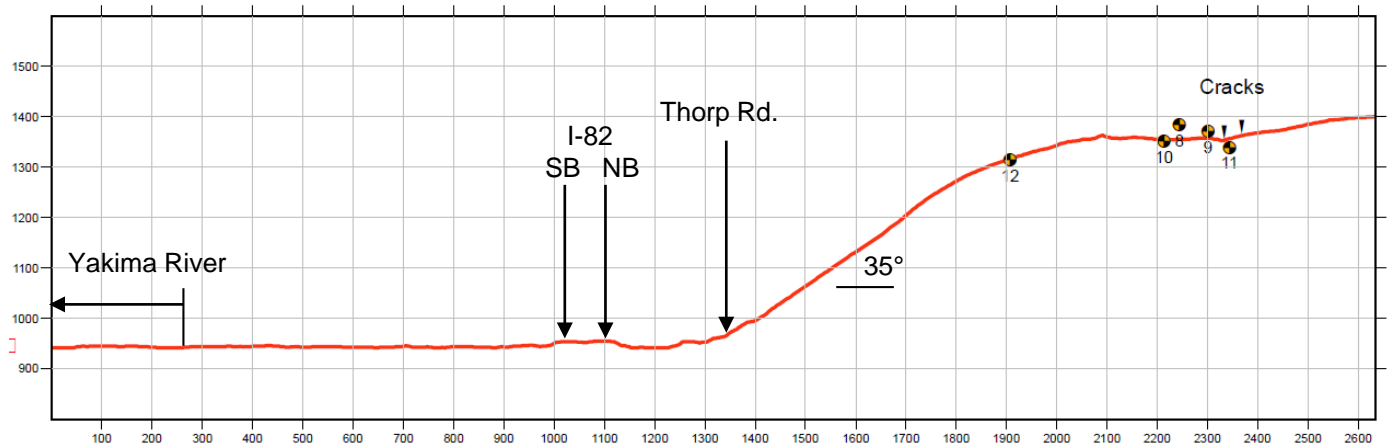
JOB # STATE ROUTE 082 MILEPOST(S)



PREPARED BY TropleT Date: January 19, 2018

## Section N2 – N2'

(See Figure 12)



### Presumptive Material Properties:

Slide mass basalt: UCS = 20,000 psi, GSI = 50, D = 1.0,  $\gamma$  = 165 pcf

Interbed:  $\Phi$  = 10°, c=0, Unit weight = 140 pcf

In situ basalt: UCS = 20,000 psi, GSI = 50, D = 0.0,  $\gamma$  = 175 pcf

Slope is fully drained.

UCS = unconfined compressive strength (intact rock)

GSI = Geological Strength Index

D = disturbance factor (1.0 = maximum disturbance)

$\Phi$  = friction angle

c = cohesion

$\gamma$  = unit weight

Figure 13

## Stability Analyses of West-Facing Slope



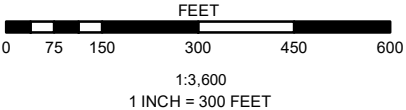
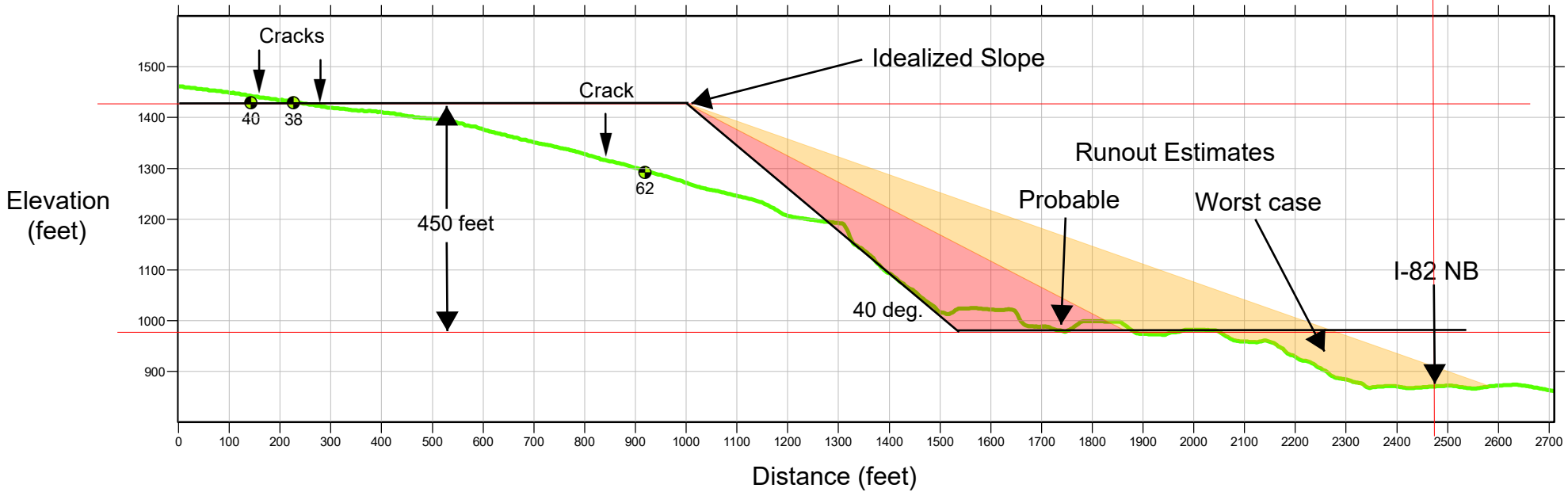


**Legend**

- Profile Azimuth 195
- Columbia Total Station Prisms
- Columbia GPS Monitoring
- WSDOT Total Station Prism
- Cracks



**Figure 14**  
**Runout Analysis for Idealized Slope**

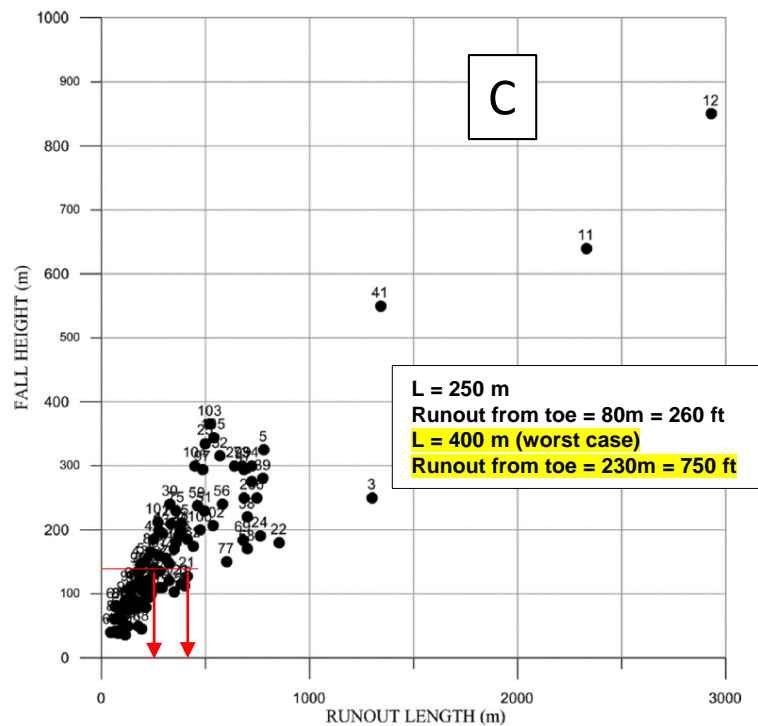
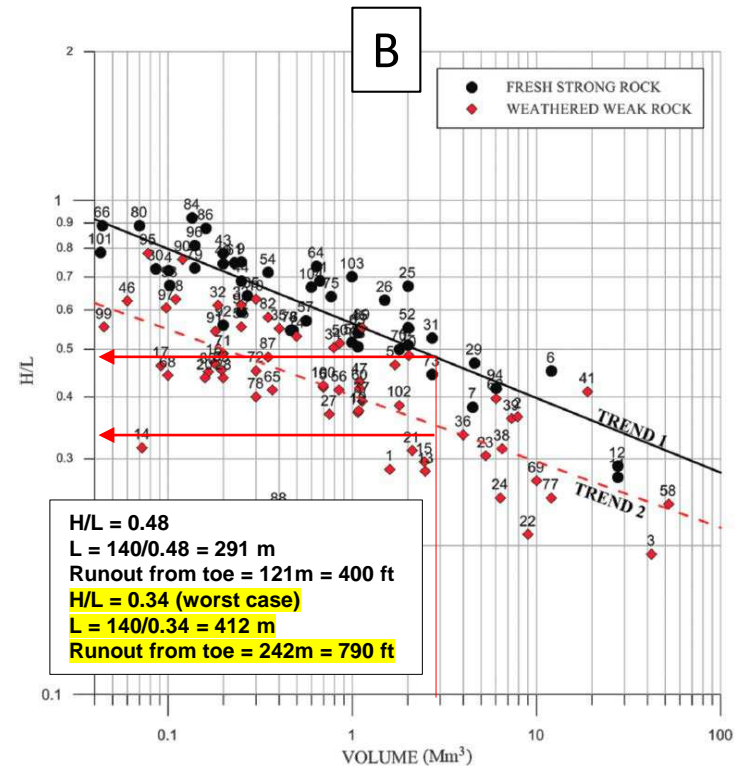
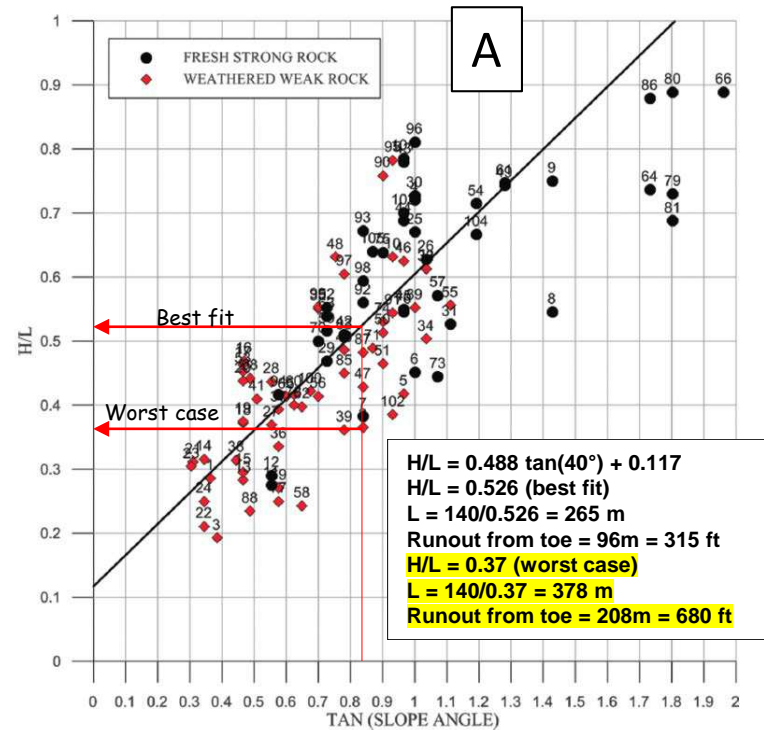


See disclaimer Section 7.1

JOB #            STATE ROUTE 082 MILEPOST(S)           



PREPARED BY TropelT Date: January 16, 2018



**For Rattlesnake Ridge (Idealized):**

slope height,  $H = 450$  ft = 140m

slope angle =  $40^\circ$

potential failure volume ~ 2.8 M m<sup>3</sup>

runout from toe ~ (L – 170m)

rock mass = fresh strong rock (dilative)

**Notes:**

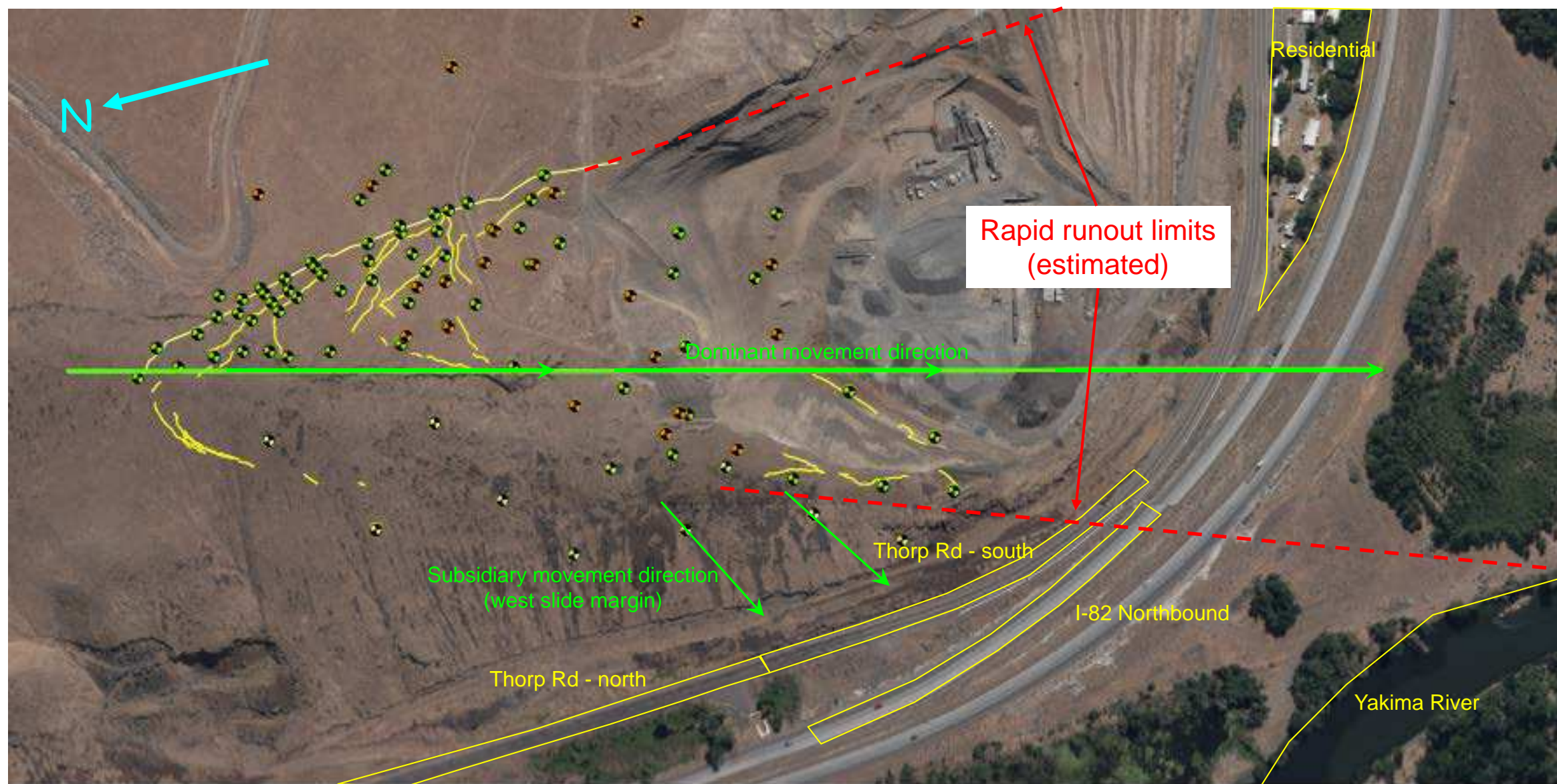
1. All graphs from Whittall et al. (2016)
2. Estimates are highly uncertain - see Disclaimer Section 7.1.

Figure 15

**Empirical Runout Analyses**

Rattlesnake Ridge Landslide Evaluation





Location	Hazard Description	Probability	Mitigation Options
Thorp Rd - south	Rockfalls, small scale failures	Very probable	Closure
Thorp Rd - north	Rockfalls, small scale failures	Possible	Closure
I-82 Northbound	Rockfalls, small scale failures	Improbable	Barriers, monitoring
I-82 North and Southbound, Residential area, Yakima River	Runout from large-scale failure within estimated limits shown	<b>Very improbable</b>	Residential evacuation until slide stabilizes (possible multi-year) or abandonment, long-term slope monitoring, contingency planning

**Figure 16**  
**Risk to Infrastructure**

# **Appendix A**

## **Decision Tree Assessment of the Post-Failure Velocity for the Rattlesnake Ridge Landslide**

(After Glastonbury and Fell, 2008)

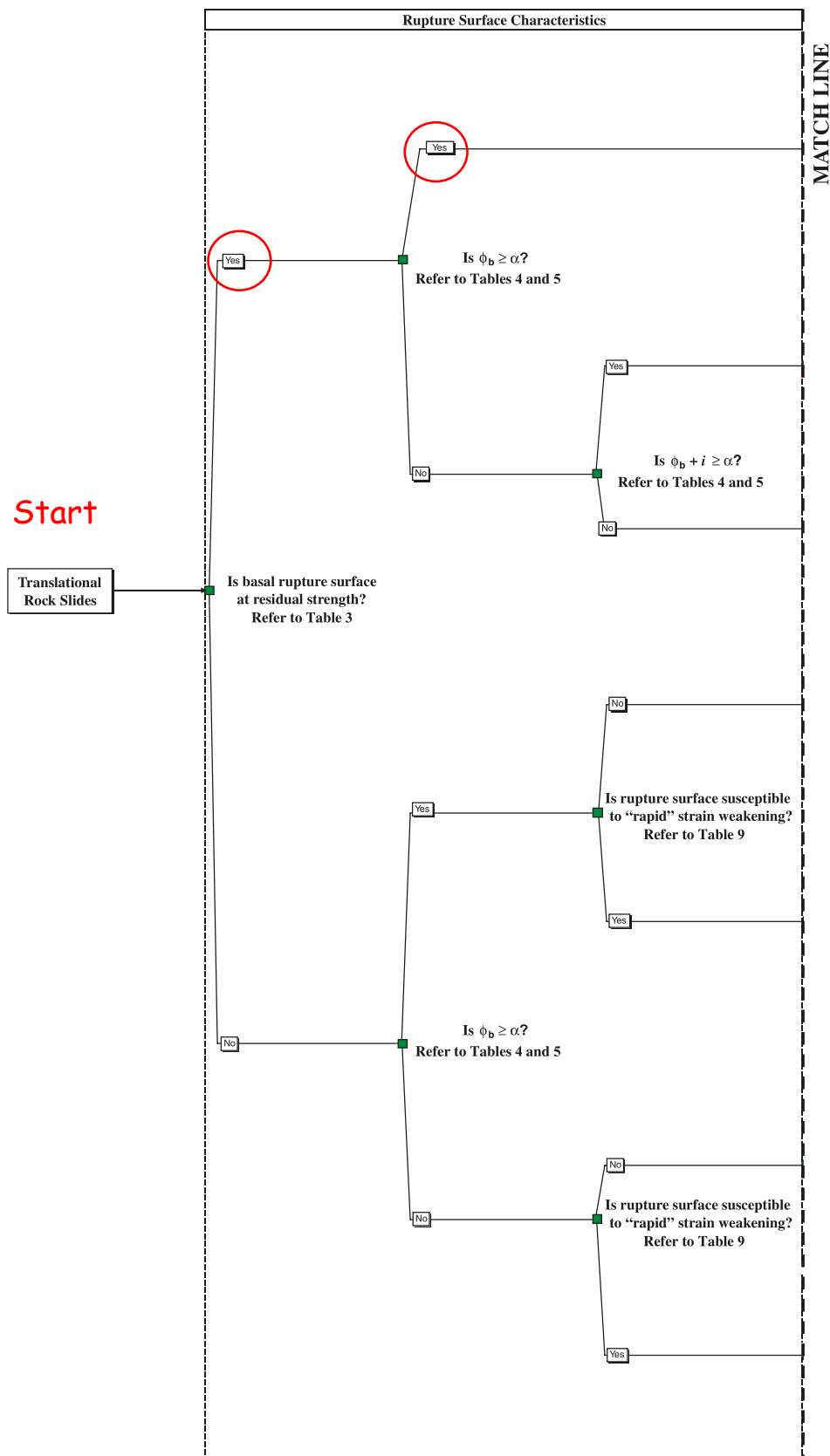
**Fig. 4.** Decision tree for assessment of the post-failure velocity of translational slides from natural rock slopes.

Fig. 4 (concluded).

MATCH LINE	Lateral Restraint and Toe Buttrressing	Triggering and Stress Conditions	Conditional Probability of Velocity Class	Path
<div><div>No</div><div>Yes</div></div>	Are lateral or toe buttress restraints present? Refer to Table 6	<div>No</div> <div>Is rapid and sustained external loading possible? Refer to Fig. 7, Path C</div>	EXT SLOW - SLOW = 95% MODERATE = 5% RAPID = 0% VERY RAPID - EXT RAPID = 0%	A
		<div>Yes</div>	EXT SLOW - SLOW = 70% MODERATE = 20% RAPID = 5% VERY RAPID - EXT RAPID = 5%	B
		<div>No</div>	EXT SLOW - SLOW = 85% MODERATE = 10% RAPID = 5% VERY RAPID - EXT RAPID = 0%	C
		<div>Yes</div>	EXT SLOW - SLOW = 50% MODERATE = 30% RAPID = 15% VERY RAPID - EXT RAPID = 5%	D
<div><div>No</div><div>Yes</div></div>	Are lateral or toe buttress restraints present? Refer to Table 6	<div>No</div> <div>Is rapid and sustained external loading possible? Refer to Fig. 7, Path C</div>	EXT SLOW - SLOW = 95% MODERATE = 5% RAPID = 0% VERY RAPID - EXT RAPID = 0%	E
		<div>Yes</div>	EXT SLOW - SLOW = 70% MODERATE = 20% RAPID = 5% VERY RAPID - EXT RAPID = 5%	F
		<div>No</div>	EXT SLOW - SLOW = 85% MODERATE = 10% RAPID = 5% VERY RAPID - EXT RAPID = 0%	G
		<div>Yes</div>	EXT SLOW - SLOW = 50% MODERATE = 30% RAPID = 15% VERY RAPID - EXT RAPID = 5%	H
<div><div>No</div><div>Yes</div></div>	Are lateral or toe buttress restraints present? Refer to Table 6	<div>No</div> <div>Is rapid and sustained external loading possible? Refer to Fig. 7, Path C</div>	EXT SLOW - SLOW = 10% MODERATE = 15% RAPID = 35% VERY RAPID - EXT RAPID = 40%	I
		<div>Yes</div>	EXT SLOW - SLOW = 0% MODERATE = 5% RAPID = 30% VERY RAPID - EXT RAPID = 65%	J
		<div>No</div>	EXT SLOW - SLOW = 60% MODERATE = 25% RAPID = 10% VERY RAPID - EXT RAPID = 5%	K
		<div>Yes</div>	EXT SLOW - SLOW = 45% MODERATE = 25% RAPID = 20% VERY RAPID - EXT RAPID = 10%	L
<div><div>No</div><div>Yes</div></div>	Are lateral or toe buttress restraints present? Refer to Table 6	<div>No</div> <div>Is rapid and sustained external loading possible? Refer to Fig. 7, Path C</div>	EXT SLOW - SLOW = 35% MODERATE = 35% RAPID = 25% VERY RAPID - EXT RAPID = 5%	M
		<div>Yes</div>	EXT SLOW - SLOW = 15% MODERATE = 25% RAPID = 40% VERY RAPID - EXT RAPID = 20%	N
		<div>No</div>	EXT SLOW - SLOW = 30% MODERATE = 25% RAPID = 25% VERY RAPID - EXT RAPID = 20%	O
		<div>Yes</div>	EXT SLOW - SLOW = 10% MODERATE = 20% RAPID = 30% VERY RAPID - EXT RAPID = 40%	P
<div><div>No</div><div>Yes</div></div>	Are lateral or toe buttress restraints present? Refer to Table 6	<div>No</div> <div>Is rapid and sustained external loading possible? Refer to Fig. 7, Path C</div>	EXT SLOW - SLOW = 20% MODERATE = 25% RAPID = 25% VERY RAPID - EXT RAPID = 30%	Q
		<div>Yes</div>	EXT SLOW - SLOW = 15% MODERATE = 20% RAPID = 20% VERY RAPID - EXT RAPID = 45%	R
		<div>No</div>	EXT SLOW - SLOW = 20% MODERATE = 25% RAPID = 35% VERY RAPID - EXT RAPID = 20%	S
		<div>Yes</div>	EXT SLOW - SLOW = 10% MODERATE = 30% RAPID = 25% VERY RAPID - EXT RAPID = 35%	T
<div><div>No</div><div>Yes</div></div>	Are lateral or toe buttress restraints present? Refer to Table 6	<div>No</div> <div>Is rapid and sustained external loading possible? Refer to Fig. 7, Path C</div>	EXT SLOW - SLOW = 15% MODERATE = 25% RAPID = 30% VERY RAPID - EXT RAPID = 30%	U
		<div>Yes</div>	EXT SLOW - SLOW = 10% MODERATE = 20% RAPID = 30% VERY RAPID - EXT RAPID = 40%	V
		<div>No</div>	EXT SLOW - SLOW = 5% MODERATE = 10% RAPID = 15% VERY RAPID - EXT RAPID = 70%	W
		<div>Yes</div>	EXT SLOW - SLOW = 0% MODERATE = 5% RAPID = 15% VERY RAPID - EXT RAPID = 80%	X
<div><div>No</div><div>Yes</div></div>	Are lateral or toe buttress restraints present? Refer to Table 6	<div>No</div> <div>Is rapid and sustained external loading possible? Refer to Fig. 7, Path C</div>	EXT SLOW - SLOW = 5% MODERATE = 10% RAPID = 10% VERY RAPID - EXT RAPID = 75%	Y
		<div>Yes</div>	EXT SLOW - SLOW = 0% MODERATE = 5% RAPID = 10% VERY RAPID - EXT RAPID = 85%	Z

GPS Hubs :

#22: 11.36 ft 10/4/2017 to 1/10/2018

#30: 11.01 ft 10/4/2017 to 1/10/2018

Reasonable to assume that with inclusion of pre-monitoring displacement, total displacement = 12 feet.

Length of slide plane = 1400 ft.

Composite strain =  $12/1400 = 0.9\%$

$$\text{Level of confidence} = \frac{1.0 \cdot 0.9 + 0.5 \cdot 0.8 + 0.5 \cdot 0.8 + 0.33 \cdot 0.75}{1.0 + 0.5 + 0.5 + 0.33} = 84\%$$

**Table 3.** Translational slides: Is basal rupture surface at residual strength?

Weighting <sup>b</sup>	Indicator	Level of confidence in yes answer <sup>a</sup>				
		Very likely (0.85–0.90) <sup>c</sup>	Likely (0.75–0.80)	Even chance (0.45–0.55)	Unlikely (0.20–0.25)	Very unlikely (0.10–0.15)
1	Geomorphologic evidence	Distinct geomorphologic features showing movement of complete slide mass >1% strain <sup>d</sup>		Minor geomorphologic evidence of localized movement less than 0.5% strain		No geomorphologic evidence of any movement
1	Subsurface displacement monitoring not available	Movement on distinct shear surface across complete slide mass in excess of 500 mm		Movement on shear surface in localized parts of slide less than 500 mm		No measured subsurface displacement
0.5	Laboratory testing not available	Residual strength on multiple samples across rupture surface		Variable strengths on samples across the rupture surface		Peak strength on multiple samples across rupture surface
0.5	Visual observations of rupture surface	Multiple exposures of slickensided rupture surface	0.8	Limited rupture surface exposures showing variable characteristics		Multiple exposures of nonsheared rupture surface
0.5	Subsurface investigation not available	Multiple intersections of distinct sheared rupture surface		Intersections of rupture surface showing variable characteristics		Intersections showing rough rupture surface texture
0.5	Surface monitoring	Movement measured across complete slide mass >1% strain	0.8	Localized movements measured at less than 0.5% strain		Monitoring shows no surface movement
0.33	Geological evidence	Extensive folding and faulting parallel to rupture surface	0.75	Some folding or faulting – not parallel to rupture surface		No evidence or geological history of folding or faulting

<sup>a</sup>Probability of overall yes answer to be calculated according to eq. [1] and judgement.

<sup>b</sup>Weighting factor of 1 represents higher quality indicator, 0.33 equals lower quality indicator.

<sup>c</sup>Range of probabilities for each indicator. Interpolate between values as appropriate.

<sup>d</sup>Strain defined as displacement normalized against down slope length from slide head to toe.



**Table 4.** Translational slides: rupture surface friction angle versus inclination – data assessment rating (1 represents high quality data, 5 represents low quality data).

Data for assessment of $\phi_b$ and $i^a$		Data for assessment of $\alpha^b$				
Assessment of $i$	Assessment of $\phi_b$	Extensive surface and subsurface investigation	Complete surface exposure visible	Moderate subsurface investigation	Limited surface exposure visible and limited subsurface investigation	Single localized surface exposure
Detailed field mapping of rupture surface	Extensive sampling and lab testing using various methods	1	1	2	2	3
Moderate level of field mapping – rupture surface and other discontinuities	Moderate sampling and testing	1	2	2	3	4
Back-analysis of shear strength at onset of movement	Low level sampling and testing	2	2	3	3	4
Preliminary field mapping – mostly mapping of discontinuities other than rupture surface	Visual observations of rupture surface, assessment based on published results of tests on similar materials	3	3	4	4	5
Estimate based on similar failures in similar geology	No observations of rupture surface, assessment based on published results of tests on similar materials	3	4	4	5	5

<sup>a</sup> $\phi_b$ , basic friction angle on basal rupture surface (assumed equal to laboratory measured residual friction angle);  $i$ , relevant field scale dilation angle (refer to McMahon 1985 for guidance).  
<sup>b</sup> $\alpha$ , inclination of basal rupture surface.

**Table 5.** Translational slides: rupture surface friction angle versus inclination – probability assessment.

$(\phi_b + i)$ vs. $\alpha$	$\phi_b$ vs. $\alpha$	Data assessment rating (from Table 10) <sup>a</sup>				
		1	2	3	4	5
$\Delta > 20^\circ$ <sup>b</sup>	$\Delta > 15^\circ$	0.98	0.90	0.80	0.75	0.70
$\Delta = 8^\circ - 20^\circ$	$\Delta = 5^\circ - 15^\circ$	0.95	0.85	0.75	0.70	0.65
$\Delta = 3^\circ - 8^\circ$	$\Delta = 2^\circ - 5^\circ$	0.85	0.80	0.70	0.65	0.55
$\Delta < 3^\circ$	$\Delta < 2^\circ$	0.80	0.75	0.65	0.60	0.50

**Note:** This table answers both the questions  $\phi_b \geq \alpha$  and  $(\phi_b + i) \geq \alpha$  (answer whichever question is relevant to the decision tree path).

<sup>a</sup>Data quality (i.e., data assessment rating) is considered against the magnitude of the difference between friction angle and inclination.

<sup>b</sup> $\Delta$  is the difference between friction angle and inclination.

- Translational rock debris slides exhibited a long history of slow movement as evidenced by long-term monitoring and geomorphologic characteristics. However, one translational rock debris slide reached a velocity in the rapid range, but this was only for a short period. There is some likelihood that the rupture surface on this slide was not at residual strength.
- Mudslides have characteristics that result in probabilities for each of the questions along Path B in the very likely range (0.85–0.90). These landslides have similar characteristics to the translational rock debris slides except that they are more susceptible to rapid and sustained external loading (due to their low permeability). These cases exhibited maximum post-failure velocities predominantly in the extremely slow to slow range. However, 5 of the 14 cases (35%) reached maximum velocities in the moderate range or lower end of the rapid range.
- Slow translational rock slides and block type slope movements were also observed to have characteristics that tend to follow Paths A and B.
- Characteristics of the large rock glides are such that they likely follow Paths I and J. Although no monitoring of these slides took place prior to collapse, they were all observed to have exhibited post-failure velocities in the rapid to extremely rapid range. Based on the observed characteristics of the large rock glides (including very low rupture surface inclination) it is expected that these slides may have a reduced likelihood of velocities in the very rapid to extremely rapid range when compared to other classes of translational slides.
- The characteristics rough translational slides are such that they have high probabilities assigned to Paths W, X, Y, and Z. The mechanics of these slides, including peak strength and steep inclined rupture surfaces, are such that there is little conceivable likelihood of post-failure velocities less than rapid.
- Planar translational slides were observed to have characteristics largely split between Paths I, J, U, and V. Some had residual strength basal rupture surfaces while others did not. Although no instrumented monitoring of these slides took place prior to collapse, they were all observed to have exhibited post-failure velocities in the rapid to extremely rapid range. Based on the observed characteristics of this class (including some cases with residual strength rupture surfaces and others with argillaceous infill) it is



$$\text{Level of confidence} = \frac{1.0 \times 0.55 + 0.33 \times 0.75 + 1.0 \times 0.25 + 0.5 \times 0.55 + 0.5 \times 0.75 + 0.33 \times 0.5}{1.0 + 0.33 + 1.0 + 0.5 + 0.5 + 0.33}$$

$$= 43\%$$

**Table 6.** Translational slides: Are lateral or toe buttress restraints present?

		Level of confidence in yes answer <sup>a</sup>				
Indicator	Weighting <sup>b</sup>	Very likely (0.85–0.90) <sup>c</sup>	Likely (0.75–0.80)	Even chance (0.45–0.55)	Unlikely (0.20–0.25)	Very unlikely (0.10–0.15)
<b>Lateral margins</b>						
Geological – geomorphic evidence	1	Rough, irregular surfaces on lateral margins plus high in situ stresses (judgement or field measurement)		Continuous structures of unknown characteristics defining lateral margins 0.55	Presheared planar structures forming lateral margins in low stress environment	
Deformation behaviour	0.33	Consistent vector magnitude and direction across complete slide mass	0.75	Spatial variation in deformation behaviour not known	Variable magnitude and direction of vectors adjacent to lateral margins	
Slide mass characteristics	0.5	Intact slide mass (Typ. RQD > 75%)	Typical core RQD = 50%–75%		Disaggregated slide mass (Typ. RQD < 50%)	
not available	0.33	Very thick slide mass or very long slide mass bound on both sides	Thin or short slide mass		No material adjacent to slide mass on either margin or highly disaggregated slide mass	
<b>Toe buttress</b>						
Slide geometry	1	Nondaylighting basal rupture surface across complete slide width		Location of basal rupture surface is uncertain	0.25	Basal rupture surface exposed at toe of slide across complete slide width
Geological – geomorphic evidence	0.5	Change in rock mass structure at toe with nondaylighting defects		Variation in rock mass structure across slide mass is unknown 0.55	No change in rock mass structure across complete slide mass	
Deformation behaviour	0.5	Bulging at toe with no break-out – reduced movement at toe of slide	0.75	Spatial variation in deformation behaviour not known	Consistent vector magnitude and direction across complete slide mass	
Rock mass strength	0.33	High strength brittle rock mass at toe – structure normal to shearing direction		Highly disaggregated, low strength rock mass at toe 0.50	No rock mass at toe of slide	

**Note:** RQD, rock quality designation.

<sup>a</sup>Probability of overall yes answer to be calculated according to eq. [1] and judgement.

<sup>b</sup>Weighting factor of 1 represents higher quality indicator, 0.33 equals lower quality indicator.

<sup>c</sup>Range of probabilities for each indicator. Interpolate between values as appropriate.