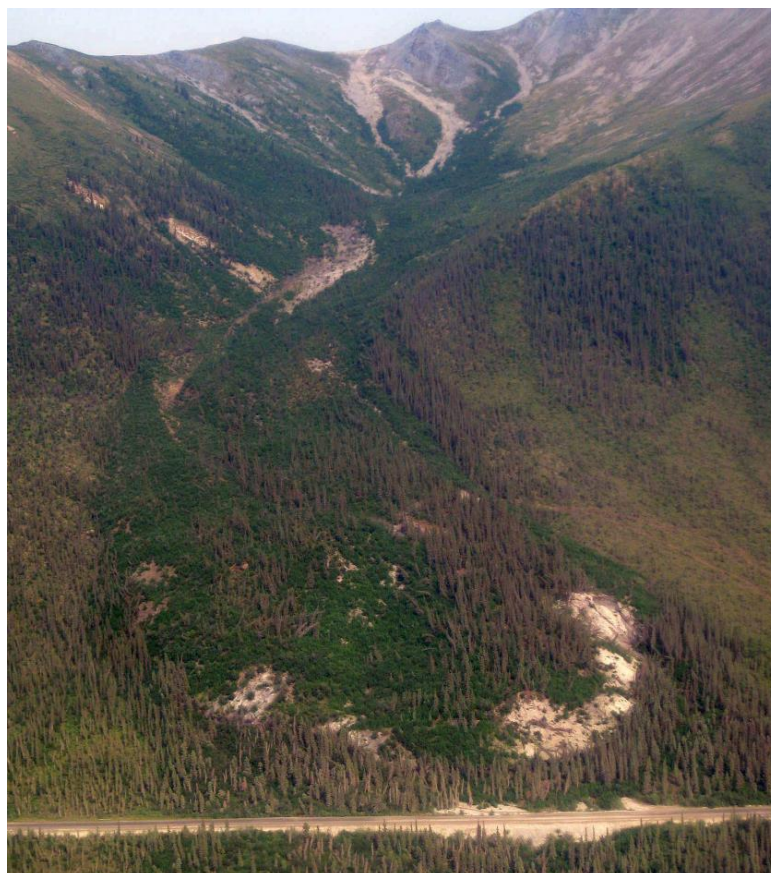


Monitoring and Analysis of Frozen Debris Lobes, Phase IB



FDL-A at MP219 along the Dalton Highway in June 2013.

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Frozen debris lobes (FDLs) are slow-moving landslides in permafrost, many of which are present within the Dalton Highway corridor in the Brooks Range of Alaska. During this phase of the research, we continued our investigations of FDL-A (the closest to the Dalton Highway), and extended the research to include monitoring of seven additional FDLs. The investigated FDLs move at a variety of rates from less than a meter per year to 20 m per year. All of the FDLs investigated during this phase of research have characteristics of increasing instability. As analysis of subsurface data from FDL-A indicates, the movement of FDLs is temperature-dependent, which suggests the need for ongoing monitoring as temperature and precipitation in the area change in the future. Many FDLs are located uphill of important infrastructure within the State of Alaska. Changes within these permafrost features may yield insight into how frozen slopes throughout the State respond to changing climate. We recommend continued annual measurements of the surfaces of the eight investigated FDLs, additional drilling and geophysical surveys of FDL-A for better subsurface characterization, and development of a slope stability model that incorporates temperature effects.

14. KEYWORDS : Frozen debris lobe, landslide (Jbgem), Dalton Highway, Alaska, Permafrost (Rbespfp)

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>					<u>LENGTH</u>				
in	inches	25.4	mm	mm	millimeters	0.039	inches	in	
ft	feet	0.3048	m	m	meters	3.28	feet	ft	
yd	yards	0.914	m	m	meters	1.09	yards	yd	
mi	Miles (statute)	1.61	km	km	kilometers	0.621	Miles (statute)	mi	
<u>AREA</u>					<u>AREA</u>				
in ²	square inches	645.2	millimeters squared	cm ²	mm ²	millimeters squared	0.0016	square inches	in ²
ft ²	square feet	0.0929	meters squared	m ²	m ²	meters squared	10.764	square feet	ft ²
yd ²	square yards	0.836	meters squared	m ²	km ²	kilometers squared	0.39	square miles	mi ²
mi ²	square miles	2.59	kilometers squared	km ²	ha	hectares (10,000 m ²)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
<u>MASS (weight)</u>					<u>MASS (weight)</u>				
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
<u>VOLUME</u>					<u>VOLUME</u>				
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft ³	cubic feet	0.0283	meters cubed	m ³	m ³	meters cubed	35.315	cubic feet	ft ³
yd ³	cubic yards	0.765	meters cubed	m ³	m ³	meters cubed	1.308	cubic yards	yd ³
Note: Volumes greater than 1000 L shall be shown in m ³									
<u>TEMPERATURE (exact)</u>					<u>TEMPERATURE (exact)</u>				
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
<u>ILLUMINATION</u>					<u>ILLUMINATION</u>				
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m ²	cd/cm ²	cd/cm ²	candela/m ²	0.2919	foot-lamberts	fl
<u>FORCE and PRESSURE or STRESS</u>					<u>FORCE and PRESSURE or STRESS</u>				
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi
These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements									

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EXECUTIVE SUMMARY

Frozen debris lobes (FDLs) are slow-moving landslides in permafrost, many of which are present along the Dalton Highway in the Brooks Range of Alaska. While twenty-three FDLs are within a mile uphill of the highway, the closest (FDL-A) is 39.6 m from the toe of the highway embankment (as of May 2015). FDL-A is about 1200-m long, up to 260-m wide, and about 20-m high at the toe. When it reaches the highway, we estimate that it will place 22,000 tons of debris on the road every year.

The overall goal of this project was to continue work done for the 2012 Phase 1 of the FDL study. The additional funding supported fieldwork and data collection, data analysis, and synthesis. The analysis was disseminated as a presentation to the Alaska Department of Transportation and Public Facilities and through multiple oral updates to Alyeska Pipeline Service Company personnel. The analysis also was or will be disseminated in a conference paper, two journal publications, and a Master's thesis. As most of the results from this research either have been or will be released through peer-reviewed conference and journal publications, this final report serves as a brief summary of the content of those articles.

During this phase of the research, we continued our investigations of FDL-A, and extended the research to include monitoring of seven additional FDLs. While specific values will be included in forthcoming publications, the investigated FDLs move at a variety of rates from less than a meter per year to 20 m per year. All of the FDLs investigated during this phase of research have characteristics of increasing instability. As analysis of subsurface data from FDL-A indicates, the movement of FDLs is temperature-dependent, which suggests the need for ongoing monitoring as temperature and precipitation in the area change in the future.

Many FDLs are located uphill of important infrastructure within the State of Alaska. Changes within these permafrost features may yield insight into how frozen slopes throughout the State respond to changing climate. With these facts in mind, we recommend the following.

- Continue annual measurements of the surface marker pins on the eight investigated FDLs to monitor for increases in movement rates as these features progress downhill.
- Conduct additional drilling on FDL-A to determine location of the bedrock surface beneath the lobe, lobe thickness and depth to the shear zone, and the distribution of water pressure in multiple locations.
- Conduct geophysical surveys jointly with the drilling program.
- Develop a slope stability model that incorporates temperature effects. Such a model could be used to predict how these features, as well as other permafrost slopes, will respond to changes in climate.

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CHAPTER 1

INTRODUCTION

Frozen debris lobes (FDLs) are slow-moving landslides in permafrost, many of which are present along the Dalton Highway in the Brooks Range of Alaska (see Figure 1). While twenty-three FDLs are within a mile uphill of the highway, the closest, FDL-A at Mile Post (MP) 219, is 39.6 m from the toe of the highway embankment (as of May 2015). FDL-A is about 1200-m long, up to 260-m wide, and about 20-m high at the toe. When it reaches the highway, we estimate that it will place 22,000 tons of debris on the road every year. In 2012, a Phase I study provided preliminary characterization of the internal structure of FDL-A (Darrow et al. 2012); however, additional study is needed to define further the movement mechanisms of the FDLs and to characterize better their internal makeup. This information is necessary to identify the best mitigation technique/s for implementation.

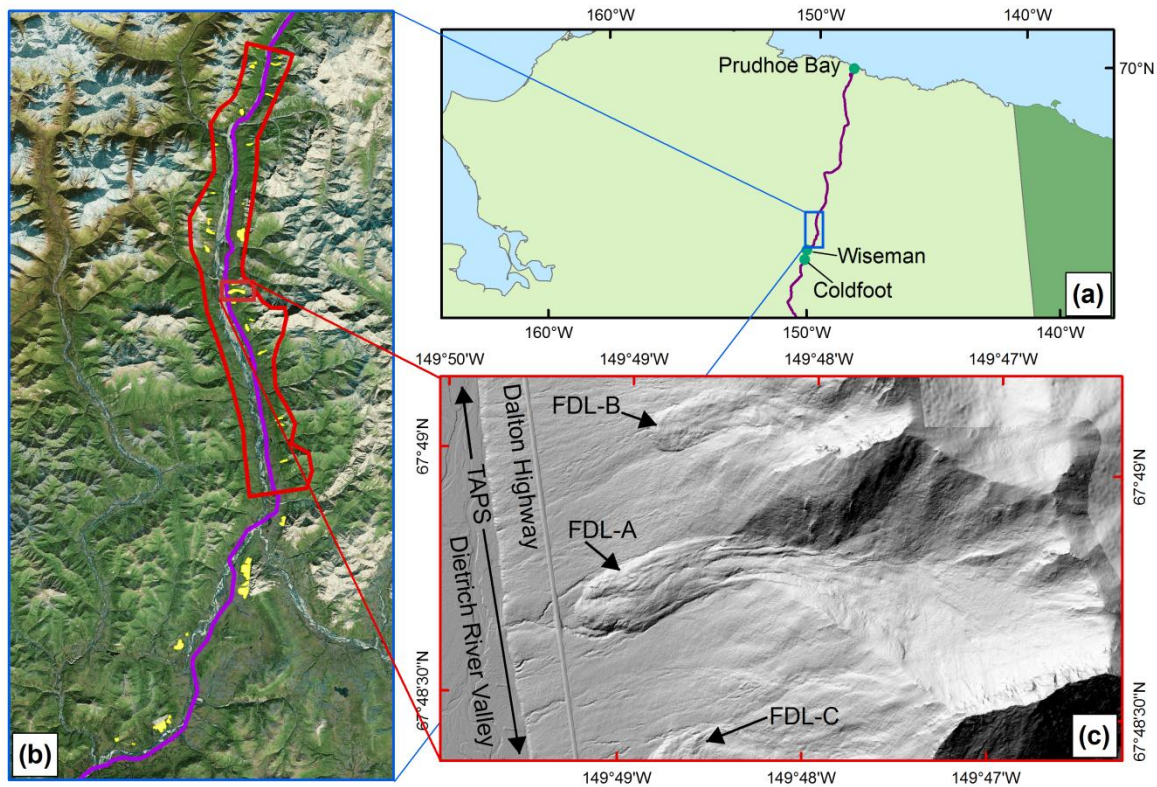


Figure 1. Location map of the study area. (a) Overall research area in blue rectangle relative to the Dalton Highway and nearest communities; (b) identified FDLs (shown in yellow) along the Dalton Highway. The red inset (c) is an example of LiDAR coverage of FDLs, showing FDL-A and portions of the adjacent FDLs. (Base map data from ASGDC 2014, GINA 2014, and Hubbard et al. 2011.)

SCOPE OF WORK

The overall goal of this project was to continue work first supported by the Alaska Department of Transportation and Public Facilities (ADOT&PF) and the Alaska University Transportation Center (AUTC) in the 2012 Phase 1 of the FDL study (Darrow et al. 2012). This additional funding supported fieldwork and data collection, data analysis, and the synthesis of data collected both previously and during the funding period. PI Darrow traveled to the field (with colleagues Daanen and Hubbard from the Alaska Division of Geological & Geophysical Surveys [DGGS]) in August 2014, March 2015, and May 2015 to measure the location of surface marker pins on FDLs along the Dalton Highway. During these trips, we also downloaded data from the automated data acquisition systems currently in position on and near FDL-A. Darrow and Simpson, the MS student working on this project, analyzed the data from 2014 and prior trips, establishing trends in movement rates and directions.

This analysis was synthesized and disseminated as a presentation to ADOT&PF and through multiple oral updates to Alyeska Pipeline Service Company personnel. The analysis also was or will be disseminated in a conference paper (Darrow et al. 2015), in two journal publications (Simpson et al. in review; submitted to *Environmental and Engineering Geoscience*); Darrow et al. (in preparation for submission to *The Cryosphere*), as a Master's thesis (Simpson 2015, in print) and as this final report.

In addition to the scope of work specified in the proposal and completed as outlined above, work was done on a concurrent and related project "Monitoring and Analysis of Frozen Debris Lobes Using Remote Sensing," funded by the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology (OASRT). Specifically, PI Darrow and an undergraduate research assistant, Gyswyt, analyzed historic images of the FDL area of interest (AOI) to determine changes in rate of movement from 1955 to the current time.

As most of the results from this research either have been or will be released through peer-reviewed conference and journal publications, this final report serves as a brief summary of the content of those articles. The reader is encouraged to seek out the individual articles or contact the PI (<http://ine.uaf.edu/people/researchers/margaret-darrow/>) for more details on each article, as these summaries are brief to avoid copyright infringement.

CHAPTER 2

FINDINGS

This chapter contains summaries of the peer-reviewed conference and journal publications through which the results of this research will be disseminated.

Darrow, M. M., Simpson, J. M., Daanen, R. P., Hubbard, T. (2015). "Characterizing a frozen debris lobe, Dalton Highway, Alaska." *Cold Regions Engineering 2015, Proceedings, Salt Lake City, Utah (July 2015), pp. 57-67.*

Darrow presented a summary of 2013 and 2014 work on FDL-A at the 2015 ASCE Cold Regions Engineering conference. The presentation and companion paper summarized the continuation of fieldwork and data analysis focused on FDL-A since the initial findings in Phase I of the project (Darrow et al. 2012, 2013). As part of Phase I, we drilled within and around FDL-A. The sampled FDL-A soil consisted of silty sand with gravel, and was 26.4-m thick over chloritic schist bedrock. We did not intercept any massive ice while drilling. During the subsurface exploration, we installed geomechanical instrumentation, including a MEMS-based in-place inclinometer (M-IPI). The device was sheared off in late October 2012, but we continue to retrieve data from the upper 20 m of the device.

Movement of FDL-A occurs mainly as shear within a zone near the bottom of the lobe (see Figure 2). The M-IPI data reveal that movement also occurs as internal flow, which is temperature-dependent (see Figure 3). Combining these two modes of movement, FDL-A currently moves about 7 m per year in its upper reaches, and about 4 to 5 m per year near the toe (see Figure 4). Over the 2013-2014 measurement year, it moved at an average rate of 1.3 cm per day. Data for the 2014-2015 measurement year are currently being analyzed to determine movement rates.

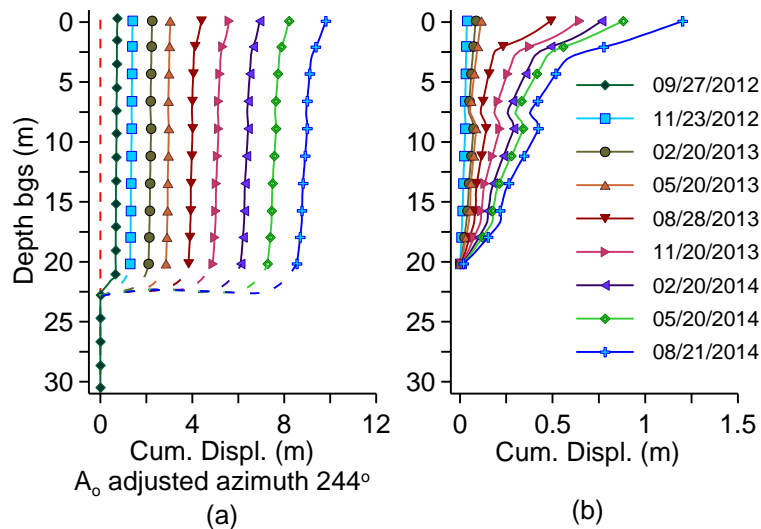


Figure 2. Cumulative displacement measurements reported by the M-IPI device installed within FDL-A. Shear zone is approximated with dashed lines (a). The data in (b) show only movement from above the shear zone at 20.1 m below the ground surface (bgs).

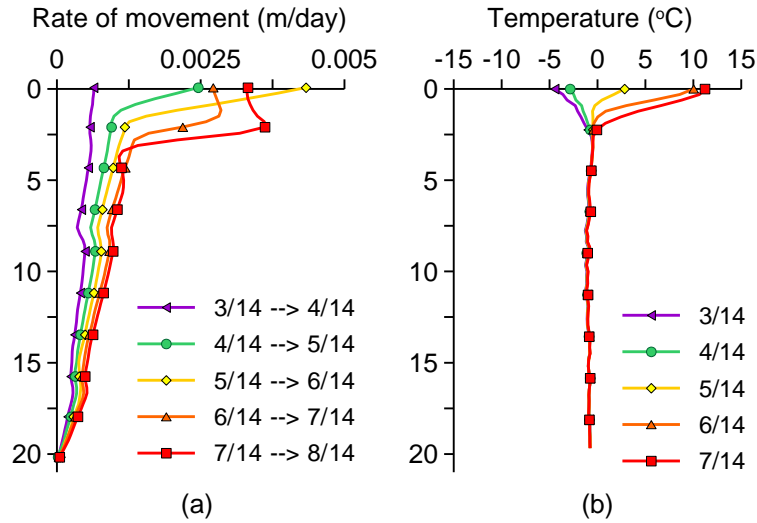


Figure 3. Monthly rate of movement (a) and subsurface temperatures (b) of FDL-A, for part of 2014.

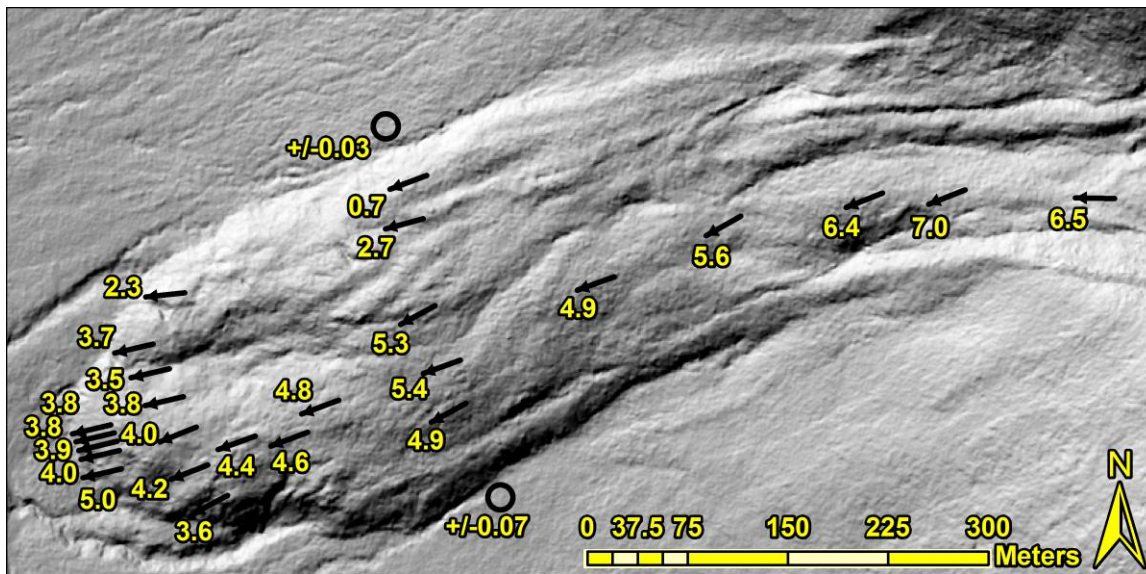


Figure 4. Summary of movement of FDL-A from August 28, 2013 to August 21, 2014. Arrows indicate direction of movement, and numbers are amount of movement in meters. (Base map data from Hubbard et al. 2011.)

Simpson, J. M., Darrow, M. M., Huang, S. L., Daanen, R. P., Hubbard, T. "Investigating movement and characteristics of a frozen debris lobe, south-central Brooks Range, Alaska." Submitted to Environmental and Engineering Geoscience (in review).

In addition to summarizing the fieldwork conducted on FDL-A since 2012, this paper presents the GIS analysis of FDL-A and its catchment, investigating characteristics such as catchment and lobe area, slope angle, slope aspect, geology, and vegetation height and coverage. The GIS analysis was conducted as a pilot study to guide future GIS work when high-resolution

LiDAR data is obtained for the AOI. The paper also presents the results of direct shear testing of frozen soil samples collected from FDL-A in 2012, and the integration of these results into a conventional slope stability model. After conducting all of this analysis, we suggest that more subsurface exploration is needed with a geophysics component to locate the bedrock surface and the shear zone within FDL-A, and to determine water conditions and the extent of massive ice within the lobe. We also recommend the development of a slope stability model that incorporates temperature effects. Such a model could be used to investigate how other permafrost slopes along our infrastructure may respond to increasing temperatures.

Darrow, M. M., Gyswyt, N. G., Simpson, J. M., Daanen, R. P., Hubbard, T. "Monitoring and change detection of frozen debris lobes, southern Brooks Range, Alaska." In preparation for submission to *The Cryosphere*.

This paper will serve as an overview of the eight FDLs that we have observed and measured since 2013. We will include a summary of the bedrock geology of the FDL catchments, uniaxial compressive strengths of tested rock samples, and lobe characteristics including results from a suite of laboratory tests on soil samples. We will present an analysis of the current surface movement rates as measured in the field with a differential global positioning system (DGPS) unit, and compare these rates to those obtained through analysis of historic imagery dating back to 1955. This paper will be submitted to *The Cryosphere* journal by December 2015. Figure 5 is an example of the catchment and lobe delineation of FDL-A presented in the paper, and Figure 6 illustrates the progression of FDL-D downslope since 1955 based on the analysis of historic images. Figures containing similar data for all eight FDLs investigated will be presented in the journal paper.

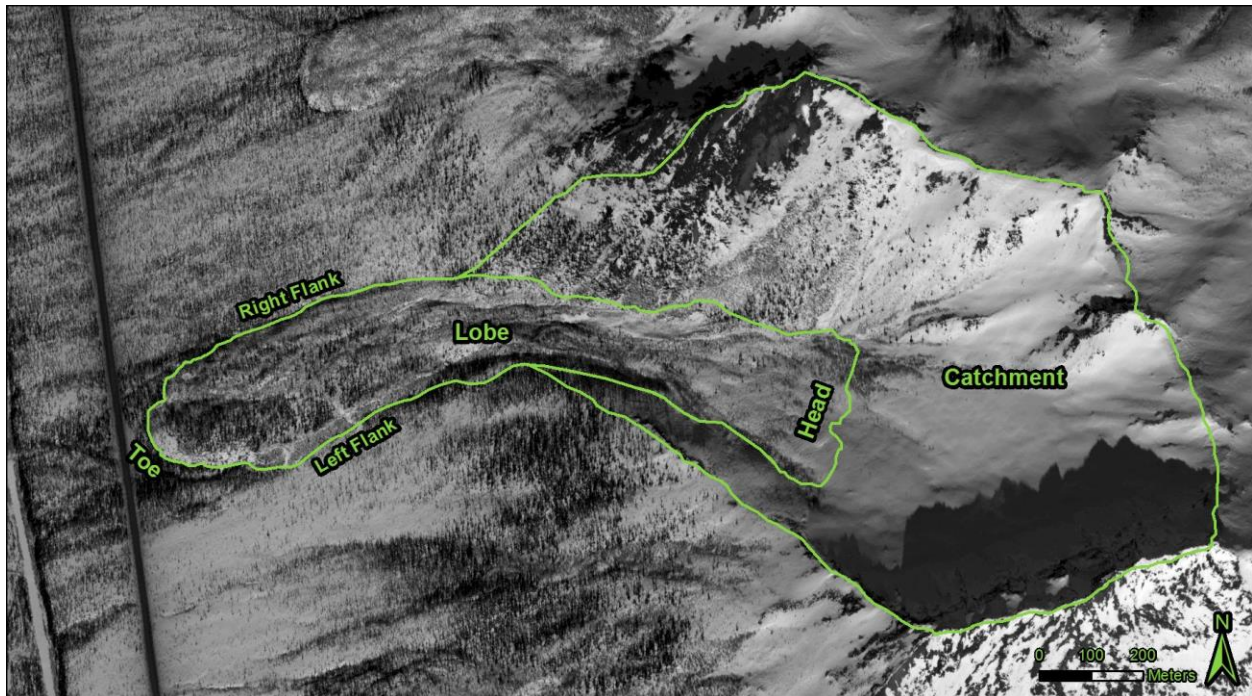


Figure 5. Delineation of FDL-A lobe and catchment extents. (Base map data Copyright 2014 DigitalGlobe, Inc.)

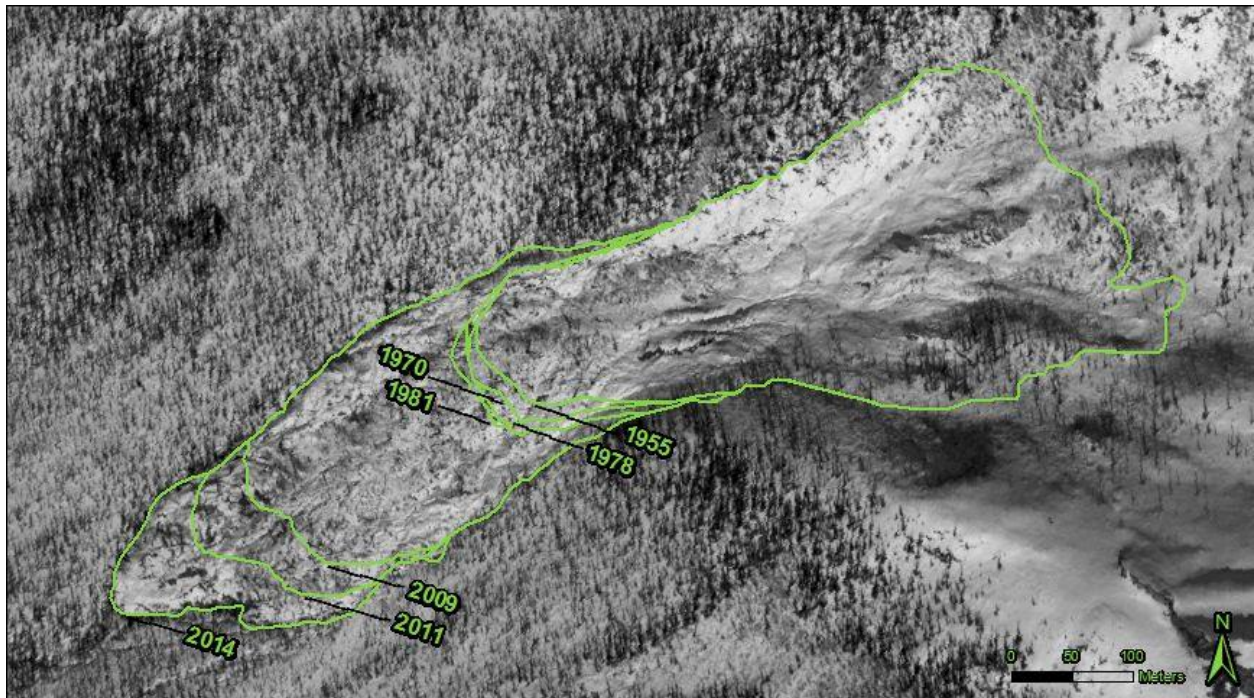


Figure 6. Progression of FDL-D downslope based on analysis of historic imagery. (Base map data Copyright 2014 DigitalGlobe, Inc.)

CHAPTER 3

CONCLUSIONS AND RECOMMENDATIONS

During Phase 1B of this research, we continued our investigations of FDL-A started in 2012, and extended the research to include monitoring of seven additional FDLs. While specific values will be included in forthcoming publications, the investigated FDLs move at a variety of rates from less than a meter per year to 20 m per year. Those that have the slower rates should not be discounted, however. Analysis of historic imagery indicates that the FDLs have moved asynchronously since 1955, with currently slow-moving FDLs demonstrating high rates of movement in the past. All of the FDLs investigated in the field during this phase of research have characteristics of increasing instability, including scarps in their catchments that formed within the last thirty years. As analysis of subsurface data from FDL-A indicates, the movement of FDLs is temperature-dependent, which suggests the need for ongoing monitoring as temperature and precipitation in the area change in the future.

Many FDLs are located uphill of important infrastructure in the State of Alaska. Changes within these permafrost features may yield insight into how frozen slopes throughout the State respond to changing climate. With these facts in mind, we recommend the following.

- Continue annual measurements of the surface marker pins using a DGPS device. Such surface markers are installed on eight FDLs that were chosen based on their proximity to the road and/or movement rates. Annual measurements will alert us to any increase in movement rates as these features head downhill towards infrastructure.
- Conduct additional drilling on FDL-A. Although costly, additional subsurface data will answer important questions, such as the location of the bedrock surface beneath the lobe, lobe thickness and depth to the shear zone, and the distribution of water pressure in other locations. We received a wealth of information from the M-IPI device, even after the device was sheared. Thus we recommend the investment in another M-IPI installation, along with vibrating wire piezometers, to record subsurface movement and pore water pressure, respectively. Such a boring should be backfilled with a specialized grout containing an antifreeze component so that the piezometer readings are not affected by the subfreezing temperatures.
- Drilling should be conducted jointly with geophysical surveys. Geophysical methods cover greater cross-sectional area than individual borings. The recommended method is Induced Polarization Tomography (IPT). This method has the best potential to produce cross sections of FDL conditions deep enough for delineating the FDL-A shear zone and for identifying the zones of high pore pressure within FDL-A.
- Finally, results from traditional modeling demonstrated limitations due to lack of subsurface information. The modeling did not sufficiently address the temperature-dependence of the frozen soils' strength nor the presence of massive ice and thus a source of water within an FDL. We recommend the development of a model that incorporates temperature effects to predict how these features, as well as other permafrost slopes, will respond to changes in climate. This more rigorous model could be used to evaluate the success of mitigation measures such as cooling FDL-A to reduce or eliminate its progress towards infrastructure.

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