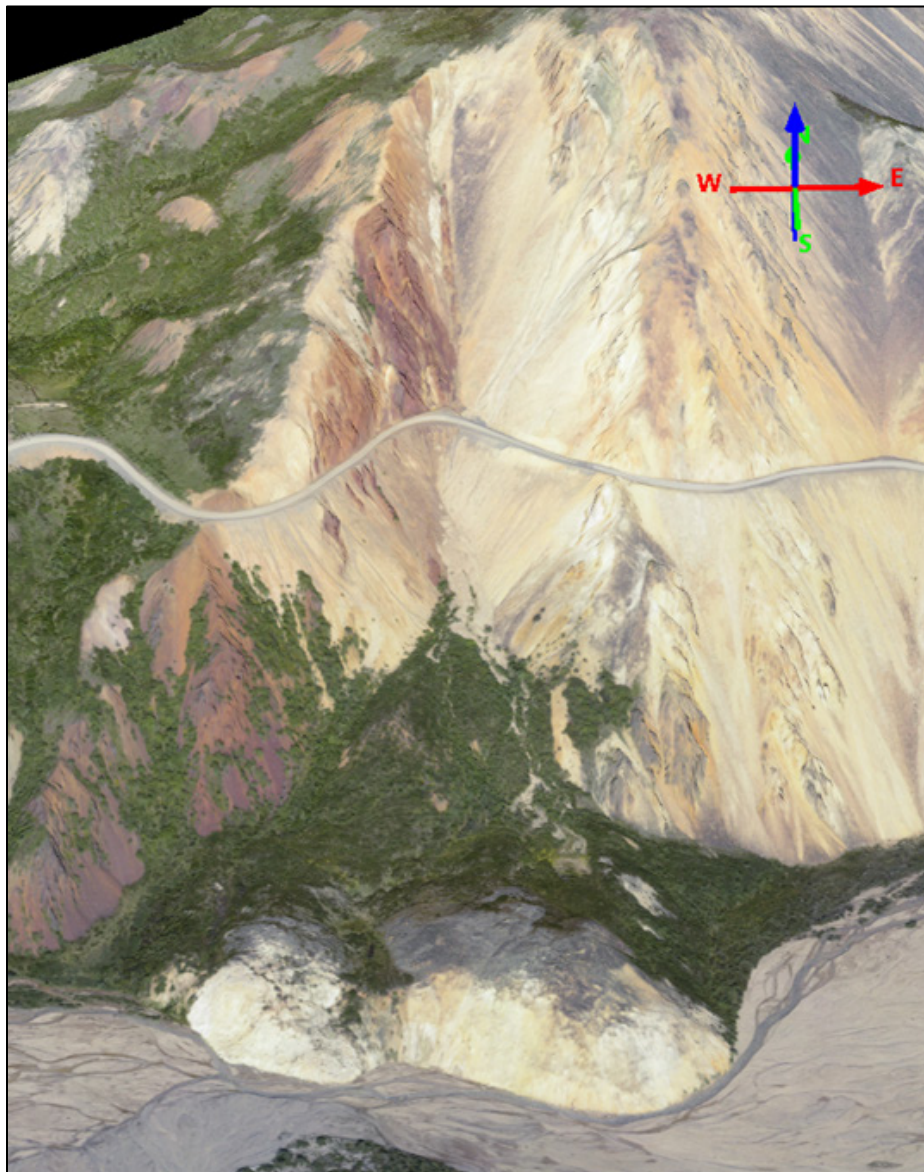




A Geotechnical Investigation of Pretty Rocks Landslide, Mile 45.4, Denali Park Road, Denali National Park, Alaska

Natural Resource Report NPS/DENA/NRR—2022/2365



ON THE COVER

Aerial View of the Pretty Rocks Landslide Area,
NPS Photo

A Geotechnical Investigation of Pretty Rocks Landslide, Mile 45.4, Denali Park Road, Denali National Park, Alaska

Natural Resource Report NPS/DENA/NRR—2022/2365

Anna Stanczyk,^{1,2} Denny M. Capps,³ Douglas A. Anderson⁴

¹ University of Alaska Anchorage
Anchorage, AK

² Golder Associates Inc.
Redmond, WA

³ Denali National and Preserve
Denali Park, AK 99755

⁴ Federal Highways Administration
Western Federal Lands Highway Division
Vancouver, WA, 98661

March 2022

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible and technically accurate.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from the [Natural Resource Publications Management website](#). If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

Stanczyk, A., D. M. Capps, and D. A. Anderson. 2022. A geotechnical investigation of Pretty Rocks Landslide, mile 45.4, Denali Park Road, Denali National Park, Alaska. Natural Resource Report NPS/DENA/NRR—2022/2365. National Park Service, Fort Collins, Colorado.
<https://doi.org/10.36967/nrr-2288333>.

Contents

	Page
Figures.....	v
Tables.....	vii
Abstract.....	viii
Acknowledgements.....	ix
Introduction.....	1
Project Area: Pretty Rocks	1
Related Debris Slides	6
Geologic Background	7
Methods.....	9
Field Methods.....	9
Lab Methods.....	9
Data and Observations	10
The Pretty Rocks Colluvium Slope	10
Mass Movement	13
Primary Failure.....	13
Secondary Failure.....	19
Unnamed Debris Slide East of Pretty Rocks.....	22
The Tri-Lobed Landslide Deposits.....	24
Surface Water: Drainage and Presence	25
Material Laboratory Test Results	27
Bore Logs	30
Interpretations	32
Modified Varnes Classification.....	32
Landslide Mass's Surficial Extent.....	32
The Failure Surface Geometry	33
Lateral variations in landslide mass characteristics.....	35

Contents (continued)

	Page
Creep Rate along the Road Corridor	35
Failure Mechanisms.....	36
Relatives Ages and Origins of Tri-Lobed Landslide Deposits.....	36
Discussion	38
Limitations of this Study	38
Further Work	38
Conclusions.....	40
Literature Cited	42
Appendix – Rock Descriptions	45

Figures

	Page
Figure 1. Location map of Denali National Park and Preserve, Alaska, USA.....	2
Figure 2. Installing geosynthetic layer reinforcement along the road surface which cross cuts the landslide.....	4
Figure 3. Vertical offset along northwestern lateral scarp (i.e., road crack) in April 2004.	5
Figure 4. Geologic map of the Polychrome Pass area modified from USGS Scientific Investigations Map 3340 (Wilson et al., 2015) and Gilbert and Redman, (1975).	7
Figure 5. Pretty Rocks colluvium slope.	10
Figure 6A. Location of slope profile, sediment sample locations, and drilling bore logs.	11
Figure 6B. A–A’ profile of slope shown in Figure 6A.	12
Figure 7. Elevation change map created by subtracting June 2015 SfM imagery from June 2016 SfM imagery.	14
Figure 8. Convex morphology downslope of the road.....	15
Figure 9. Geologic map of project area, including geomorphic features.	16
Figure 10. Southeastern, en echelon road cracks.	17
Figure 11. Lineations visible in a scarp upslope of the southeastern road crack.	18
Figure 12. Known landslide event dates compared to summer 2015 and summer 2016 temperature and precipitation data.	20
Figure 13. Debris flow paths and deposits seen looking northeast.	21
Figure 14. Surface water drainage observed in July 2016.	23
Figure 15. Predominantly rhyolitic lobes at the base of the Pretty Rocks slope.....	24
Figure 16. Pretty Rocks Landslide and associated lobe deposits seen from the East Fork Toklat River tributary.	25
Figure 17. View looking down at the lobes from the road (facing southeast).	26
Figure 18. Plasticity Chart from the USCS.....	29
Figure 19. Stratigraphic columns constructed from PLY03-1 and PLY03-2 boring logs.	31
Figure 20. Northwestern boundary of failure area which divides the homogenous upper talus from the dissected slope below, and patches of slope which lack cobble- to boulder-sized clasts.	33

Figures (continued)

	Page
Figure 21. Idealized failure surface geometry.....	34

Tables

	Page
Table 1. Sample results: sieve analysis, Atterberg limits, moisture content, organic content, and Unified Soil Classification System (USCS) classifications.	28

Abstract

As of 2016, the Pretty Rocks Landslide causes approximately 0.8 m of annual subsidence across a 90-m-long section of the Denali National Park Road. The dead-end road is the only access into the park and is a regionally important economic engine. Because of these reasons, combined with its location near the road's midpoint, the landslide is currently the highest rated unstable slope among 141 sites along the road according to the Unstable Slope Management Program for Federal Land Management Agencies.

The landslide's morphology and composition inform us about both its history and likely future. The surrounding bedrock comprises altered, highly fractured rhyolite and basalt. Two unconsolidated sediment lobes below the road are primarily rhyolitic and a third is basaltic. These are likely deposits from previous mass movement events. Surface and subsurface data demonstrate that clays are pervasive throughout the slope. These clays are weathered tuffs and Atterberg Limit tests show that they are highly plastic and have potential for shrinking and swelling. Bore logs and geophysical surveys indicate that ice-rich permafrost is present below the road surface in these clays and other coarser sediments. Because the permafrost is very near 0° Celsius, it is likely thawing, which would be consistent with regional trends. As a further complication, uncontrolled water drains both internally and externally down the steep slope.

The landslide's persistent creep-style movement is likely due to the steep topography, weak underlying clay, thawing ice-rich permafrost, and poor drainage. We classify this unstable slope as a soil slope deformation based on Hungr et al.'s modified Varnes classification system. This study compiles previous geotechnical data and provides new insight on failure history and mechanisms to support hazard and risk assessment, and potential risk reduction strategies by the National Park Service with technical assistance provided by the Federal Highway Administration.

Acknowledgements

This study would not have been possible without the support of Dr. Kristine Crossen (University of Alaska Anchorage), Craig Boeckman (Alaska Department of Transportation and Public Facilities [DOT]), Chris Schuler (University of Alaska Anchorage), Chris Bruns (DOT), Joel Cusick (National Park Service [NPS]), Brian Collins (former FHWA staff) and the NPS teams in the Anchorage Regional Office and in Denali. Funding was provided by the University of Alaska Anchorage's Office of Undergraduate Research, the Alaska Geological Society, and the Geophysical Society of Alaska. Samples were graciously processed by the DOT.

Introduction

This report is based on fieldwork conducted in 2016 and lab work and analysis through the spring of 2017. Therefore, it represents our knowledge of the topic at that time.

Project Area: Pretty Rocks

Pretty Rocks is a persistent slope failure occurring at mile 45.4, 750 m east of Polychrome Overlook on the Denali National Park Road (hereafter simply “road”). The park has a culture of referencing road distance in mileage, so that will be maintained here for the benefit of park managers and others. However, we will list all other measurements in metric units. Pretty Rocks is located near the midpoint of the park’s single dead-end road, which continues to mile 92 in the Kantishna Hills and provides access for park visitors, staff and inholdings (Figure 1). The landslide has experienced gradual, episodic and creep-style failure for approximately 50 years, though the movement rate has increased substantially in the last five years. This slope failure poses a major threat to the park’s infrastructure and access. The failure surface underlies the road on a steep colluvium slope where rerouting would be physically challenging and would require Congress’s approval due to the adjacent land’s status as federally designated wilderness. Because of these reasons, combined with its location near the road’s midpoint, the landslide is currently the highest rated unstable slope among 141 sites along the road according to the Unstable Slope Management Program for Federal Land Management Agencies (FHWA, 2019).

The purpose of this report is to compile geologic and geotechnical data collected prior to 2016, present new data collected in 2016, and make inferences about the landslide’s history and future. Existing data includes digital elevation models (DEMs), bore logs, and a five-decade history of anecdotal observations supported by several past photographs. We collected new data on geomorphological features, surface water drainage, and Pretty Rocks’ geologic setting in July 2016. We then used all available data to make inferences regarding past failures, potential failure mechanisms, the landslide’s surficial extent, the likely failure plane geometry, and the potential for future landslide activity.

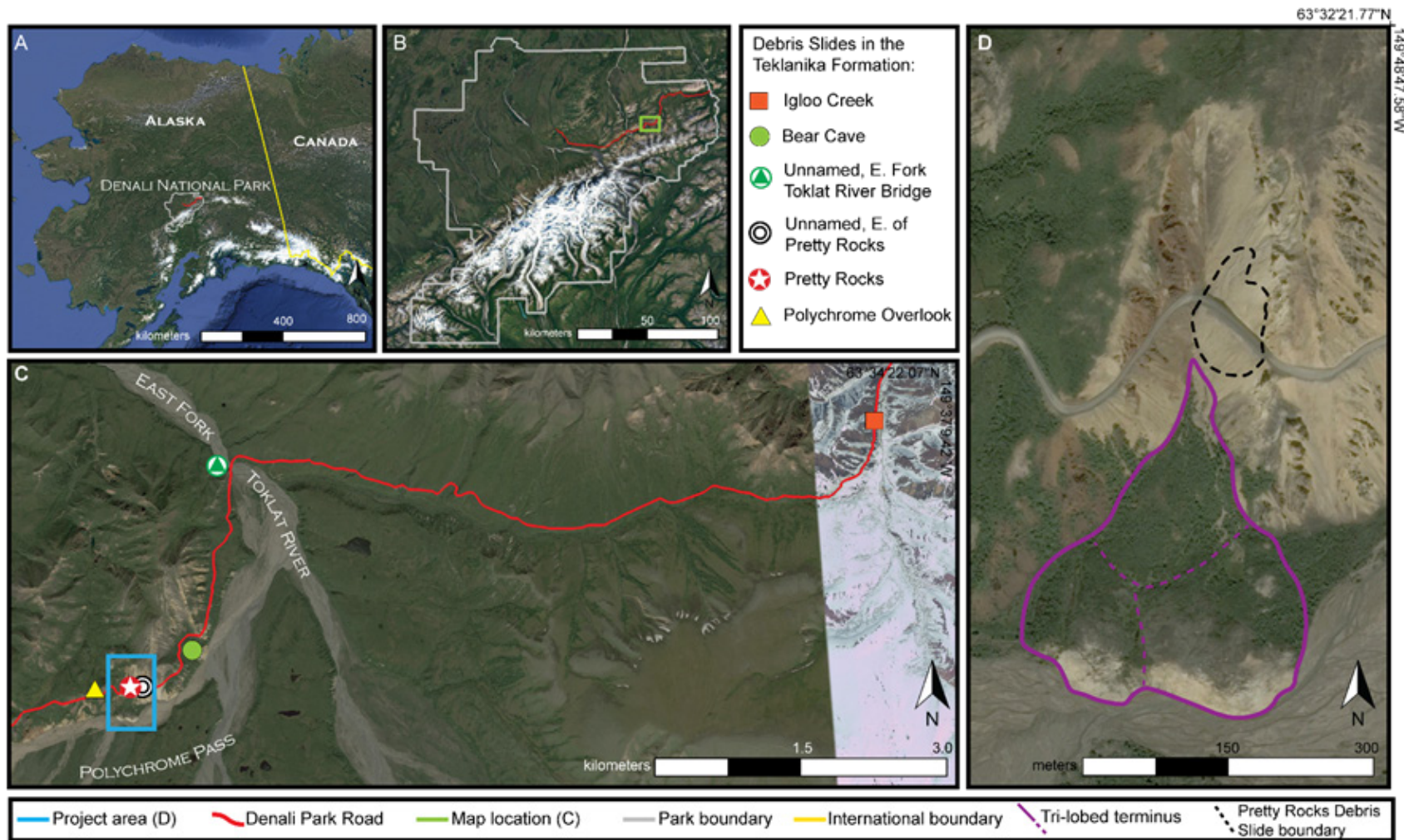


Figure 1. (A) Location map of Denali National Park and Preserve, Alaska, USA. (B) Denali National Park road and map C outline. (C) Section of road indicating debris slides that have occurred or are occurring within the Teklanika Formation. Note that four of the six debris slides are occurring near one another within the Polychrome Pass area. (D) Project area including hypothesized Pretty Rocks boundary and the tri-lobed deposits at the base of the slope. Landsat/Copernicus and DigitalGlobe imagery.

Denali National Park (DENA) with technical assistance from the Federal Highway Administration (FHWA) have performed a limited range of risk reduction efforts at Pretty Rocks. In 1987, road maintenance staff installed geotextile and rock-filled gabions to reduce road deformation from the landslide and to contain the uphill rockfall hazard (Figure 2); each was quickly consumed by the landslide following implementation. DENA maintenance staff also installed a shallow subsurface “French” drain along the upslope ditch line in the 1980s to capture and direct water from the upper landslide (Figure 2). Due to the continued landslide movement, the French drain also quickly failed with submergence into the landslide body. Road fill material has been placed across the landslide numerous times to maintain a safe road grade. For example, approximately 500 m³ of fill material was placed in 2014 to bring the sagging roadway back to a safer, drivable grade. Staff noticed an apparent increase in the landslide’s displacement magnitude immediately afterwards and assumed that the additional movement may be due to the loading effects of the new road fill. Since then, maintenance staff has installed the minimum amount of fill necessary to maintain a safe driving surface into the landslide body over the lateral landslide scarps. This is particularly problematic during spring road clearing because the failure exhibits significant downhill motion over the winter months, which consistently increases in magnitude each year (Figure 3). Because of the multiple challenges associated with Pretty Rocks (drainage, movement rate, rockfall and debris flow hazard from above the road, permafrost within the landslide debris materials, adjacent wilderness, seasonally busy and dead-end road, steep topography, high plasticity clay with a potential for shrink and swell, protected iconic views, etc.), staff have not yet implemented other risk reduction strategies. Otherwise, as with most landslide management, DENA would have installed drainage to limit pore pressure, a larger ditch to act as a catchment for rockfall and debris flows, and engineered structures to arrest displacement. Prior to this contribution DENA and FHWA staff have produced no formal scientific publications regarding Pretty Rocks, only informal communications.



Figure 2. (TOP) Installing geosynthetic layer reinforcement along the road surface which cross cuts the landslide. Photo taken 1987. (BOTTOM) Installing a French drain near the northwestern lateral scarp (i.e. road crack) location. Photo taken 1987.



Figure 3. (TOP) Vertical offset along northwestern lateral scarp (i.e., road crack) in April 2004. (BOTTOM) Vertical offset along southeastern lateral scarp (i.e., road crack) in March 2018.

Related Debris Slides

In addition to its direct impact on the road, Pretty Rocks is significant because it is one of six known debris slides that are along the road corridor within the same volcanic Teklanika Formation (Figure 1C). These other landslides include, from east to west, the Igloo Creek Debris Slide (mile 37.7), an unnamed slide north of the East Fork Toklat River bridge (mile 43.1), Bear Cave Debris Slide (mile 44.9), Perlite Debris Slide immediately east of Pretty Rocks (mile 45.4), and the Polychrome Overlook Debris Slide (mile 45.8). The $\sim 25,000 \text{ m}^3$ Igloo Creek Debris Slide occurred in October 2013 and likely was caused by the steep topography, presence of highly plastic fat clay, groundwater seepage, and permafrost thaw (Capps et al., 2017). The failure surface was exposed following the landslide and found to be a clay layer derived from Teklanika rhyolitic tuffs. Second, the unnamed slide north of the East Fork Toklat River bridge has undergone minimal investigation but appears to be a clay flow-slide in a weathered Teklanika unit. The failure is relatively small, with an estimated deposit volume of $5,000 \text{ m}^3$. Third, the $\sim 400,000 \text{ m}^3$ Bear Cave Debris Slide has been experiencing slow, downhill movement since 1991. Regular monitoring began in 1993. In 1999, a French drain was installed in the uphill road ditch to capture and reroute surface water away from the landslide body which slowed its movement substantially (Capps et al., 2017). Next, the Perlite Debris Slide $<40 \text{ m}$ east of Pretty Rocks occurs in a bed of perlite, obsidian, and other rhyolitic rock. Beginning in 2015, several minor slides and flows and one larger flow ($\sim 200 \text{ m}^3$) deposited debris on the road at this location. Lastly, a debris slide at Polychrome Overlook took place in 2002 following increased precipitation. The debris slide originated in Teklanika clay, which was removed, and the roadway was infilled with stronger aggregate materials. Shallow, subsurface perforated pipes were also added to capture and divert water away from the area (Capps et al., 2017). In all cases, movement appears correlated with clay layers produced by alteration of Teklanika rhyolitic tuffs. This investigation of Pretty Rocks hopes to contribute additional understanding of landslides in the Teklanika Formation—both current and future.

Geologic Background

The Pretty Rocks area is located in the Central Alaska Range and is located within the Mesozoic (251.9–66.0 million years ago) McKinley Terrane. This terrane is bounded on the south by the Denali Fault and on the north by the Hines Creek Fault. It is composed primarily of Mesozoic sedimentary rocks and Pennsylvanian–Triassic (323.2–201.3 Ma) volcanic rocks (Trop and Ridgway, 1997). Later formations overlie the accreted terrane, including the late Cretaceous sedimentary Cantwell Formation (71 Ma) (Tomsich et al., 2011), the Tertiary volcanic Teklanika Formation (56–60 Ma) (Cole et al., 1999), the poorly consolidated Tertiary Nenana Gravel (5.4–2.9 Ma) (Ager et al., 1994) and others (Figure 4).

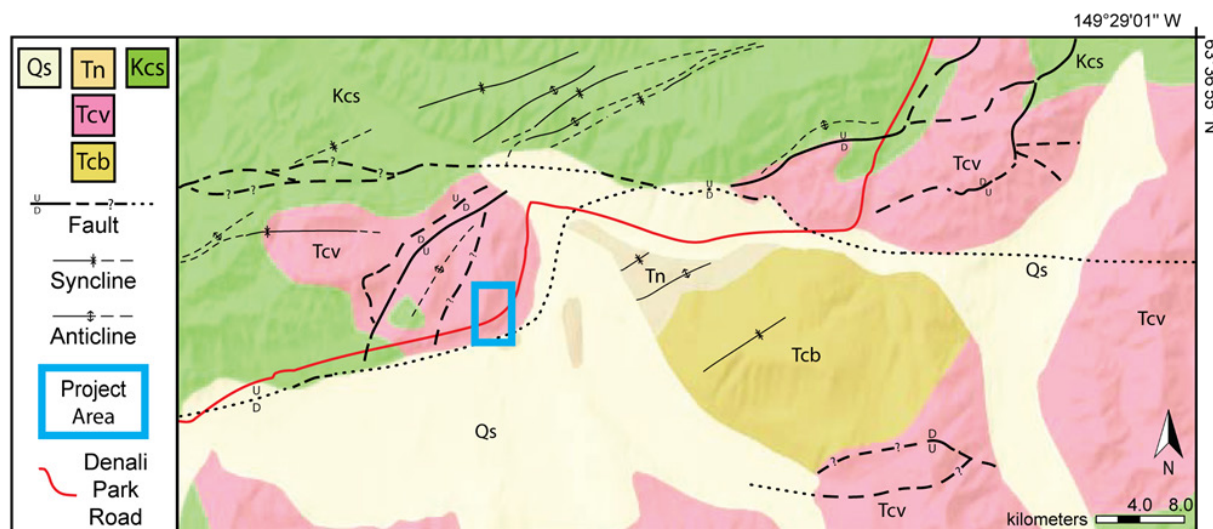


Figure 4. Geologic map of the Polychrome Pass area modified from USGS Scientific Investigations Map 3340 (Wilson et al., 2015) and Gilbert and Redman, (1975). Qs: Quaternary surficial deposits, undifferentiated. Tn: Tertiary Nenana Gravel; conglomerate and sandstone with mudstone, claystone, and lignite interbeds. Well-sorted but poorly consolidated. Appears yellowish to brownish in outcrop. Tcv: Tertiary Volcanic Rocks of the Teklanika Formation; deformed sequences of andesite, altered basalt, rhyolite and interlayered dacite flows, felsic pyroclastic rocks, and minor sandstone and mudstone. Some calcareous rocks present locally. Tcb: Tertiary coal-bearing rocks; contains cyclic sequences of siltstone, claystone, mudstone, shale, sandstone, subbituminous coal and lignite, quartz, and pebble conglomerates. Kcs: Cretaceous Cantwell Formation, Sedimentary Rocks Subunit; interlayered sequence of polymictic conglomerate, sandstone, arkosic sandstone, siltstone, argillite, and shale, and a few thin coal beds. Fault: Dashed where approximate, queried where probable, dotted where covered, U = upthrown side, D = downthrown side. Syncline and anticline: showing trace of axial surface, dashed where approximate.

Pretty Rocks is occurring in the Teklanika Formation (the Teklanika). Here, the Teklanika is folded in a northeast-southwest trending syncline, with the landslide occurring in the overturned southeastern limb (Gilbert and Redman, 1975). Previously known as the Upper Cantwell Formation, the Teklanika was redefined by Gilbert et al. (1976). The formation covers 165 square kilometers and is up to 3750-m thick. It primarily includes moderately deformed andesite and rhyolite with altered

basalts and pyroclastic flows. Teklanika dikes and other intrusive features are observed cutting through the underlying Cantwell Formation in several outcrops (Gilbert et al., 1976). In the project area, Gilbert et al. (1976) defines a geologic contact between Teklanika rhyolite flows and pyroclastic rocks to the east, and andesite and basalt flows to the west. Pretty Rocks is occurring in a rhyolite-dominated colluvium slope at this geologic contact, with rhyolitic bedrock to the east and basaltic bedrock to the west. Plafker et al. (1963) mapped and described a colluvium-covered perlite deposit in the rhyolite bedrock immediately east of Pretty Rocks. They describe it as “rhyolite, obsidian, and perlite, and yellow bentonitic clay derived from decomposition of obsidian and perlite. The local abundance of the clayey material suggests that either perlite or obsidian or both occur beneath parts of the colluvium.” They noted abundant devitrified glass and hypothesized that serpentine alteration may be responsible for the perlite’s green coloration.

Methods

Field Methods

Our Pretty Rocks investigation included three weeks of field work in July 2016. We compared a range of aerial photography to features presently found on, and adjacent to, the landslide. We used a Trimble Geo7x mapping-grade GPS to map morphological features and utilized the Trimble Pathfinder Office software for post-processing the data to increase accuracy.

We described the surrounding bedrock and characterized its structure. These descriptions included petrology, hardness, weathering, roughness, block size, and block shape. Characterization included structural discontinuities such as joints. We recorded the discontinuity types present as well as their aperture, infilling, spacing, and persistence. Rock structural measurements and observations were based on the Alaska Department of Transportation Alaska Field Rock Classification and Structural Mapping Guide (Alaska Department of Transportation & Public Facilities, 2003). See Appendix for results.

Key soil samples were collected for engineering tests using sample-grade plastic bags that were immediately sealed with zip ties to maintain moisture content. We chose sediment samples based on location within the project area, as well as color, apparent plasticity, and grain size. We targeted fine-grained sediments to test the hypothesis that clays contribute to the failure. Samples should not be considered representative of all sediment at the collection site. These samples were collected with comparison in mind, but clay mineralogy analyses were not included in this study. All samples were destroyed in analysis and therefore not included in NPS or FHWA collections.

Lab Methods

Prior to field work, we analyzed historic aerial photography and meteorological data. Various government agencies collected traditional aerial photography of the area beginning in 1953, continuing sporadically until 1996. Beginning in 2015, a contractor used Structure-from-Motion (SfM) to create orthophotos, digital surface models, and topographic difference maps of the area (Nolan and DesLauriers, 2016) at least once per year. The modern digital aerial photogrammetry products have ground sample distances as fine as 12 cm. We evaluated these products and created slope angle measurements and topographic profiles. Following field work we produced geologic maps, including morphological features, with GPS data using ArcMap 10.4. We plotted precipitation and temperature data from the Toklat Remote Automated Weather Station (RAWS), the nearest weather station to the project area, as well as the Wonder Lake RAWS which is farther from the project area but has a longer period of record. Staff at the Alaska Department of Transportation and Public Facilities (DOT) conducted material testing on some of the collected soil samples. Tests included Atterberg Limits, sieve analysis by percent passing, moisture content, and organic content (utilizing the loss-on-ignition method).

Data and Observations

The Pretty Rocks Colluvium Slope

Pretty Rocks occurs in a rhyolite- dominated colluvium slope whose clasts resemble the rhyolitic bedrock east of the slope. Material from the perlite deposit is also being introduced to the Pretty Rocks slope by colluvial and alluvial processes, as seen from the ground (Figure 5) and in aerial photography. This material includes green clays, obsidian clasts, and perlite or devitrified glass. Overall, the slope is covered by a cobble and boulder veneer which is underlain by gravel-to-fine-grained sediment. Profiles produced from the 2015 digital aerial photogrammetry reveal a 32° slope angle above and below the road (Figure 6).



Figure 5. Pretty Rocks colluvium slope. Note the drainage of dark, perlite-derived material in the slope's center, and the more homogenous, weathered colluvium in the upper left. Photo taken looking northeast.

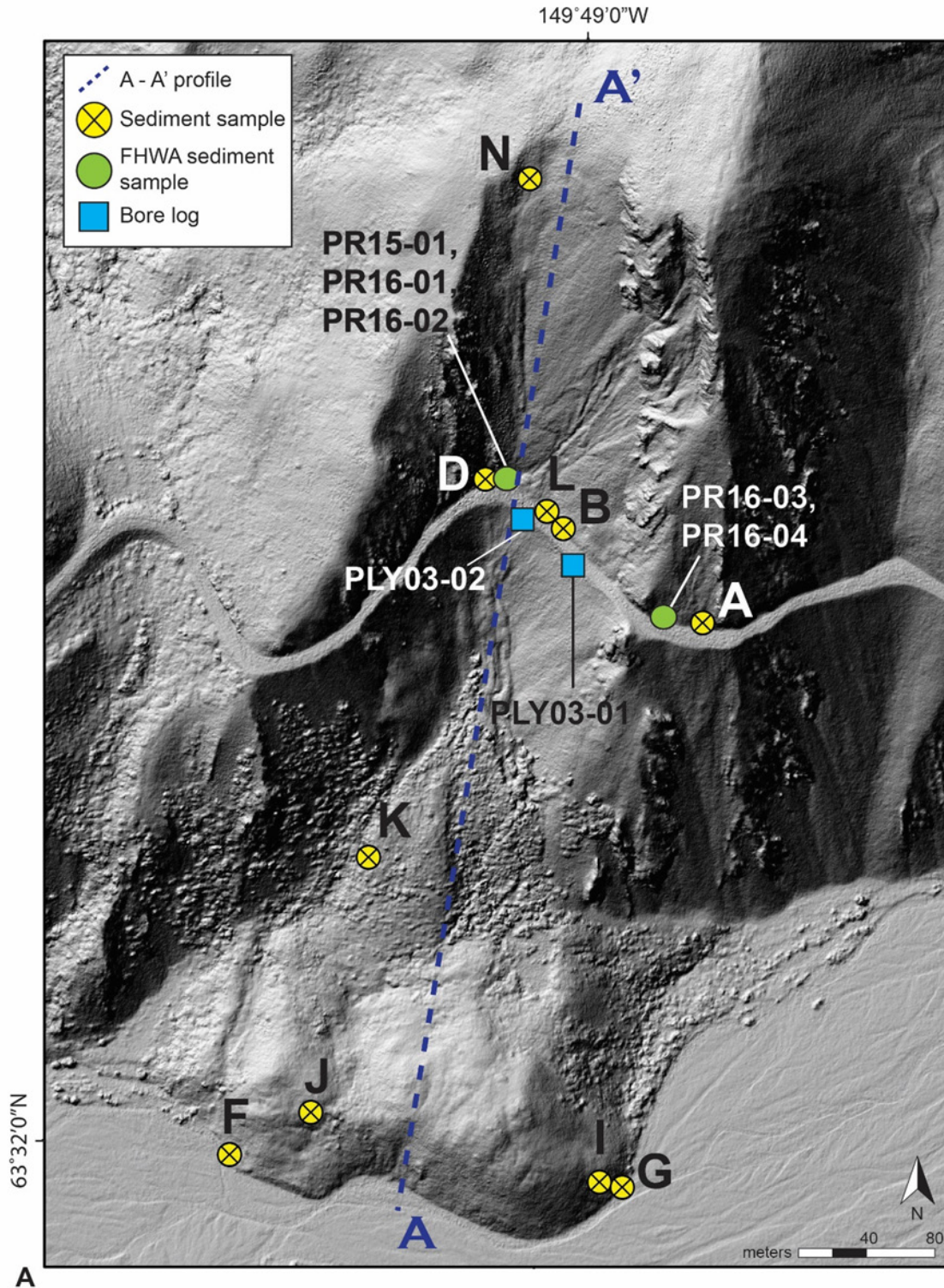


Figure 6A. (A) Location of slope profile, sediment sample locations, and drilling bore logs. Sediment samples PR15-01–PR16-04 collected by the FHWA. Samples A–N were collected during this study. Based on their location, distribution, and grain size, 10 of these samples were selected for laboratory analysis. See Engineering Test Results section for more details. Map background image 2015 SfM Digital Surface Model hillshade. (B, next page) A–A' profile.

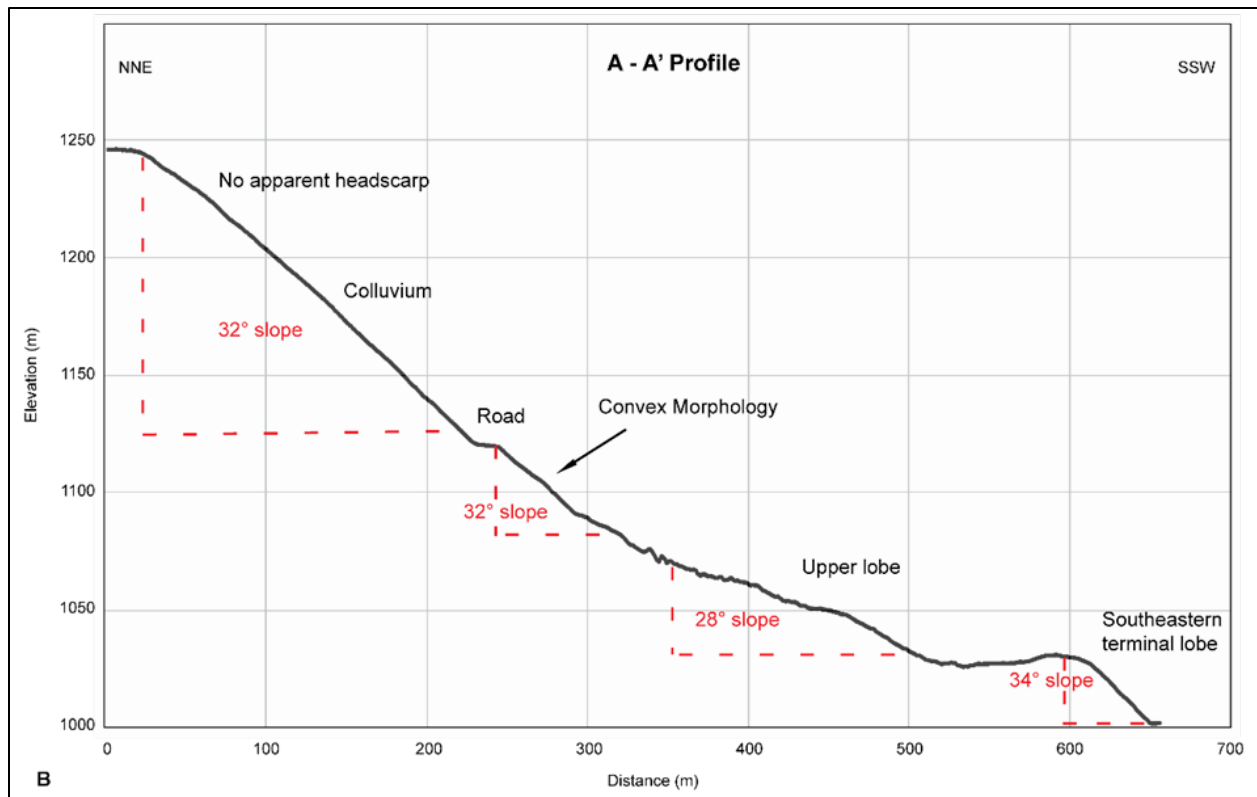


Figure 6B. A–A' profile of slope shown in Figure 6A.

Mass Movement

Primary Failure

According to the NPS, Pretty Rocks has been experiencing movement for over 50 years with increasing displacement rates since 2014. As stated previously, the landslide movement rate had been noted but rarely quantified over this time span. We produced Digital Surface Models (DSMs) of Difference (DoDs) from digital aerial photogrammetry in 2015 and 2016 using modern SfM techniques. The DoD revealed ~80 cm of landslide subsidence where the road crosses the landslide in the one-year period (Figure 7). The DoD further reveals heterogeneous changes in elevation in the slope above the road corridor. Near the midpoint of the landslide-impacted road corridor, some elevations increased at least 40 cm, but elevations decreased up to this same magnitude in the surrounding slope areas. Approximately 80 m downslope of the road, elevations in the colluvium slope increased ≤ 40 cm. The resulting convex morphology is observable on the ground (Figure 6, Figure 8). This appears to be an active landslide toe feature.

Ground truthing and field observations confirm these data. During field work, tension cracks in the road were observed at the northwestern and southeastern landslide boundaries (Figure 8, Figure 9, Figure 10). To the northwest, one dominant tension crack stretches from ~1.5–3 m upslope of the road to ~1 m downslope of the road. Occasionally, other en echelon tension cracks were observed depending on the road maintenance interval and on precipitation (Figure 9). To the southeast, tension cracks in the road surface were typically comprised of en echelon lineations with negligible horizontal and vertical offset (Figure 10). One tension crack extended ~1 m downslope of the road, turning easterly, paralleling the road's edge (Figure 10). Another tension crack extended over 30 m upslope of the road, following the boundary between the rhyolitic bedrock and the colluvium slope (Figure 10). Field-measured vertical offset was 30 cm and horizontal lineations were visible in the exposed landslide head scarp soils (Figure 11). Lastly, in July 2016, the ridge of increased elevations directly downslope of the road developed a tension crack on the downhill side, which paralleled the road.

According to the NPS, the northwestern and southeastern road tension cracks have been present for many years. Historically, these lateral landslide scarps have experienced changes in offset and aperture up to 10 cm during the open summer road season. The road is closed past Mile 3 during the winter which prevents regular observation. When the road is cleared in late spring, maintenance crews often find significant vertical road displacement within the landslide limits although the offset has rarely been measured and documented.

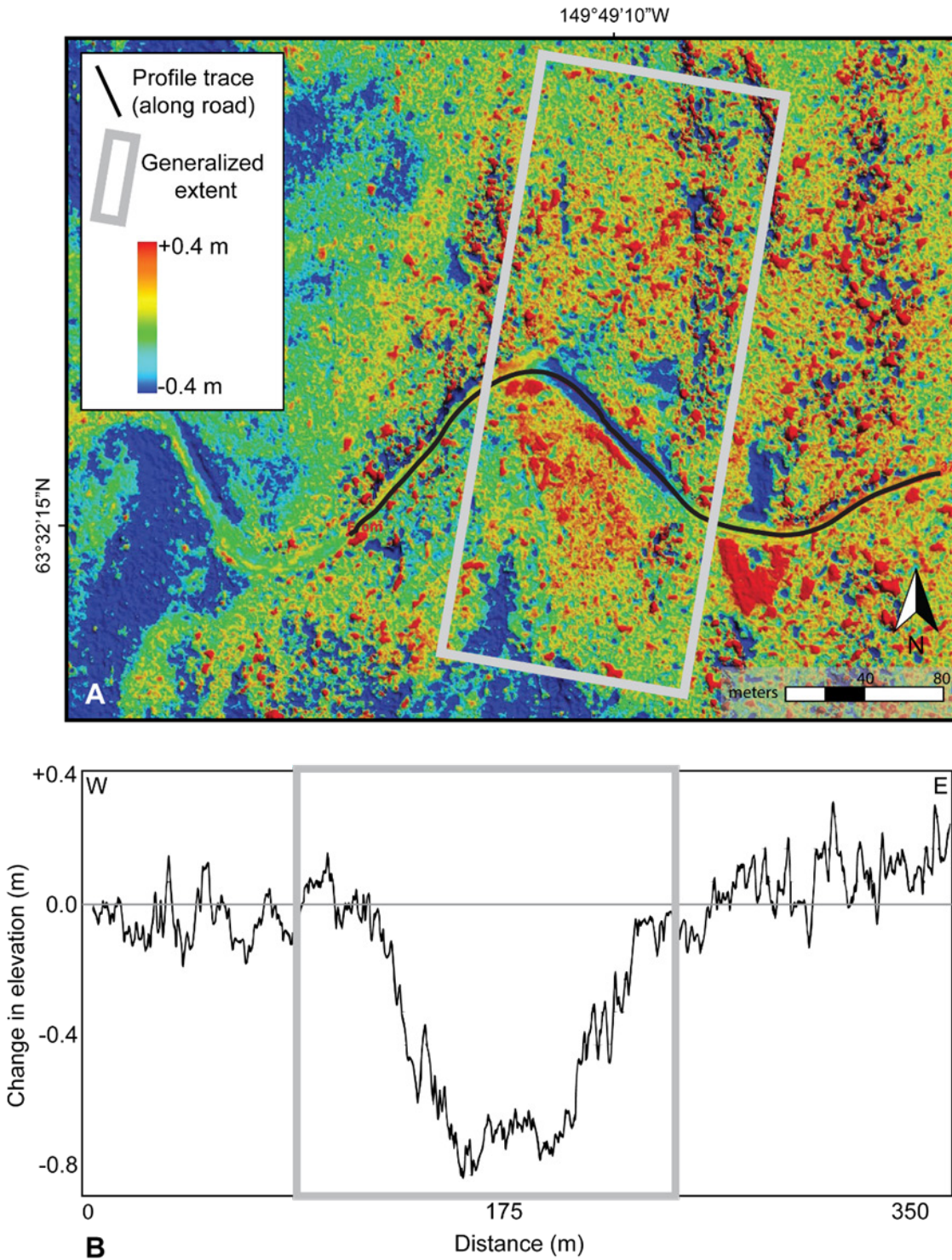


Figure 7. (A) Elevation change map created by subtracting June 2015 SfM imagery from June 2016 SfM imagery. Note decrease in elevation along and above the road within the slide area and the increased elevation below the road caused by bulging. (B) Road profile from west to east.



Figure 8. (A) Convex morphology downslope of the road. Numerous debris flow levees also visible. Person for scale (top left, wearing orange.) Photo taken looking northeast. (B) Northwestern road cracks. The westernmost crack (above, in this view) is longer, more prominent, and was visible more often during field work in July 2016. Highlights added for clarity, but do not represent full extent of cracks. Photo taken looking southwest. Road is one lane wide, for scale. (C) Detail of crack immediately upslope of northwestern road crack. Offset magnitude and aperture varied based on road maintenance interval and precipitation amount.

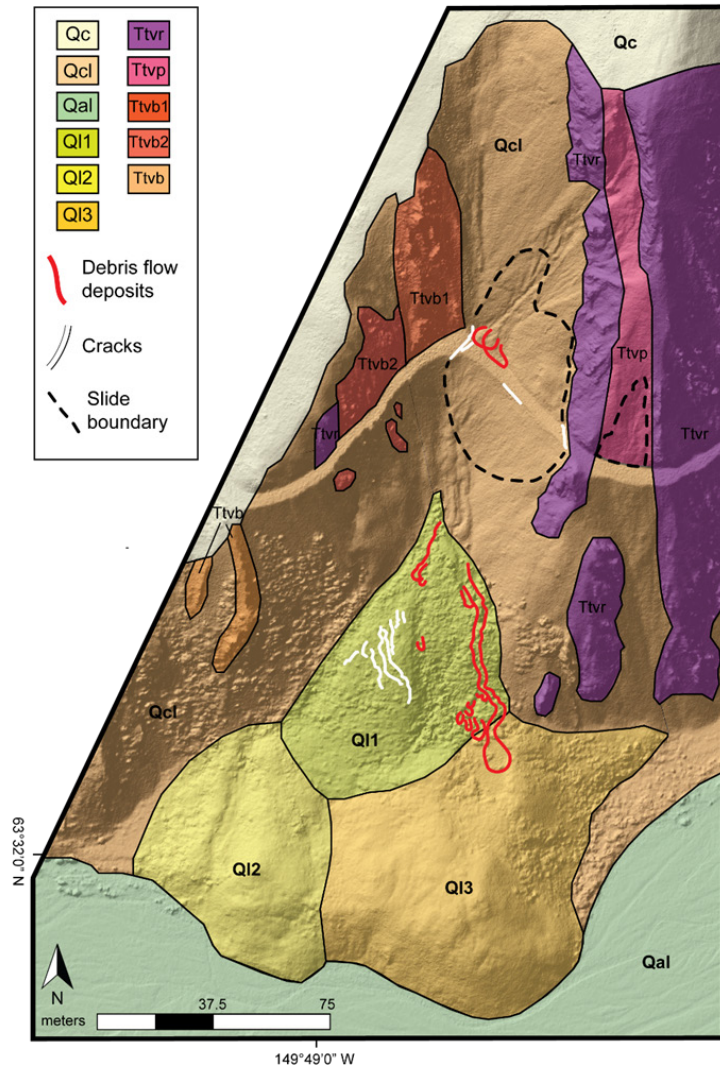


Figure 9. Geologic map of project area, including geomorphic features. Qc: Quaternary cover, undifferentiated. Qcl: Quaternary colluvium, undifferentiated. Qal: Quaternary alluvium. Ql1: Quaternary landslide deposit 1. Basaltic. Ql2: Quaternary landslide deposit 2. Rhyolitic. Ql3: Quaternary landslide deposit 3. Rhyolitic. Ttvr: Tertiary Teklanika volcanic rhyolite. White to gray with brown and purple banding. Weathers to orangey tan. Aphanitic. 1% phenocrysts. 1% infilled amygdulose. 98% groundmass. Phenocrysts are fine to medium-grained euhedral-to-subhedral sanidine. Exhibits localized flow banding and soft-sediment deformation. Ttvp: Tertiary Teklanika volcanic perlite. Gray to black, weathers grayish-green. Holohyaline (i.e., vitric) with devitrification. Gradational contacts with Ttvr exhibiting sub-cm to cm-scale continuous parallel bedding. Ttvp1: Tertiary Teklanika volcanic basalt unit 1. Dark gray, weathers purple, orange, black and yellow. Aphanitic. 1% phenocrysts, 3% infilled alteration pockets, 96% groundmass. Phenocrysts are fine-grained subhedral plagioclase. Alteration pockets are cm-scale, elongate with parallel alignment, infilled with white to purple quartz or iron oxide precipitate. Highly weathered. Ttvp2: Tertiary Teklanika volcanic basalt unit 2. Gray, weathers red, orange, black and greenish gray. Aphanitic. 100% groundmass. Some weathering to greenish gray clay. Local spheroidal weathering. Highly weathered. Ttvp: Tertiary Teklanika volcanic basalt, undifferentiated. See Appendix for detailed rock descriptions including lateral variations and structural measurements. Nomenclature and descriptions restricted to project area. Map background image 2015 SfM DSM hillshade.



Figure 10. (A) Southeastern, en echelon road cracks. Highlights added for clarity. Photo taken looking southeast. (B) Detail of southeastern road crack where it continues below the road and turns easterly to propagate parallel to the road surface. Photo taken looking northeast. Pen for scale. (C) Outline of southeastern slide boundary upslope as defined by the crack between bedrock and colluvium. Crack is a continuation of southeastern road crack. Highlight added for clarity.



Figure 11. Lineations visible in a scarp upslope of the southeastern road crack (Figure 10C). Features highlighted for clarity. Tape measure in photo is extended ~38 cm (red mark on the measuring tape indicates 1 foot).

Secondary Failure

In addition to the large-scale downhill motion, the Pretty Rocks colluvium slope above the road experiences smaller debris flows and rockfall. Two debris flows occurred on June 30, 2016 just prior to a spike in precipitation on July 1, 2016 (Figure 12). Both originated in the colluvium slope above the road, in the area affected by the perlite material drainage (Figure 13). The larger of the two flows terminated in the ditch on the road's north (uphill) side, and the smaller flow ended just above it on the colluvium slope. Additionally, 1996 aerial photography reveals a large debris flow which crossed the road and deposited on the southeastern portion of the lower southeastern lobe (Figure 8). We mapped numerous older debris flow deposits on the tri-lobed landslide deposits at the slope's base. Older deposits are assumed to be masked by vegetation and covered by more recent debris flows.

Above the landslide, highly weathered and friable bedrock erodes and delivers small, but numerous, rockfalls. We observed many rockfalls during field work. Rockfall originates from the upper cliffs. Small debris flows often occur upslope of, and immediately downslope of the roadway during heavy rainfall events. Rockfall is consistent, but much more frequent during heavy rainfall, wind events, and is abundant during freeze/thaw cycles.

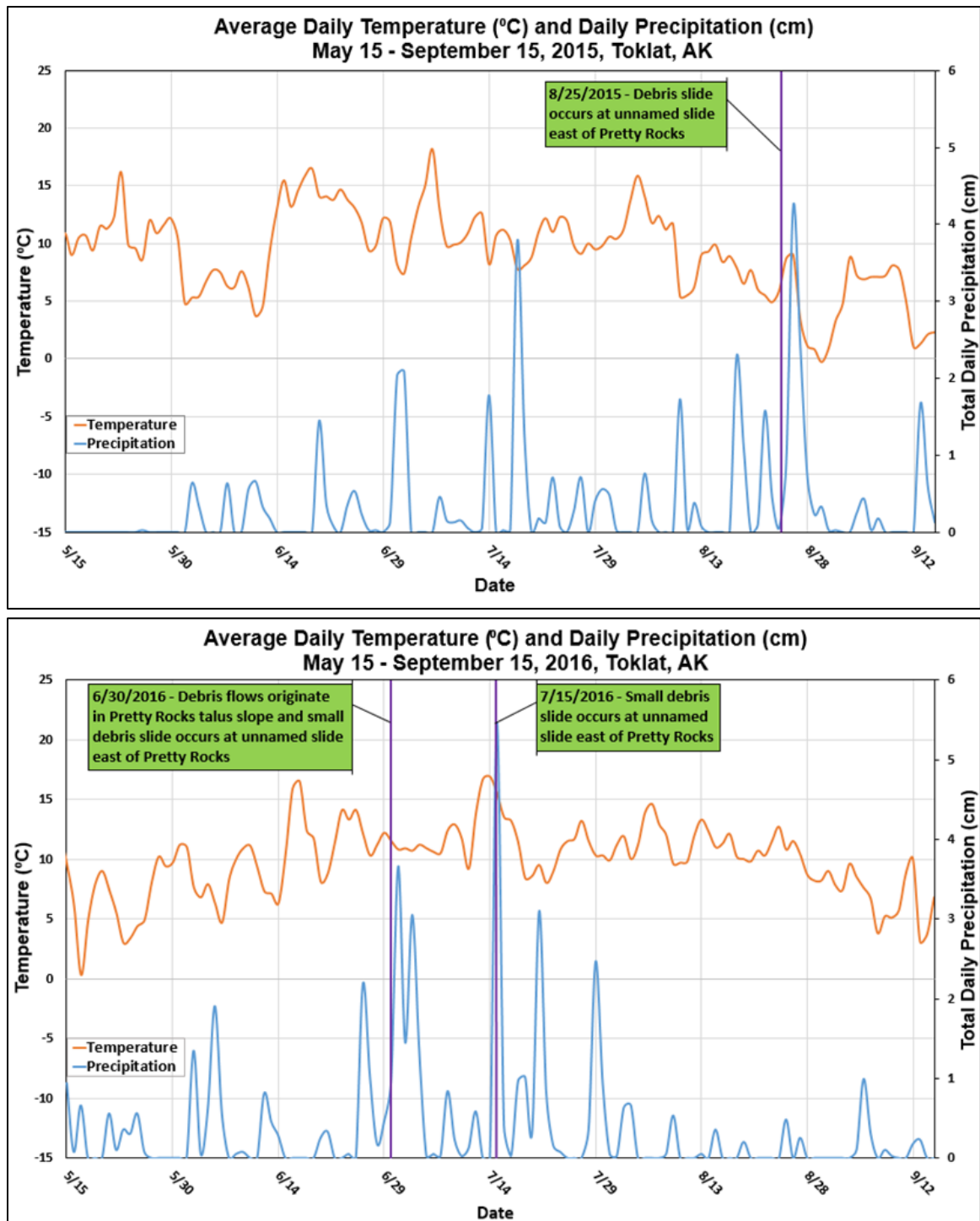


Figure 12. Known landslide event dates compared to summer 2015 and summer 2016 temperature and precipitation data. Other failures may have occurred, but these are the only failures with reliable date constraints.



Figure 13. (TOP) Debris flow paths and deposits seen looking northeast. Scarp and deposits highlighted for clarity. Eastern lobe extends beyond photo frame, see B. (BOTTOM) Larger (eastern) debris flow's lobe deposit as diverted by ditch. Photo taken looking northwest.

Unnamed Debris Slide East of Pretty Rocks

In 2015, the perlite deposit within the rhyolitic bedrock ridge to the east of Pretty Rocks began experiencing mass movement. On August 25, 2015, a landslide occurred that blocked half of the road. This failure preceded a spike in precipitation on August 26, 2015 (Figure 12). During field work in summer 2016, frequent changes in slope morphology within the perlite deposit were noted, and on July 15, 2016 the first author witnessed a small debris slide from the same location as the earlier, large debris slide failure. This landslide occurred during a spike in precipitation, and closely followed the warmest average daily temperature (16.9°C) recorded for the May 15–September 15, 2016 period at the Toklat RAWS. During the July 2016 field work, we also observed spring water flowing constantly at the geologic contact between the underlying perlite deposit and the overlying rhyolitic colluvium deposit where the landslide occurred. The water reached the road and continued eastward (Figure 14).

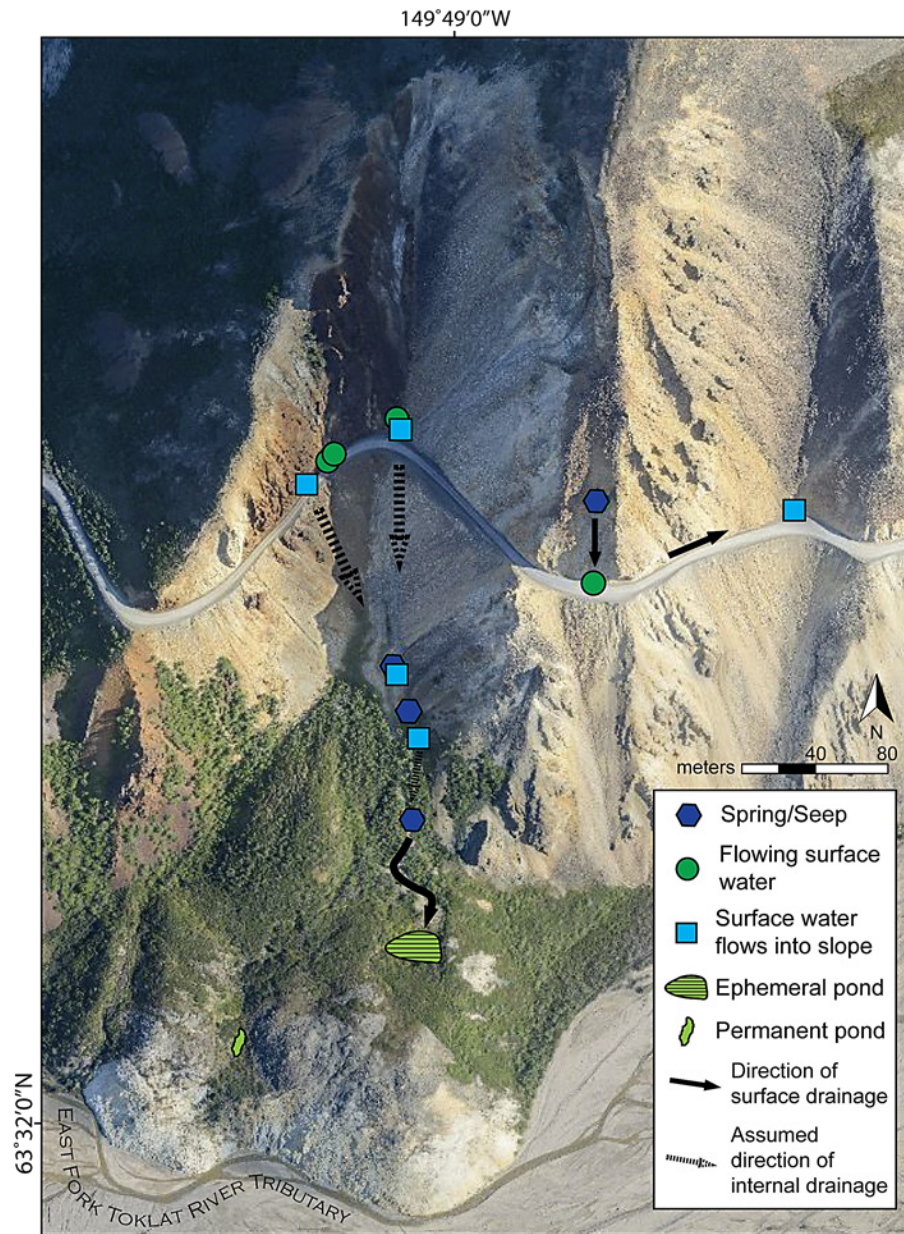


Figure 14. Surface water drainage observed in July 2016. Mapping above the road was prevented by Critical Wildlife Habitat Closure. See Discussion section. Map background image 2015 orthophoto.

The Tri-Lobed Landslide Deposits

SfM-derived products and ground surface investigation revealed three distinct lobes at the slope's base below the road. Two lobes overlie the East Fork Toklat River tributary's streambed, and the third sits atop these two (Figure 8). Cobble- to boulder-sized rhyolite clasts predominantly comprise the lower two lobes, which resemble the colluvium slope's rhyolitic composition to the northeast. Unlike that colluvium slope, both lobes are lichen-covered with the southeastern lobes exhibiting larger and darker lichens than the southwestern (Figure 15). Both lower lobes were hummocky and experiencing minor erosion at their toes by the river. When viewed from the riverbed, the coloration of the two lower lobes differs. The southeastern lobe is more yellow and oxidized, while the western lobe is predominantly white (Figure 16). Between these lobes, a clay deposit, visually similar to the green clays in the perlite deposit, was noted. Analogous green clays and devitrified glass were also observed at the lower two lobes' bases. The third upper lobe shows different characteristics than the lower two lobes. It is vegetated and mostly composed of darker, fine-grained material. Numerous surface tension cracks were observed and mapped (Figure 8). Most debris flow deposits from the colluvium slope terminate on this upper lobe.



Figure 15. (LEFT) Predominantly rhyolitic lobes at the base of the Pretty Rocks slope. Southeastern lobe in the foreground, southwestern lobe in the background. Note differences in surface coloration due to lichen coverage. Photo taken looking west. (RIGHT) Qualitative comparison of lichen coverage. Highlighted rock is representative sample from the southwestern lobe. All other rocks are in place on the southeastern lobe.



Figure 16. Pretty Rocks Landslide and associated lobe deposits seen from the East Fork Toklat River tributary. Road visible in upper slope for scale. Photo taken looking north.

Surface Water: Drainage and Presence

Several days of heavy precipitation allowed us to observe and map the surface water flow patterns on the Pretty Rocks slopes (Figure 14). Most water above the road followed the topography to the southwest, arriving at the topographic low near the road's inside turn. In the road's uphill ditch, the water drained directly into the slope at, or near the northwestern lateral landslide scarp tension crack on the road. Another drainage existed west of the colluvium slope where the road abuts the basaltic bedrock (Figure 14). Sediment-laden water flowing down the basaltic bedrock southwest of the Pretty Rocks slope disappeared into this drainage. We also observed water draining down the July 2016 debris flow channels, and heard water draining just below the ground surface in this same location on days without precipitation.

Water reappeared at the colluvium slope's base to the southeast (Figure 14). It appeared to be controlled by levees and previous debris flow channels rather than following topographic lows. At one point it was observed to be elevated between two levees which may indicate a perched water table due to the high clay content in the debris flow deposits. This small stream disappeared into the ground and reappeared several times before pooling on the southeastern lobe. According to historic aerial photography, the water collects in the lobe deposit of a large debris flow that occurred prior to 1996 (it appears fresh in the 1996 aerial photography and is not seen in the 1988 imagery). The ephemeral sediment-laden pond drains and/or evaporates approximately one week after precipitation (Figure 17).

In addition to this ephemeral surface water, several permanent surface water features exist in the project area. First, a small pond lies between the lower two landslide lobes in the area underlain by a thick package of green clays (Figure 17). Second, during the July 2016 field campaign, water flowed consistently in the Pretty Rocks catchment's natural drainage channel (Figure 14). Third, a consistent

flow existed at the Perlite Debris Slide immediately east of Pretty Rocks during the same July 2016 field work. This water disappeared into the slope at the center of the small valley east of Pretty Rocks (Figure 14).

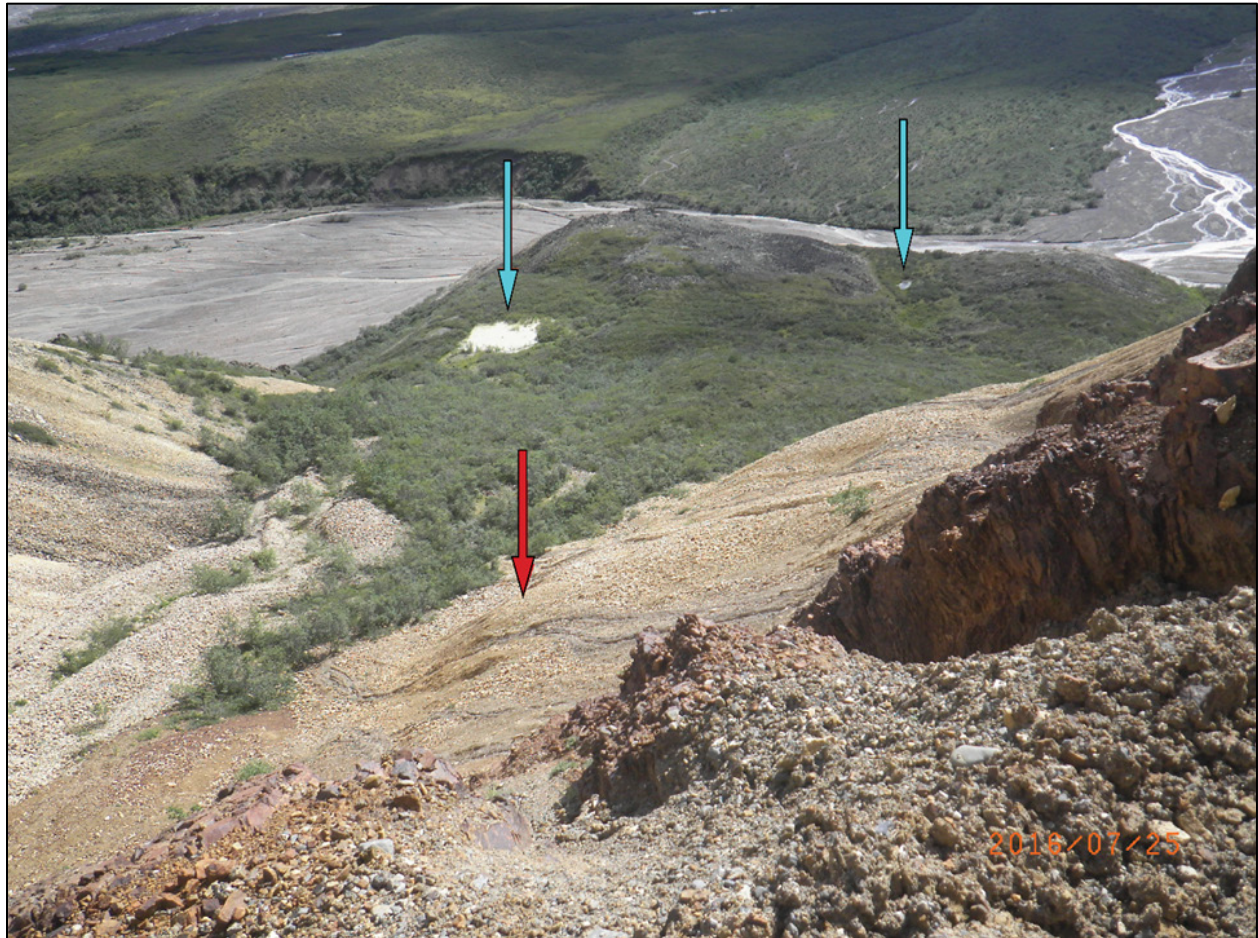


Figure 17. View looking down at the lobes from the road (facing southeast). Left blue arrow indicates sediment-laden ephemeral pond which develops on the southeastern lobe after heavy precipitation. Right blue arrow indicates small permanent pond. Red arrow indicates large bulge which stretches up and to the right, across the basaltic colluvium slope.

Material Laboratory Test Results

Two soil sampling efforts have been conducted at the project area. In May 2015 and 2016, the FHWA collected five samples (PR15-01–PR16-04). The samples laboratory testing included sieving (3/4 in–1 μ m), Atterberg Limit tests, and moisture content (Table 1, Figure 18).

Our study collected 14 samples (Samples A–N). We selected samples based on location within the project area, as well as color, plasticity and grain size. We targeted fine-grained sediments to test the hypothesis that the clays are very weak and contribute to the landsliding. Based on their location, distribution, and grain size, 10 of these samples were ultimately selected for laboratory analysis. Samples B, K, and L were composed predominantly of coarser grain sizes, and therefore underwent sieve analysis (3/4 in – #200). No further tests were performed on these three samples. Samples A, D, F, G, I, J, and N were visually determined to be comprised of silt and clay. These were tested for Atterberg Limits, moisture content, and organic content (Table 1, Figure 18). No sieve analyses were conducted on these samples.

Table 1. Sample results: sieve analysis, Atterberg limits, moisture content, organic content, and Unified Soil Classification System (USCS) classifications.

Origin	Sample	Gravel (sieve analysis, percent passing)				Sand (sieve analysis, percent passing)				Fines (sieve analysis, percent passing)					Atterberg Limits			Moisture (%)	Organic (%)	USCS Soil Classification
		3/4 in	1/2 in	3/8 in	#4	#10	#40	#100	#200	20µm	10µm	5µm	2µm	1µm	LL	PL	PI			
This study ^a	A	–	–	–	–	–	–	–	–	–	–	–	–	–	97	43	54	86.8	3.0	Silt (MH)
	B	–	–	100	100	94	74	53	37.7	–	–	–	–	–	–	–	–	–	–	Clayey or Silty Sand (SC-SM)
	D	–	–	–	–	–	–	–	–	–	–	–	–	–	66	23	43	27.8	2.1	Fat clay (CH)
	F	–	–	–	–	–	–	–	–	–	–	–	–	–	91	32	59	–	–	Fat clay (CH)
	G	–	–	–	–	–	–	–	–	–	–	–	–	–	50	21	29	–	–	Lean clay (CL)
	I	–	–	–	–	–	–	–	–	–	–	–	–	–	78	26	52	27.0	2.9	Fat clay (CH)
	J	–	–	–	–	–	–	–	–	–	–	–	–	–	81	23	58	39.6	2.1	Fat clay (CH)
	K	100	99	97	89	79	61	47	36	–	–	–	–	–	43	24	19	27.7	3.6	Lean clay (CL)
	L	100	93	87	70	53	27	15	11.1	–	–	–	–	–	–	–	–	–	–	Clayey or Silty Sand (SC-SM)
	N	–	–	–	–	–	–	–	–	–	–	–	–	–	105	27	78	44.6	5.1	Fat clay (CH)
FHWA ^b	PR15-01	100	99.8	99.3	98.2	88.4	76.5	–	66.8	46.9	34.7	28.7	23.6	21.3	65	23	42	–	–	Fat clay (CH)
	PR16-01	100	98.6	97.7	95	89.9	75.4	–	65.2	55.3	48.2	40	35.6	32.1	104	23	81	39.6	–	Fat clay (CH)
	PR16-02	100	97.4	95.9	93.5	75.9	63.3	–	56.4	51.1	47.2	41.8	37.1	34.8	116	22	94	67.3	–	Fat clay (CH)
	PR16-03	–	100	99.6	96.7	92.1	85.6	–	79.5	75.1	69.5	63.4	51.9	40.8	91	40	51	25	–	Elastic silt/fat clay (CH/MH)
	PR16-04	–	–	–	100	100	97.3	–	84.9	78.7	72.6	63.4	49.5	39.7	92	38	54	75.4	–	Fat clay (CH)

^a Samples A–N from this study. We selected original sediment samples based on location within the project area, as well as color, plasticity and grain size. Samples were then selected for testing based on their apparent grain sizes (coarser samples were selected for sieve testing), as well as their location (Figure 4). Note that classifications for Samples B and L cannot be further constrained since they were not processed through finer sieve sizes.

^b Sample results PR1501–PR1604 provided by the FHWA.

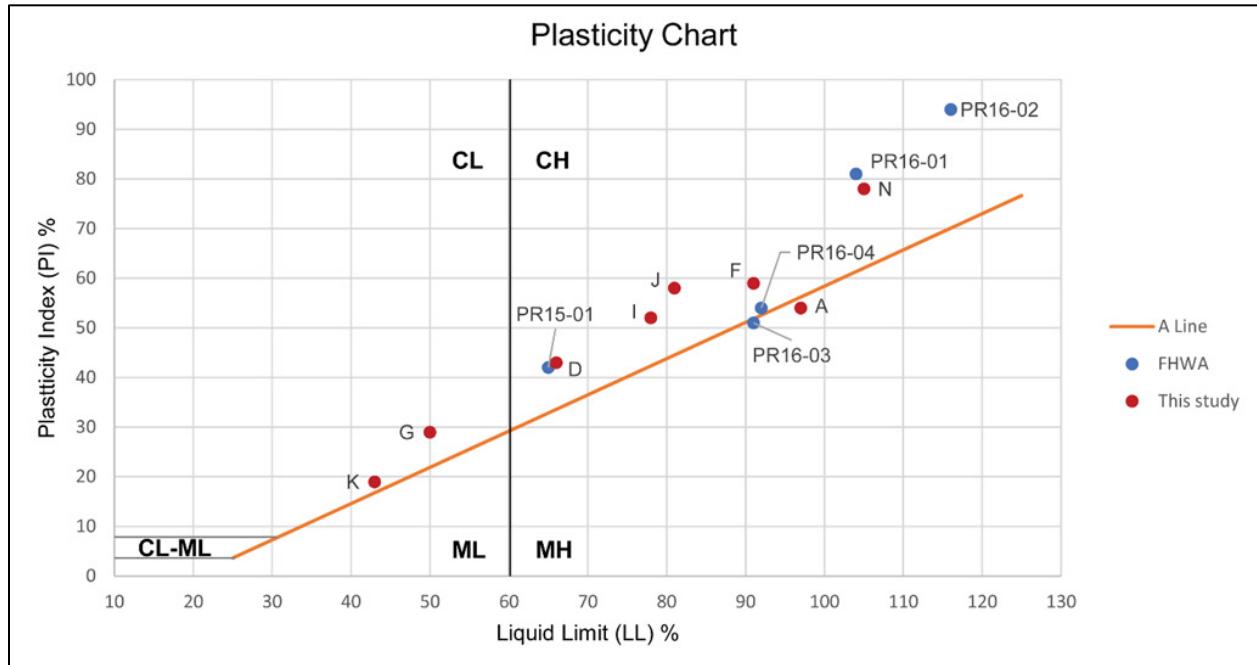


Figure 18. Plasticity Chart from the USCS (U.S. Department of Agriculture Soil Conservation Service, 1990). Plasticity index is the difference between the Liquid Limit and the Plastic Limit, or the range in which a soil behaves plastically. The A-Line ($PI=0.73(LL-20)$) separates silts from clays. CH = fat clays (high liquid limit). CL = lean clays (low liquid limit). MH = elastic silts (high liquid limit). ML = silt (low liquid limit).

The Atterberg Limits define the moisture contents at which a dry sediment sample changes from behaving as a solid, to behaving plastically, and finally to behaving as a liquid. The plastic limit (PL) is the percent water content at which the sample changes from semi-solid to plastic. The liquid limit (LL) is the percent water content at which the sample changes from plastic to liquid. The plastic index (PI) is the range of water content percentages where the sediment exhibits plastic behavior ($PI = LL - PL$). When plotted on a Plasticity Chart they can be used to classify fine sediments (Casagrande, 1948; Holtz and Kovacs, 1981; US Department of Agriculture, 1990; Ohlmacher, 2000). For the purposes of this study, classification is based on particle size (silt vs. clay), plasticity index, and liquid limit as defined by the Unified Soil Classification System (USCS). Clays with high LL and a moderate-to-high PI are called fat clays (symbolized as CH) while silts with a high LL and low-to-high PI are elastic silts (MH). Clays with a low LL and low-to-moderate PI are classified as lean clays (CL), and silts with a low LL and low PI are silts (ML) (US Department of Agriculture, 1990).

Atterberg Limits also reveal physical properties of fine-grained soils such as shear strength, shrinking and swelling, and compressibility (Holtz and Kovacs, 1981; US Department of Agriculture, 1990; Ohlmacher, 2000; Yalcin, 2007). Shear strength of earthen materials is defined by a combination of friction and cohesion. Fat clays tend to have poor shear strength because most of the strength is derived from cohesion. Over time, when poised upon slopes with elevated moisture contents these soils are subject to downhill motion or landsliding (US Department of Agriculture, 1990; Ohlmacher,

2000). Silts and lean clays typically have fair shear strength, and elastic silts have fair to poor shear strength. Swelling potential may also be estimated with PI. Soils with a PI greater than 20 typically have moderate to high swelling potential, while a PI exceeding 35 suggests very high swelling potential. Overall, swelling caused by elevated moisture content markedly decreases soil strength (US Department of Agriculture, 1990; Ohlmacher, 2000; Yalcin, 2007). Finally, compressibility is the potential decrease in volume of a soil that is subjected to a load. Silts and lean clays have medium-to-high compressibility, elastic silts have high compressibility, and fat clays have very high compressibility when adequate moisture content is present (U.S. Department of Agriculture Soil Conservation Service, 1990). Atterberg Limit testing results from our work and FHWA's earlier efforts show a LL range from 43–116, a PL range from 21–43 and a PI range from 19–94. Further, 10 out of the 15 total samples are classified as fat clays based on grain size and/or Atterberg Limits.

Bore Logs

In June 2003, the FHWA drilled two borings—PLY03-1 and PLY03-2—through the road surface into the landslide (Figure 6, Figure 19). Soil and rock descriptions and uncorrected standard penetration test (SPT) rate blow counts were provided. PLY03-1 was drilled to a depth of 16.9 m and ground ice was first observed at 6.2 m. PLY03 2 was drilled to a depth of 30.9 m and ground ice was first recorded at ~12.3 m. In September 2003, thermistor string readings were collected from PLY03-2. Temperatures ranged from 0.3°C at 2.7 m to 3.7°C at 20.1 m at the base of the thermistor string.

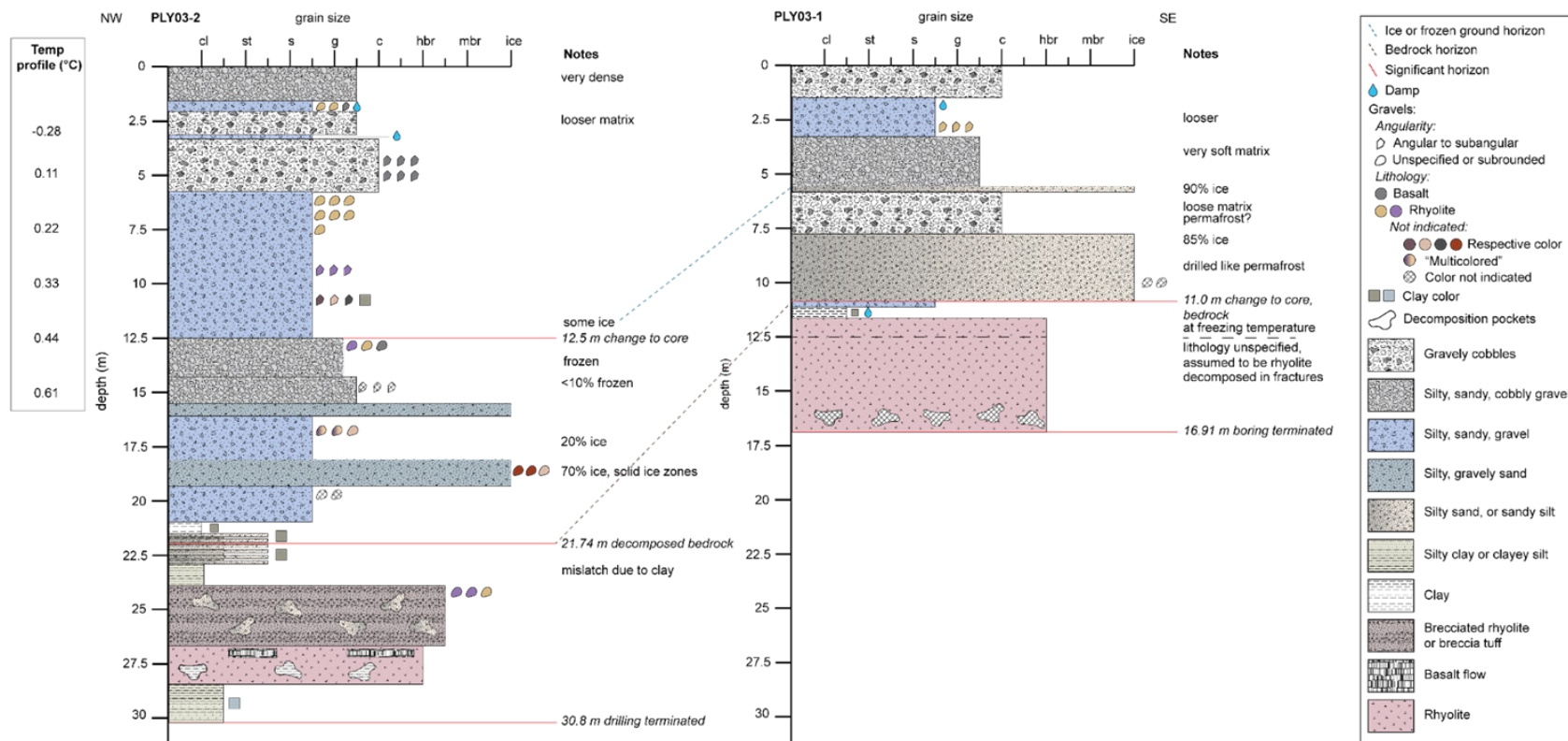


Figure 19. Stratigraphic columns constructed from PLY03-1 and PLY03-2 boring logs. Grain sizes: cl = clay; st = silt; s = sand (undifferentiated); g = gravel; c = cobble; hbr = highly weathered bedrock; mbr = moderately weathered bedrock; ice = $\geq 70\%$ ice. Drilling took place in June 2003. Temperature log was recorded in PLY03-2 in September 2003. Note the close proximity to the freezing temperature. The blue dashed lines correlate the first mentions of ground ice in each profile, while the red dashed line correlates the first mentions of bedrock.

Interpretations

Modified Varnes Classification

According to the modified Varnes classification system, as described by Hungr et al. (2014), Pretty Rocks is best classified as a soil slope deformation, although it also has attributes of an earthflow. Soil slope deformation are described as “Deep-seated, slow to extremely slow deformation of valley or hill slopes formed of (usually cohesive) soils. Often present in permafrost slopes with high ice content” (Hungr et al., 2014).

Based on its morphology we characterize Pretty Rocks as having deep-seated deformation. The material is cohesive because of clay and ice-rich permafrost content. Earthflows are characterized by intermittent flow-like movement of plastic, clayey-soils (Hungr et al., 2014). The Atterberg Limit tests and observations at the Pretty Rocks slope confirm the presence of the plastic, clay-rich soils. Further work to temporally constrain the movement could clarify this interpretation. Similarly, the lobate deposits at the slope’s base could be attributed to prehistoric surges which fully evacuated the talus slope. Lastly, it should be noted that Pretty Rocks provides a unique setting because earthflows are typically associated with slope angles less than 12° (Hungr et al., 2014). The ground ice’s presence is thought to strengthen the slope’s shear strength properties; however, when the ice thaws it then weakens the slope’s shear strength properties.

Landslide Mass’s Surficial Extent

The landslide mass’s proposed surficial extent can be seen in Figure 8. We base this interpretation on several lines of evidence. First, we correlate the southeastern and northwestern extents along the road corridor to the location of the respective road (tension) cracks. Second, we establish the lowermost boundary using the convex morphology below the road (Figure 6B, Figure 9A). This morphology is interpreted as the surface expression of the failure plane’s lower boundary, where it extends over the original ground level (Cruden and Varnes, 1996; Hungr et al., 2014). Third, we base the upper boundary on three features. To the west, it is defined by multiple patches in the talus slope which lack the characteristic cobble- to boulder-sized clasts. These patches generally align and proceed uphill to the east, dividing the homogenous upper talus from the dissected slope below (Figure 20). To the east, we define the extent by the southeastern road cracks’ continuation along the boundary between talus and bedrock (Figure 10C). Third, these extents correlate with the outline of significant elevation changes observed in the DoDs (Figure 7).



Figure 20. Northwestern boundary of failure area which divides the homogenous upper talus from the dissected slope below, and patches of slope which lack cobble- to boulder-sized clasts. Photo taken above the location of the northwestern road crack, looking north.

The Failure Surface Geometry

We interpret the underlying failure-surface to be parabola shaped, thinning at the top, bottom, and sides of the landslide (Figure 21). The apparent failure surface follows the highly weathered sediment/bedrock interface at the landslide head scarp and along the lateral margins that cross the roadway. Near the bottom of the embankment slope there appears to be a landslide toe that bulges out of the embankment slope and deposits material onto the colluvium below, as evidenced by the convex morphology (Figure 6 B). The northwestern-most limb of the parabola shape likely has a steeper limb than the others, as it gets pinched by non-planar topography there.

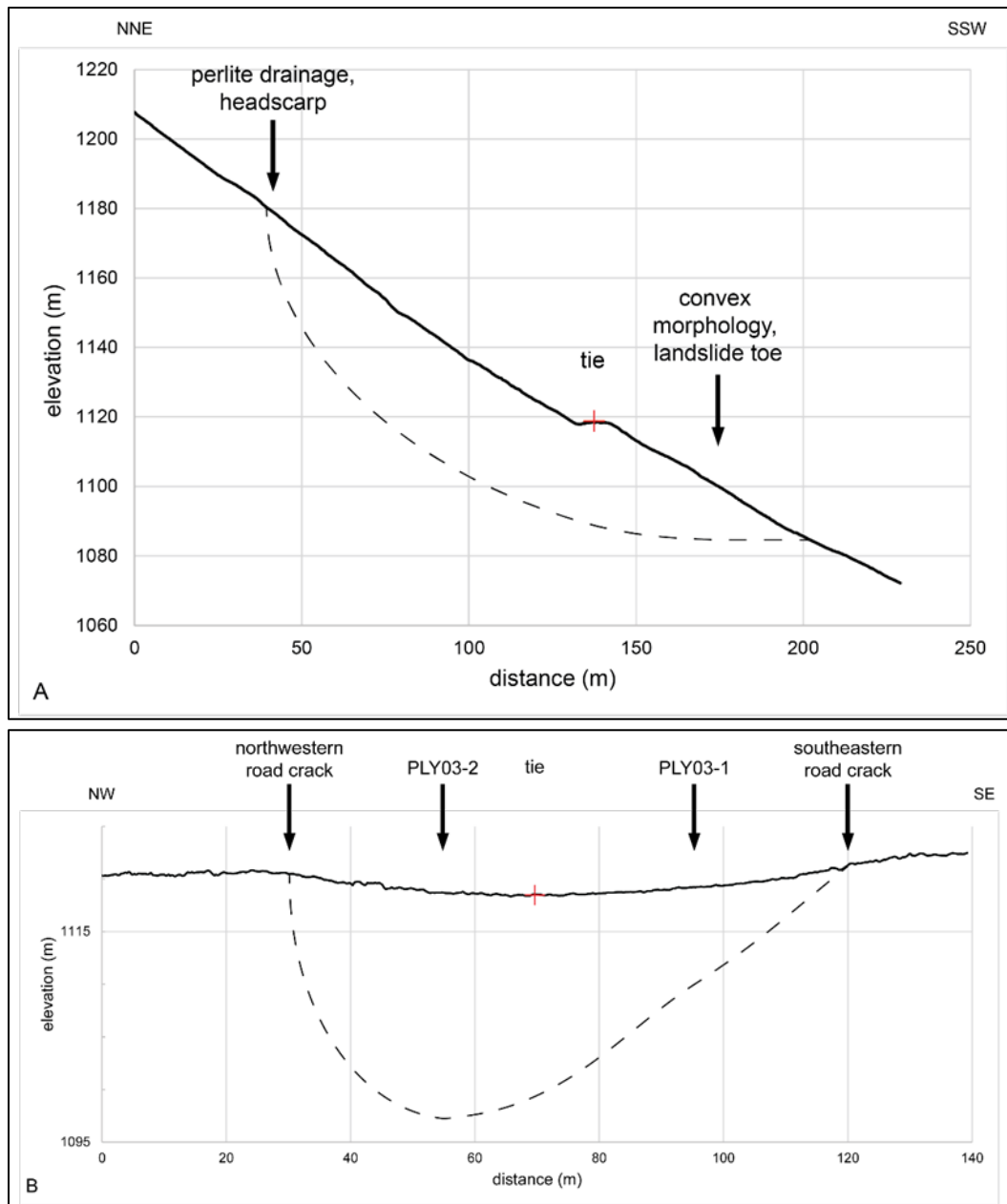


Figure 21. Idealized failure surface geometry. The tie point indicates the location at which these perpendicular profiles intersect one another in map view. (A) Long profile drawn along slope. Upper and lower boundary based on the slide's surficial extent. Depth at tie based on road profile depth at corresponding location. (B) Cross profile drawn along road. Extents based on location of respective road cracks. Depths based on depth to bedrock in PLY03-1 and PLY03-1.

Lateral variations in landslide mass characteristics

Observations indicate that differential deformation occurs across the landslide mass. This may result from differential ground saturation and additional fine-sediment supply in some areas of the landslide mass. The northwestern portion is likely often saturated. The slope's concave topography around the landslide focuses water into the northwestern margin. Continued landslide movement along the northwestern margin creates roadway subsidence and road maintenance staff maintain the road with as little new road material as possible to make it safe and passable while limiting extra weight added to the landslide. In following normal protocol for attempting to maintain a road across the landslide's upper portion, they have inadvertently created a small topographic depression on the road's uphill side in the northwestern corner. During heavier rains we observe surface water pooling here (Figure 14). In contrast, the failure area's southeastern portion is believed to be less wet because it is higher in elevation and is close to the bedrock drainage divide that runs along the landslide's southeast margin. These differences in slope saturation may contribute to the dissimilar nature and frequency of the road tension cracks development. The northwestern road crack is visible in the road material but its trace quickly disappears upslope of the road. In contrast, the southeastern road crack visibly propagates for an estimated 60 m upslope of the road.

Lastly, the slope's northwestern portion likely receives more fine-grained sediment than the southeastern portion due to the drainage patterns and bedrock lithology. Sediment-laden water was observed flowing directly into the northwestern road crack following heavy precipitation. The sediment load includes perlite-derived fines because drainage from the deposit leads directly to the landslide mass's northwestern portion. A fat clay deposit is present along the northwestern margin of the landslide, where it crosses the roadway (Figure 5). Sediment samples directly from the perlite deposit indicate the presence of elastic silts and fat clays (Figure 6, Figure 18). Additionally, the 2016 debris flows originating in the perlite drainage path indicate that the material has low shear strength and is prone to mass movement. It could be postulated that the internal drainage may carry these materials directly to the landslide failure surface and decrease the resisting forces to landsliding.

Creep Rate along the Road Corridor

The SfM-derived DoD quantified changes in elevation over an 11-month period from June 2015 to May 2016. The most concentrated, dramatic subsidence (>80 cm) occurred along the road surface (Figure 7). We interpret the relatively large road surface subsidence as magnification of downhill movement by a strong vertical landslide displacement component. This magnified displacement could be attributed to addition of externally derived road fill, traffic loads along the road corridor, and/or changes in permafrost. Recently, road maintenance staff have used onsite colluvium material to maintain the roadway rather than importing denser, heavier fill materials from external sites. They also no longer use vibratory methods to compact the road fill within the landslide area. Even with this approach, it is likely that these repeated efforts to maintain the roadway section for passage by buses are exacerbating landslide movement. However, there is little else that can be done without a thorough geotechnical investigation resulting in conceptual design alternatives in such an active landslide mass.

Failure Mechanisms

Clay likely contributes to mass movement at this site. Supporting evidence includes numerous other failures associated with clay in the Teklanika Formation (Figure 1), soil material test results that indicate fat clays within the landslide areas (Table 1, Figure 18), and the presence of clays throughout the landslide. Clay was identified above the landslide area, in bore logs from within the landslide, and in lobes at the slope's base (Figure 6, Figure 19). Fat clays are susceptible to moisture, resulting in swelling which decreases shear strength (US Department of Agriculture, 1990; Ohlmacher, 2000; Yalcin, 2007) and is susceptible to frost which could result in frost heaving (Armstrong, 1963; Chamberlain, 1981; Arenson et al., 2008). Both properties could be exacerbated by water flowing internally through the slope which would help to decrease the clays' strength and increase pore pressures within the landslide mass (Marc et al., 2017).

Massive ground ice also likely contributes to failure at this site. Bore logs indicate large lenses of massive ground ice. An increase in slope movement appears to occur during and immediately following spikes in precipitation (Figure 12). Massive ground ice can provide a failure-surface and/or inhibit internal groundwater flow (Dallimore et al., 1996; Tart, 1996). Additionally, ice thaw could: (1) provide additional water to the landslide mass which would result in increased pore pressure and swelling of fat clays, thereby reducing the slope's shear strength; and (2) deflate the landslide mass due to ice mass loss. Many studies have been conducted on the relationship between degrading permafrost and slope instability (McRoberts and Morgenstern, 1974; Huscroft et al., 2004; Lewkowicz and Harris, 2005; Gruber and Haeberli, 2007; Darrow et al., 2012; Huggel et al., 2012; Tyszkowski et al., 2015; Simpson et al., 2016; Coe et al., 2017). These preliminary surface observations should be confirmed by in situ instrumentation during future geotechnical subsurface investigations.

Relatives Ages and Origins of Tri-Lobed Landslide Deposits

The three lobate deposits at the slope's base have different ages and geologic origins. We interpret the rhyolite-rich lobes as deposits from separate mass wasting events. We consider the southeastern lobe to be the oldest deposit based on the lichen coverage and the more advanced stages of oxidation.

The third lobe sits atop the lower two and is interpreted as the youngest based on superposition (Figure 8). We interpret this lobe as a deposit accumulated from multiple slope failures in the basaltic and rhyolitic colluvium, which has been reshaped by alluvial and debris-flow processes which contribute to its fan-like morphology. At present, SfM products and ground-based observations show tension cracks and a large hummock in the basaltic colluvium directly above, and to the west of this upper lobe (Figure 17). This landslide morphology likely results from a small rotational slide that will eventually contribute additional material to the upper lobe.

The type of mass wasting event responsible for the lower lobes' deposition is difficult to identify. First, the braided East Fork Toklat River erodes the deposits, leaving behind an incomplete record of past events. Second, we observed no stratigraphy within the lobate deposits which could help to determine the mode of mass wasting. Drilling and trenching may yield stratigraphic information and materials suitable for radiometric dating. Overall, it is likely that a failure mechanism similar to that observed in the modern slope was responsible for the previous landslides although they clearly

resulted in a substantial volume of material being transported to base level (i.e., the streambed) in episodic landslide events.

Discussion

Overall, the Pretty Rocks Landslide, the adjacent basaltic colluvium slope, and the basal lobate deposits are understood to be a system of previous and ongoing landslide movement. The previous failures' lobate deposits may now be supporting the active landslide. Past and current landslide movements are likely linked by physical and compositional slope properties including the abundant Teklanika-derived clays and ground ice. Triggers and modes of failure may differ, although further work on the lobate deposits may explain the timing and types of failures.

Limitations of this Study

Multiple limitations were encountered in this study and should be noted. First, during the July 2016 field work, a Critical Wildlife Habitat Closure prevented field work beyond 3 m upslope of the road. This prohibited our investigation of the upper colluvium slope and bedrock, effectively reducing the original field project area by 40% and resulting in less detailed mapping above the road. Second, Polychrome Overlook and the adjacent road corridor is considered one of the park's more spectacular areas and is an important viewshed to visitors. As such, field instrumentation was prohibited due to its visual impact. Temperature and precipitation data was only available from locations significantly outside the project area and may not reflect microclimates at Pretty Rocks. Finally, the only available bore logs were drilled in 2003. Since then, average annual temperatures have increased from -1.83°C in 2004 to -0.78°C in 2016 based on temperature data from the Wonder Lake RAWs (data incomplete for 2003). Although the Toklat RAWs is closer to the project area, complete data does not begin until 2006. Increasing temperatures may have changed the ground ice's extent and depth in the study area.

Further Work

This report presents the first formalized, well-documented investigation into Pretty Rocks and attempts to incorporate existing data. This report does not include risk mitigation. Final hazard and risk assessment plans should be preceded by an additional geotechnical investigation. Further work on the landslide slope should include drilling new bore holes to verify ground ice location(s), and installing slope inclinometers, vibrating wire piezometers to determine water levels, and thermistor strings to determine ground temperatures. Simple stakes should also be installed below the roadway across the landslide's width to confirm our interpreted deformation shape and visualize potential variations in failure rates across the slope. It would also be valuable to install a weather station, conduct additional subsurface material laboratory testing, and determine the ages of previous failures using radiocarbon, cosmogenic dating, or lichenometry. We also recommend coordinating with the road maintenance crew to systematize the recording of changes in the slope, and failures that occur.

Continuous monitoring could verify and/or constrain the seasonal timing of movement. If movement is continuous, deep-seated sediment deformation and ground ice are likely at multiple depths and may contribute differing movement magnitudes. For example, the upper failure surface may be moving more quickly than deeper failure planes within the landslide mass.

If movement is episodic and primarily occurs in the winter, ground ice construction is likely increasing pore pressures and destabilizing the slope (Tart 1996). If maximum movement takes place in the summer, failure is more likely to be related to precipitation and melting massive ground ice.

Conclusions

- Pretty Rocks should be classified as a soil slope deformation based on Hungr et al.'s modified Varnes classification system (Cruden and Varnes, 1996; Hungr et al., 2014).
- While most of the area within this small catchment contributes material to the landslide, the active landslide mass's extent appears to be bounded by the northwestern and southeastern road tension cracks and the subtle landslide head scarp upslope of the road. The convex morphology below the road in the long embankment slope appears to be where the landslide toe is developing. The lateral landslide scarps in the road surface are obvious bounding features that reappear at the same locations as landslide movement progresses. The active landslide extents upslope and downslope of the road are more difficult to identify.
- We interpret the landslide morphology from our mapping effort and bore log data to indicate that the landslide's failure surface is generally parabola-shaped with an irregular lower bounding surface that may be in contact with bedrock in some areas.
- Direct observation of tension crack growth and analysis of SfM-derived DoDs shows the road prism's downhill landslide movement rate. We interpret the road surface's subsidence as magnification of downhill movement by a strong vertical landslide displacement component which could be due to the addition of externally derived road fill and traffic loads along the road corridor. Therefore, the rate of movement within the road prism may not be an accurate measure of the active landslide's overall downhill movement.
- Modern failure appears to be driven by the abundant volcanic clays from the Teklanika Formation, high pore pressures caused by inhibited internal drainage of groundwater through the clayey slope, and the presence of massive ground ice. Much of the clay originates from the perlite deposit above the active landslide and contributes to the landsliding. Diversion of surface water to prevent internal wetting of the clays and elevating groundwater pressures within the landslide mass would probably reduce slope movement, yet past efforts of inexpensive cutoff trenches in the landslide mass have failed. The tight road geometry, location, and adjacent wilderness boundary are compounding limitations, especially when combined with the permafrost and the fat clays which overlie poor bedrock conditions. Pretty Rocks provides several challenges to the engineering geologists and geotechnical engineers that will characterize this landslide and offer conceptual alternatives in the near future.
- We interpret the two lowermost lobes as deposits from previous mass wasting events in the rhyolitic bedrock and/or rhyolitic colluvium. We interpret the third, upper lobe, as an accumulated, mostly basaltic colluvium deposit from multiple debris flows and/or debris slides. The active landslide is primarily composed of rhyolitic material.
- We recommend further work to verify the presence of massive ice, subsurface temperatures, bedrock and colluvium characteristics, groundwater levels, failure planes, potential seasonality of movement, and age of the different lobes.

- Staff including road maintenance crews, park rangers, and others who frequent the road corridor should be asked to contribute observations on changes in the slope and failures that occur, including date, time, and photographs, if possible.
- The project area should be understood as a system of past and present failure linked by composition. Lobate deposits from previous failures may now be supporting the active landslide.

Literature Cited

- Ager, T.A., Matthews, J. V., J., and Yeend, W., 1994, Pliocene terrace gravels of the ancestral Yukon River near Circle, Alaska: palynology, paleobotany, paleoenvironmental reconstruction and regional correlation: *Quaternary International*, v. 22/23, p. 22.
- Alaska, D. of T.& P.F., 2003, Alaska field rock classification and structural mapping guide: , p. 31.
- Arenson, L.U., Azmatch, T.F., and Sego, D.C., 2008, A new hypothesis on ice lens formation in frost-susceptible soils: Ninth International Conference on Permafrost, p. 59–64.
- Armstrong, M.D. and T.I.C., 1963, Frost design practice in Canada: , p. 170–201, doi:33.
- Capps, D.M., McLane, S.C., and Chang, L., 2017, Denali National Park and Preserve Geology Road Guide: Denali National Park and Preserve, Denali Park, Alaska., National Park Service, 89 p.
- Casagrande, A., 1948, Classification and identification of soils: *Transactions of the American Society of Civil Engineers*, v. 113, p. 901–930.
- Chamberlain, E.J., 1981, Frost susceptibility of soil: Review of index tests.:
- Coe, J.A., Bessette-Kirton, E.K., and Geertsema, M., 2017, Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery: Landslides, doi:10.1007/s10346-017-0879-7.
- Cole, R.B., Ridgway, K.D., Layer, P.W., and Drake, J., 1999, Kinematics of basin development during the transition from terrane accretion to strike-slip tectonics, Late Cretaceous-early Tertiary Cantwell Formation, south central Alaska: *Tectonics*, v. 18, p. 1224–1244.
- Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, in *Landslides, Investigation and Mitigation: Special Report 247*, Transportation Research Board, Washington, p. 36–75.
- Dallimore, S.R., Nixon, F.M., Egginton, P.A., and Bisson, J.G., 1996, Deep-seated creep of massive ground ice, Tuktoyaktuk, NWT, Canada: *Permafrost and Periglacial Processes*, v. 7, p. 337–347, [http://dx.doi.org/10.1002/\(SICI\)1099-1530\(199610\)7:4%3C337::AID-PPP232%3E3.0.CO;2-3](http://dx.doi.org/10.1002/(SICI)1099-1530(199610)7:4%3C337::AID-PPP232%3E3.0.CO;2-3).
- Darrow, M.M., Bray, M.T., and Huang, S.L., 2012, Analysis of a deep-seated landslide in permafrost, Richardson highway, South-Central Alaska: *Environmental and Engineering Geoscience*, v. 18, p. 261–280, doi:10.2113/gseegeosci.18.3.261.
- FHWA, 2019, Unstable Slope Management Program for Federal Land Management Agencies: FHWA-FLH-19-002, 173 p.
- Gilbert, W.G., Ferrell, V.M., and Turner, D.L., 1976, The Teklanika Formation: a new Paleocene volcanic formation in the central Alaska Range: Alaska Division of Geological and Geophysical Surveys Geologic Report, v. 47, p. 1–26, <http://dggs.alaska.gov/webpubs/dggs/gr/text/gr047.pdf>.

- Gilbert, W.G., and Redman, E.C., 1975, Geologic map and structure sections of Healy C-6 Quadrangle, Alaska, <http://doi.org/10.14509/176>.
- Gruber, S., and Haeberli, W., 2007, Permafrost in steep bedrock slopes and its temperatures-related destabilization following climate change: *Journal of Geophysical Research: Earth Surface*, v. 112, p. 1–10, doi:10.1029/2006JF000547.
- Holtz, R.D., and Kovacs, W.D., 1981, *An Introduction to Geotechnical Engineering*: Englewood Cliffs, New Jersey, Prentice-Hall, 746 p.
- Huggel, C., Clague, J.J., and Korup, O., 2012, Is climate change responsible for changing landslide activity in high mountains? *Earth Surface Processes and Landforms*, v. 37, p. 77–91, doi:10.1002/esp.2223.
- Hungr, O., Leroueil, S., and Picarelli, L., 2014, The Varnes classification of landslide types, an update: *Landslides*, v. 11, p. 167–194, doi:10.1007/s10346-013-0436-y.
- Huscroft, C. a, Lipovsky, P.S., and Bond, J.D., 2004, Permafrost and landslide activity: Case studies from southwestern Yukon Territory: *Yukon Exploration and Geology* 2003, p. 107–119.
- Lewkowicz, A.G., and Harris, C., 2005, Morphology and geotechnique of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada: *Geomorphology*, v. 69, p. 275–297, doi:10.1016/j.geomorph.2005.01.011.
- Marc, V., Bertrand, C., Malet, J.P., Carry, N., Simler, R., and Cervi, F., 2017, Groundwater—Surface waters interactions at slope and catchment scales: implications for landsliding in clay-rich slopes: *Hydrological Processes*, v. 31, p. 364–381, doi:10.1002/hyp.11030.
- McRoberts, E.C., and Morgenstern, N.R., 1974, The Stability of Thawing Slopes: *Canadian Geotechnical Journal*, v. II, p. 447–469.
- Nolan, M., and DesLauriers, K., 2016, Which are the highest peaks in the US Arctic? Fodar settles the debate: *The Cryosphere*, v. 10, p. 1245–1257.
- Ohlmacher, G., 2000, The Relationship between geology and landslide hazards of Atchison, Kansas, and vicinity: *Geology*, <http://www.kgs.ku.edu/Current/2000/ohlmacher/ohlmacher.pdf>.
- Plafker, G., Wahrhartig, C., Eckhart, R.A., and Moxham, R.M., 1963, Investigations for perlite in the Alaska Range, in *Contributions to economic geology of alaska*: *Geological Survey Bulletin* 1155, Washington, D.C., p. 49–65.
- Simpson, J.M., Darrow, M.M., Huang, S.L., Daanen, R.P., and Hubbard, T.D., 2016, Investigating Movement and Characteristics of a Frozen Debris Lobe, South-Central Brooks Range, Alaska: *Environmental & Engineering Geoscience*, v. 22, p. 259–277, doi:10.2113/gseegeosci.22.3.259.
- Tart, R.G., 1996, Permafrost, in Turner, K.A. and Schuster, R.L. eds., *Landslides: investigation and mitigation*, Washington, D.C., Transportation Research Board, p. 620–645.

- Tomsich, C.S., McCarthy, P.J., Fiorillo, A.R., Stone, D.B., Benowitz, J.A., and O'Sullivan, P.B., 2011, New zircon U-Pb ages for the lower Cantwell Formation: implications for the Late Cretaceous paleoecology and paleoenvironment of the lower Cantwell Formation near Sable Mountain, Denali National Park and Preserve, central Alaska Range, USA, in *Proceedings International Conference on Arctic Margins VI*, Fairbanks, AK, p. 19–60.
- Trop, J.M., and Ridgway, K.D., 1997, Petrofacies and provenance of a Late Cretaceous suture zone thrust-top basin, Cantwell Basin, Central Alaska Range: *Journal of Sedimentary Research*, v. 67, p. 17.
- Tyszkowski, S., Kaczmarek, H., Słowiński, M., Kozyreva, E., Brykała, D., Rybchenko, A., and Babicheva, V.A., 2015, Geology, permafrost, and lake level changes as factors initiating landslides on Olkhon Island (Lake Baikal, Siberia): *Landslides*, v. 12, p. 573–583, doi:10.1007/s10346-014-0488-7.
- US Department of Agriculture, S.C.S., 1990, *Engineering Field Manual: Engineering Field Manual*, p. 1–60.
- Wilson, F.H., Hults, C.P., Mull, C., and Karl, S.M., 2015, *Geologic map of Alaska: U.S. Geological Survey Scientific Investigations Map 3340*:
- Yalcin, A., 2007, The effects of clay on landslides: A case study: *Applied Clay Science*, v. 38, p. 77–85, doi:10.1016/j.clay.2007.01.007.

Appendix – Rock Descriptions

Table A-1. Rock descriptions.

Description	Unit	Rock Description	Structural Features										Notes
			Hardness	Weathering	Discontinuities	Aperture	Infilling	Roughness	Spacing	Persistence	Block Size and Shape	Seepage	
1	Ttvr Tertiary Teklanika volcanic rhyolite	White with bands of brown and purple. Weathers to orangey tan. Aphanitic. 1% phenocrysts. 1% infilled amygdules. 98% groundmass. Phenocrysts are medium to finegrained subhedral sanidine. Exhibits flow banding, soft sediment deformation. Amygdules filled with white, chalky material interpreted as devitrification texture.	Strong	Slight	Joints Fractures	1–5 mm, 2 mm typical	Little to none. Some small grains and some weathering material from bedrock	Smooth	• Plane 1: 3–10 cm • Plane 2: 1–25 cm • Plane 3: 1–20 cm	• Plane 1: Low • Plane 2: Low • Plane 3: Low	Tabular to columnar	2	–
2	Ttvr	Same, except purple coloring and no banding. Soft sediment deformation present. Purple coloration appears in amorphous shapes, interpreted as devitrification product. Rough.	Strong	Slight	Joints Fractures	1–5 mm, 3 mm typical	Little to none. (Same.)	Rough	• Plane 1: 6–16 cm • Plane 2: 5–40 cm • Plane 3: 4–40 cm	• Plane 1: V. low–low • Plane 2: Medium • Plane 3: Medium	Tabular	2	Larger block size than description 1. Plane 1 is visibly undulating. Surface of Plane 1 more irregular. Seems that presence of purple material makes joint planes break more unevenly and become more persistent.
3	Ttvr	Same.	Strong	Slight	Joints Fractures	1–5 mm, 2 mm typical	Same	Rough	• Plane 1: 4–10 cm • Plane 2: 4–61 cm • Plane 3: 2–66 cm	• Plane 1: Very low • Plane 2: Very low • Plane 3: Medium	Tabular	2	Similar to Descr. 2 with exception of persistence of plane 2. Blocks still larger and more irregular than Descr. 1.
4	Ttvr	Similar, except with inclusion of soft white, chalky material which are similar in shape to the amorphous occurrences of purple material. Weathers differently than surrounding material—same tan color, but weathered texture is more bumpy and irregular. White material interpreted as devitrification product.	Strong (chalky material excepted)	Slight	Joints Fractures	1–5 mm, 3 mm typical	Same	Rough (Rougher than previous locations where white material located)	• Plane 1: 3–20 cm • Plane 2: 10–37 cm • Plane 3: 8–40 cm	• Plane 1: Very low • Plane 2: V. low–low • Plane 3: High	Irregular, varied, some tabular	2–3	Varying orientation of Plane 2 are unique, as is presence of chalky material. Blocks less regular and decrease in size going up rock face.

Table A-1 (continued). Rock descriptions.

Description	Unit	Rock Description	Structural Features										Notes
			Hardness	Weathering	Discontinuities	Aperture	Infilling	Roughness	Spacing	Persistence	Block Size and Shape	Seepage	
5	Ttvr	Similar. Purple, weathering purple/orange. Seemingly more iron oxide. Hardest yet. Minor occurrence of white chalky material.	V. Strong	Slight Large bands of iron oxide in joints.	Joints Fractures	1–8 mm, 2 mm typical	Same	Smooth (Esp. Plane 1)	• Plane 1: 19 cm–2 m • Plane 2: 1–2 m • Plane 3: 10 cm–1.5 m	• Plane 1: Medium • Plane 2: Low • Plane 3: High	Blocky/Irregular Shapes become more tabular and decrease in size upsection.	2	Change in size and shape of blocks seems to correlate with decrease in hard purple material. Plane 1 is very undulatory. Overall, more purple, harder, bigger blocks, more persistence esp. in Plane 1.
6	Ttvr	Between description #5 and #6, rock face is irregular without well developed planes. Soft, white material common, forming rough weathered exterior. At description #6 site, returns to rock type seen at #5 with lots of purple and well-developed joint planes.	Strong	Slight	Joints Fractures	1–20 mm, bimodal many are 1 mm, many are around 20 mm, few in between	Same	Rough	• Plane 1: 50 cm—not many locations available for measurement • Plane 2: 1.5 m • Plane 3: 55 cm–2.5 m	• Plane 1: Low • Plane 2: Medium • Plane 3: Medium	Blocky to tabular—blocks are large	2	–
7	Ttvr	Ends with gradational contact into perlite bed. Rock classification similar. Minor flow banding seen for the first time since description #1. Still some chalky material. Rock appears irregular, and more fractured possibly due to proximity to contact.	Strong	Moderate	Joints Fractures	1–4 mm	Same	Rough	• Plane 1: 18–24 cm—very difficult to discern in this irregular area • Plane 2: 6–50 cm • Plane 3: 18–30 cm: area north fractured and irregular. Difficult to discern plane spacing	• Plane 1: Very low • Plane 2: Low • Plane 3: Very Low	Irregular—fractured	2	Joint plane 1 very irregular
Overall	Ttvr	85 m thick along road Strike: 335, Dip: 62 NE (RHR)	–	–	–	–	–	–	–	–	–	–	–
1	Ttvp Tertiary Teklanika volcanic perlite.	Gray to black, weathers gray to green. Holohyaline (i.e. vitric). Gradational contacts with Ttvr exhibiting sub-cm to cm-scale bedding.	Very soft	High to decomposed	NA	NA	NA	NA	NA	NA	NA	NA	Weathering to green clay. Slide area above road.

Table A-1 (continued). Rock descriptions.

Description	Unit	Rock Description	Structural Features										Notes
			Hardness	Weathering	Discontinuities	Aperture	Infilling	Roughness	Spacing	Persistence	Block Size and Shape	Seepage	
1	Ttvr	Gray, weathering tan to orange, aphanitic rhyolite, with fine to medium grained sanidine phenocrysts. Texture is dense, hard, seemingly compact. White speckles of devitrification texture throughout. 1% phenocrysts. 99% groundmass. All phenocrysts are euhedral sanidine.	Strong to Very Strong, difficult to break	Slight	Joints Fractures Possible bedding planes	0–2 mm	None	Smooth with slickenslides (slickenslides only on plane 1 appears to be primary failure plane)	- Plane 1: 2–20 cm - Plane 2: 0.5–10 cm (most 2–3 cm) - Plane 3: 14–58 cm	- Plane 1: Very low - Plane 2: Medium - Plane 3: Very low	Columnnar	1 to 2	Slickensides along some planes
2	Ttvr	Same.	Strong	Slight	Joints Fractures	0–1 mm	None	- Plane 1: smooth with slickenslides - Plane 2: rough but with minor slickenslides	- Plane 1: 1–34 cm - Plane 2: 14–80 cm	- Plane 1: Medium - Plane 2: Medium	Columnnar, but lacking a distinct 3rd plane	1 to 2	Slickensides along some planes
3	Ttvr	Similar but with increasing occurrence of chalky material and evident flow banding. Evidence of previous toppling failure. As seen previously, chalky material produces more irregular exterior weathering texture.	Strong	Slight	Joints Fractures	0–8 mm 1–2 mm typical	None	Rough	- Plane 1: 55 cm - Plane 2: 18–60 cm	- Plane 1: Medium - Plane 2: Medium	Tabular/Columnnar	1 to 2	–
4	Ttvr	More highly fractured—increased occurrence of chalky material, which is much softer and seems to weaken the bedrock and decrease the persistence of joint planes. Lacking phenocrysts.	Strong	Slight	Joints Fractures	0–2 mm	None	Rough but with occurrences of slickenslides in deposit of iron oxide	- Plane 1: 10–20 cm Highly fractured and difficult to establish - Plane 2: 6–18 cm highly fractured	- Plane 1: Very Low - Plane 2: Very Low	Irregular	1 to 2	–
5	Ttvr	Gray, weathers orange, aphanitic rhyolite. Localized flow banding. Euhedral very fine grain sanidine phenocrysts. 1% phenocrysts, 99% groundmass	Strong	Slight–Moderate	Joints Faults Fractures	Joints: 2 mm Fractures: up to 40 mm	None	Rough	- Plane 1: Too Fractured - Plane 2: 15–34 cm - Plane 3: Too Fractured	- Plane 1: Very Low - Plane 2: Very Low - Plane 3: Very Low	–	–	–

Table A-1 (continued). Rock descriptions.

Description	Unit	Rock Description	Structural Features										Notes
			Hardness	Weathering	Discontinuities	Aperture	Infilling	Roughness	Spacing	Persistence	Block Size and Shape	Seepage	
Overall	Ttvr	Highly fractured. Competency decreases, fracture increases east to west. Planes are curved. Devitrification texture present. 30 m thick along road. Strike: 005, Dip: 45 E (RHR)	–	–	–	–	–	–	–	–	–	–	–
1	Ttvb1 Tertiary Teklanika volcanic basalt, unit 1	Dark gray, weathers purple, orange, black and yellow. Aphanitic. 1 % phenocrysts, 3% alteration pockets, 96% groundmass. Fine-grained plagioclase phenocrysts and pockets of alteration filled with secondary minerals. These pockets and elongate with parallel alignment. Alteration pockets infilled with white to purple quartz, or iron oxide precipitate.	Strong	Slight–Moderate	Joints Fractures	0–2 mm	None	Smooth	• Plane 1: 5–15 cm • Plane 2: 6–18 cm • Plane 3: 6–22 cm	• Plane 1: Low • Plane 2: Very Low • Plane 3: Very Low	Small blocks, cut up appearance, fractured. Plane 1	1 to 2	–
2	Ttvb1	Same.	Strong	Slight–Moderate	Joints Fractures Faults	0–3 mm	None Some yellow clay	Smooth	• Plane 1: 6–24 cm • Plane 2: 6–30 cm • Plane 3: 5–40 cm	• Plane 1: Very Low • Plane 2: Low • Plane 3: Very Low	–	1 to 2	–
3	Ttvb1	Similar. 100% groundmass. Weathering is extensive, difficult to find fresh rock face.	Strong	Slight	Joints Fractures Faults	0–2 mm	None	Smooth	• Plane 1: 25–42 cm • Plane 2: 23 cm–1.5 m • Plane 3: 12–33 cm	–	Blocky	1	–
4	Ttvb1	Same.	Strong	Slight–Moderate	Joints Fractures Faults?	0–5 mm	None	Smooth–Rough	• Plane 1: 8 cm–1 m • Plane 2: 5 cm–62 cm • Plane 3: 15 cm–1 m	• Plane 1: Medium • Plane 2: Low • Plane 3: Very Low	Columnar to Tabular	2	–
5	Ttvb1	Same.	Strong	Slight	Joints Faults Fractures	0–3 mm	• Joints: none • Faults: clay gouge	Smooth–Rough	• Plane 1: 4–20 cm • Plane 2: 7–26 cm • Plane 3: 5–22 cm • Plane 4: 5–15 cm	• Plane 1: Medium • Plane 2: Very Low • Plane 3: Very Low • Plane 4: Very Low	Blocky	–	–
6	Ttvb1	Same.	Strong	Slight–Moderate	Joints Fractures Faults	0–3 mm 1 mm typical	Only along faults	Rough—increased by	• Plane 1: 2–8 cm • Plane 2: 3–30 cm • Plane 3: 5–23 cm	• Plane 1: Very Low • Plane 2: Medium • Plane 3: Very Low	Blocky	1 to 2	–

Table A-1 (continued). Rock descriptions.[illegible]

Table A-1 (continued). Rock descriptions.

Description	Unit	Rock Description	Structural Features										Notes
			Hardness	Weathering	Discontinuities	Aperture	Infilling	Roughness	Spacing	Persistence	Block Size and Shape	Seepage	
1	Ttvr1 Tertiary Teklanika volcanic rhyolite, unit 1	Purple, white, pink, weathers to tan and orange. Aphanitic. 3% quartz and sanidine phenocrysts. 97% groundmass. Minor occurrence of white chalky material as seen in the eastern unit, though to a lesser extent.	Strong	Slight	Joints Fractures Faults	1–4 mm	None to localized breccia and	Smooth, w/ rough patches	• Plane 1: 4–40 cm • Plane 2: 9–53 cm • Plane 3: 6–54 cm	• Plane 1: Low • Plane 2: Very Low • Plane 3: Medium	Blocky/Irregular	1 to 2	–
Overall	Ttvr1	V. well defined blocks and jointing planes. Less cut up than basalt. Bigger blocks. 6 m thick along road.	–	–	–	–	–	–	–	–	–	–	–

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 184/179680, March 2022

National Park Service
U.S. Department of the Interior



[Natural Resource Stewardship and Science](#)

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525