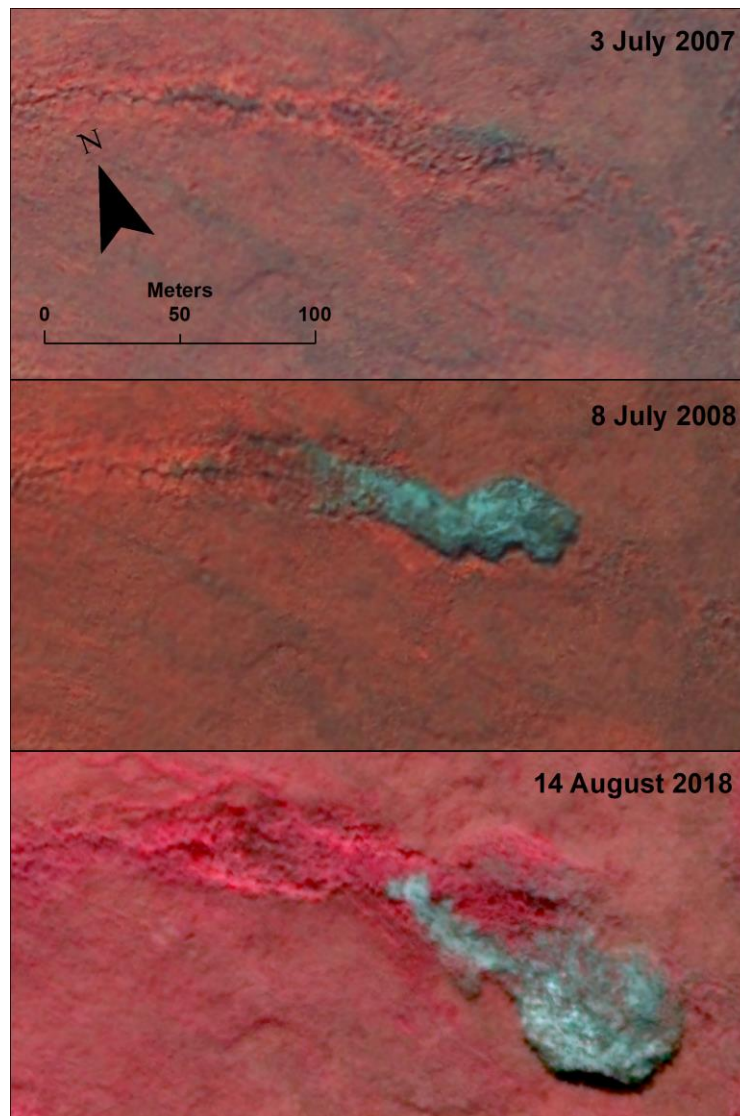




Monitoring of Permafrost Slope Failures in Alaska's Arctic National Parks

Updates from 2018 Satellite Images

Natural Resource Data Series NPS/ARCN/NRDS—2020/1251



ON THE COVER

An active-layer detachment (ALD) that formed in 2007 and then continued to grow as a retrogressive thaw slump (RTS). The slope is downhill to the left. The ground surface was undisturbed in July 2007, then an 80 m-long ALD formed and was visible in July 2008. By 2018 the original ALD was mostly revegetated, but erosion continued by retrogressive thaw slumping from the southeastern side of the ALD, and it advanced another 70 m in 10 years. These are high-resolution satellite images (IKONOS 2007 and 2008; Worldview-2 2018) in color-infrared color scheme, which shows green vegetation as red. The location is near longitude -161.729°, latitude 67.589°

Monitoring of Permafrost Slope Failures in Alaska's Arctic National Parks

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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 Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Abstract

Permafrost is an important component of Arctic ecosystems that is monitored by the Arctic Inventory and Monitoring Network (ARCN) of the National Park Service. As a part of ARCN Permafrost Vital Sign, we monitor landforms caused by thaw of permafrost. This monitoring includes 1) mapping over extensive areas of small landslides caused by thaw of ice-rich frozen ground: retrogressive thaw slumps (RTS) and active-layer detachments (ALD); and 2) intensive monitoring of selected high-impact RTS. This report contains results from 2018 satellite high-resolution imagery for both projects.

Images from 2018 were available for an area of about 800 km² in the Maiyumerak Mountains of southwestern Noatak National Preserve. This area was previously mapped on images from 2007-2009. The area of ALD and RTS both declined greatly from 2007-2009 to 2018; the area of bare soil in ALD decreased from 245,796 to 9,060 m² and bare soil exposed in RTS decreased from 75,151 to 10,455 m². Most of the ALD present in 2007-2009 had revegetated, and the ALD mapped in 2018 were mostly newly formed in other locations. About half of the RTS in 2018 had developed from ALD mapped in 2007-2009, and the remainder were newly formed or persisted from RTS mapped in 2007-2009.

A mass initiation event of ALD and RTS occurred around 2004, just prior to the images used in the previous mapping effort. The results presented here support our informal observations suggesting that as of 2018, no major new ALD and RTS events had occurred in ARCN.

An image from 2018 was also available to update intensive monitoring of the Noatak Slump, a large RTS located directly on the Noatak River. This slump had 6 previous measurements from 2008 to 2016, during which time it had grown rapidly. However, from 2016 to 2018 it grew by just 370 m², which was less than 1% of the 2018 area (42,913 m² or 4.3 ha). The main escarpment was active only on a small portion of the slump, where it retreated a maximum of about 8 m in the two years. The slump has apparently largely stabilized, though most of it still remained un-vegetated.

Glossary

Active layer. The surface layer of ground over permafrost that thaws and re-freezes annually.

Active-layer detachment (ALD). A small landslide that occurs on vegetated slopes with permafrost. ALDs develop over a period of days to weeks in a single thaw season. A layer of thawed material roughly 1 m thick slides downhill on saturated fine-grained material over permafrost. An ALD exposes an area of bare soil and has a deformed mat of soil and vegetation at its lower end.

Thaw degree-day. An index of the heat available for thaw. The difference between the daily mean temperature and 0° C is computed for each day and summed over a period of days, such as a single thaw season.

Multispectral. An image containing two or more wavelength bands across the spectrum.

Normalized Difference Vegetation Index (NDVI). A numerical index computed from multispectral imagery by the following formula: $NDVI = (NIR - R) / (NIR + R)$, where NIR is a near-infrared (0.757 to 0.853 μm on IKONOS images) reflectance measurement and R is a red (0.632 to 0.698 μm on IKONOS images) reflectance measurement. NDVI is an indicator of the greenness of vegetation and can be used to estimate leaf area.

Orthorectification. The process by which an aerial photograph is corrected for distortions due to perspective, the camera, and terrain to produce an image with map coordinates and a consistent scale.

Panchromatic. Image that contains one wavelength band corresponding to a sum of all visible wavelengths.

Permafrost. Ground that remains at or below the 0°C for 2 or more consecutive years. Most permafrost in Alaska has been frozen for many years, even thousands of years. Permafrost may be present in materials that contain considerable ice, or materials such as bedrock with very little ice.

Retrogressive thaw slump (RTS). A slope failure in which a cut-bank advances by thaw into ice-rich permafrost as material thaws in the steep bank, falls or slumps onto the adjacent more gentle slope, and then is transported away by water erosion, sliding, or viscous flow. RTS can persist and grow for many years.

Slope failure. Mass movement of material downslope by gravity. “Failure” refers to the loss of cohesion in the material that allows a mass of material to move downslope.

Introduction

Permafrost thaw can lead to subsidence of the ground surface, mass movement of material on slopes, and exposure of bare soil to erosion by water. Two important types of thaw-induced slope failures in the National Parks of northern Alaska are active-layer detachments (ALD) and retrogressive thaw slumps (RTS; Balser et al. 2014, Swanson 2014, Swanson and Nolan 2018). ALD are small landslides that occur on vegetated slopes over a period of days to weeks in a single thaw season (Fig. 1). A layer of thawed material roughly 1 m thick slides downhill on wet mud over the underlying frozen ground. RTS occur where a cut-bank advances into ice-rich permafrost as material thaws in the steep bank, falls or slumps onto the adjacent more gentle slope, and then is transported away by water erosion, sliding, or viscous flow (Fig. 2). In contrast to ALD, an RTS can persist and grow for many years.

Concerns about the changing state of permafrost led the National Park Service Arctic Inventory and Monitoring Network (ARCN, Fig. 3), to include permafrost as a monitoring “Vital Sign” (Lawler et al. 2009, Swanson 2017a). ARCN permafrost monitoring includes 1) mapping of ALD and RTS over extensive areas to determine if these features are becoming more or less common, and 2) intensive monitoring of selected large and high-impact RTS. The present report is an update, based on imagery taken in 2018, to both of these projects.

Our initial map of ALD and RTS (Swanson 2014) covered all of ARCN and was possible because NPS acquired nearly complete coverage of ARCN by cloud-free, high-resolution satellite imagery from 2006-2009. Our monitoring protocol calls for re-visiting selected areas at approximately 10-year intervals. Thus in 2018 I submitted a request for new high-resolution satellite imagery of areas known to have significant ALD and RTS activity from the initial mapping. This request was made to the “Commercial Remote Sensing Space Policy” (CRSSP, U.S. Geological Survey 2019) program for free access to high-resolution imagery for federal government agencies. Most areas of interest submitted in 2018 were returned with imagery that was unusable due to clouds or very low sun angle. However, suitable imagery was returned for two areas of interest and are reported here.

The two areas of interest with high-quality 2018 imagery include 1) a large RTS on the Noatak River (the “Noatak Slump”) in the Noatak National Preserve (NOAT) where we have conducted intensive monitoring (Figs. 2 and 3), and 2) the Maiyumerak Mountains (in the far western Baird Mountains in western NOAT), an area known from our initial map to have numerous ALD and, to a lesser extent, RTS (Fig. 3).

The Noatak Slump (Fig. 2) is one of the largest slumps in terms of area and has the tallest escarpment of any known slump in ARCN (Swanson and Nolan 2018; it is referred to there as slump “NOAT265”). The Noatak Slump is also of interest because it is located on a major river (the Noatak) and has shed sediment into the river for over a decade. The slump grew steadily in area from our first image in 2008 through our most recent previous image in 2016, with a slight slowdown in rate between 2012 and 2016. Intensive monitoring of other selected RTS identified by that initial inventory suggests that many of them have become stabilized, or their rate of growth has slowed in

recent years (Swanson and Nolan 2018). Here I analyze the 2018 image to determine if the growth rate of the Noatak Slump continued to decline between 2016 and 2018.

Our ARCN-wide map of ALD and RTS, based on images from 2006 to 2009 (Swanson 2014), revealed hundreds of ALD and RTS, many of which were initiated in 2004 by unusual weather (Balser 2014, 2015; Swanson 2014). Subjective observations based on flights by the author and others since that time suggest that no new ALD events comparable to the one in 2004 have occurred, and most ALD from that era have re-vegetated. The Maiyumerak Mountains had a dense concentration of ALD and a few RTS in our initial inventory (Fig. 3). The purpose of the re-mapping effort using images from 2018 was to learn if the ALD mapped previously become re-vegetated, and if new ALD or RTS had formed during the approximately 10 years since the preceding survey.

Terminology note

In previous publications we have used the term *thermal erosion* for the processes that act to form ALS and RTS. A strict reading of the definition of this term (van Everdingen 1998) suggest that it should be restricted to features that form only by the erosive action of water, and thus it is not used here. ALD and RTS are both forms of *slope failure*. However, my mapping method delineates only bare soil areas and not the entire area affected by slope failure; the latter can include areas that moved with vegetation intact, and areas where vegetation has regrown. Thus when presenting measurements of area, I refer to *erosion features* (i.e., the area of exposed bare soil) that has resulted from the slope failures. These bare soil areas are both readily mapped and are more significant in terms of impact than the vegetated or re-vegetated portions of the slope failures.

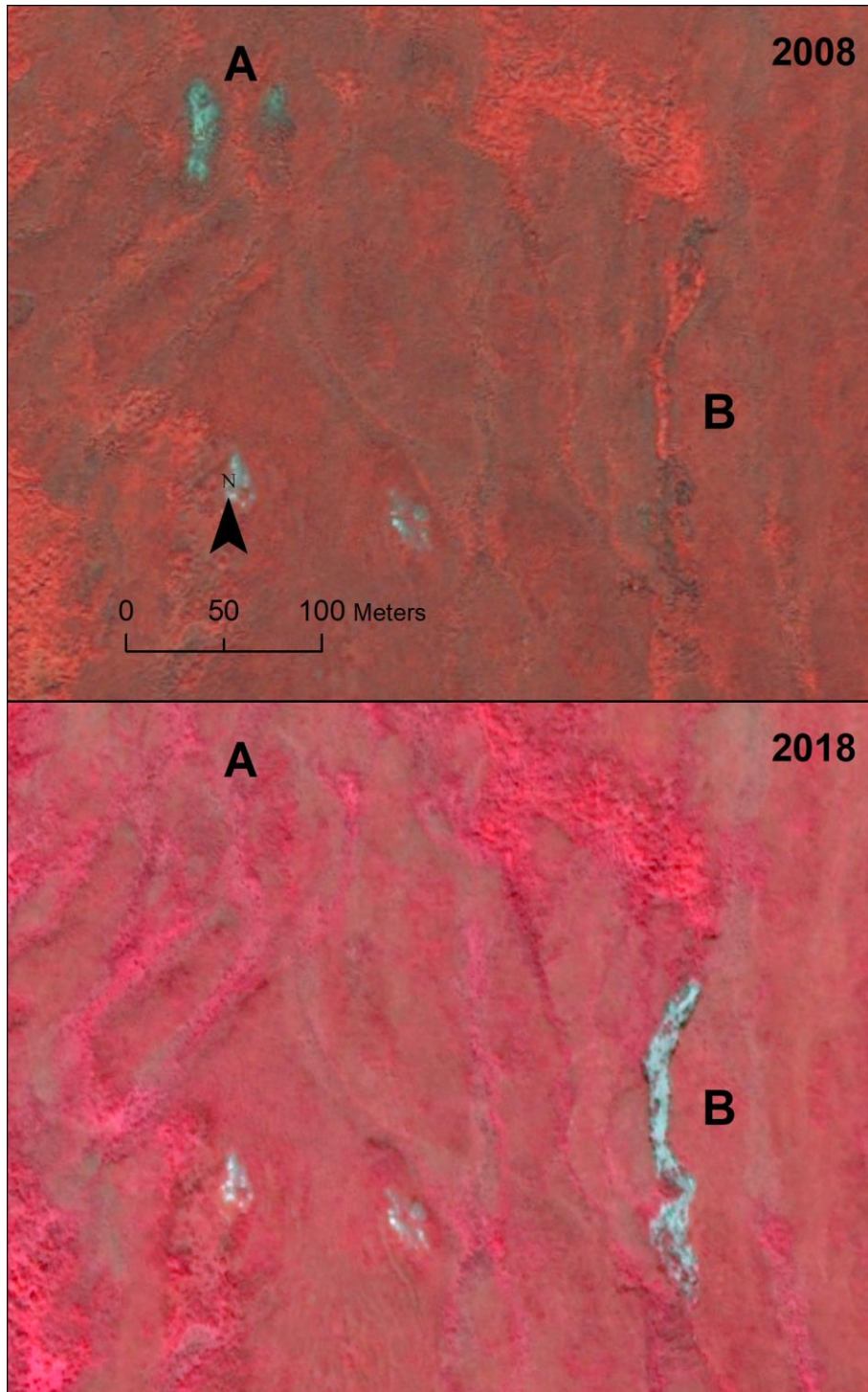


Figure 1. Active-layer detachments (ALD) in 2008 and 2018. Two ALD near letter A in the upper (2008) image had re-vegetated completely by 2018 (lower image). A new ALD is visible near the letter B in the lower (2018) image. The ground slope here is from north to south. The image center is near longitude - 161.547°, latitude 67.629°. The upper image is an IKONOS satellite image and the lower is a Worldview-2 satellite image, both in color-infrared color scheme, where vegetated areas are bright red or pink and unvegetated areas are gray.



Figure 2. The Noatak Slump on 7 July 2013. On this date the escarpment at the upper end of the slump was about 15 m high and the slump was growing rapidly. NPS photo by Rory Nichols.

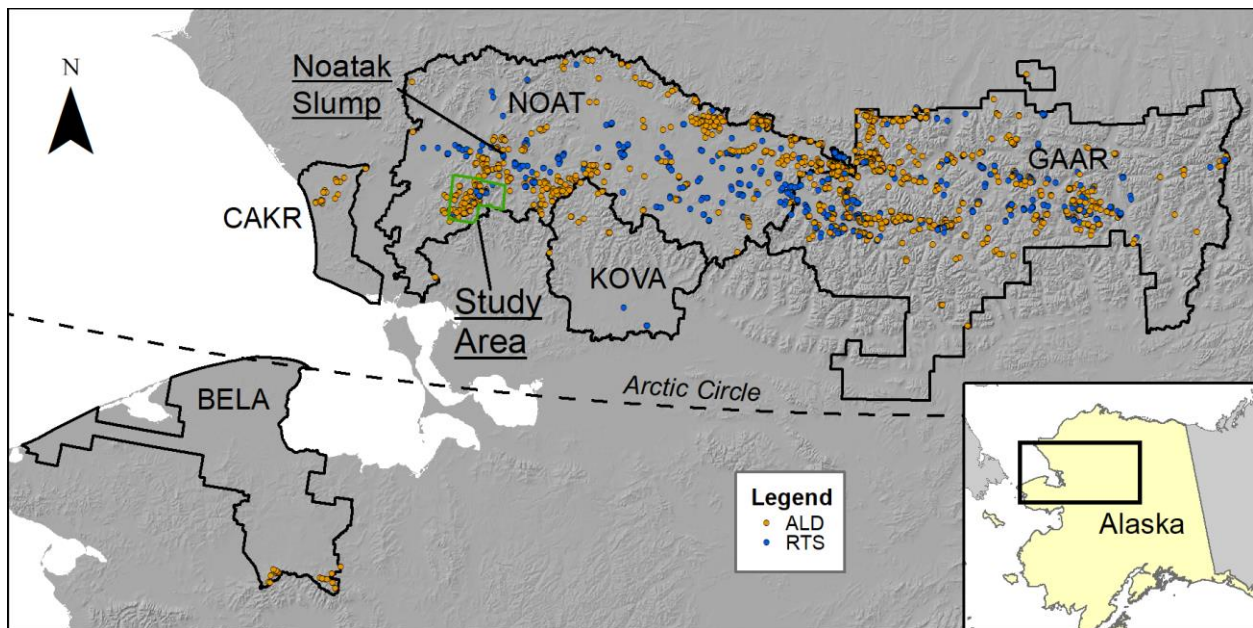


Figure 3. Location of the Arctic Inventory and Monitoring Network, the Noatak retrogressive thaw slump, and the erosion feature re-mapping study area. The National Park Units are labeled with the following abbreviations: Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), Noatak National Preserve (NOAT). Points show locations of active-layer detachments (ALD, orange) and retrogressive thaw slumps (RTS, blue) mapped network-wide on satellite images from 2006 to 2009.

Methods

The 2018 re-measurement of the Noatak RTS was made with a Worldview-3 image from 6 July 2018. It was orthorectified in ArcGIS using the satellite's orientation parameters and the Alaska statewide IFSAR digital elevation model (DEM; U.S. Geological Survey 2015). The resulting image resolution was 1.52 m (multispectral) and 0.27 m (panchromatic). The outline of this slump in 2018 was compared to outlines digitized from orthophotographs created from 35-mm digital aerial photographs taken in 2008, 2010, 2011, 2012, and 2016 as described in Swanson and Nolan (2018). For additional information on the procedure used to create these orthophotos, see the ARCN Permafrost monitoring protocol (Swanson 2017a, b). To add an additional area measurement, I also digitized the outline of this slump on the 2009 SPOT satellite mosaic of Alaska (Alaska Geospatial Council 2011). This SPOT mosaic was created from SPOT 5 images, which have a resolution of 10 m (multispectral) and 2.5 m (panchromatic). This mosaic is available orthorectified and pan-sharpened to 2.5 m in 4 bands (blue, green, red, and near infrared).

The image dates of the Noatak Slump in various years ranged from 5 July (early in the thaw season) to 11 September (near the end of the thaw season). Measurements from consecutive years could in fact be separated by more or less than a full thaw season; no growth occurs during the winter when the ground is frozen. To provide a scale for the x-axis for graphs of area growth over time, I plotted slump area vs. the cumulative sum of thaw degree-days, as measured at the nearest climate monitoring station, the Kelly Remote Area Weather Station (RAWS; Western Regional Climate Center 2019). This same convention was used in Swanson and Nolan (2018). The annual sum of thaw degree-days at the Kelley RAWS over the period of record for climate observations (1998-2018) has ranged from 1097 in 2000 to 1817 in 2007, with an average of 1457 (Fig. 4). The mean annual air temperature at the Kelley RAWS has ranged from -6.5 in 1999 to -1.3 in 2016 (Fig. 5). The three warmest years occurred recently (2014, 2016, and 2018).

Permafrost slope failures (ALD and RTS) were mapped in the Maiyumerak Mountains study area with Worldview-2 (WV-2) images from 14 Aug 2018. These images cover 793.6 km² within ARCN. I orthorectified these images in ArcGIS using the satellite's orientation parameters and the Alaska statewide IFSAR digital elevation model (U.S. Geological Survey 2015). The resulting image resolution was 2.2 m (multispectral blue, green, red, and near-infrared) and 0.6 m (panchromatic). I also mapped ALD and RTS using the 2009 SPOT satellite mosaic described above. Due to clouds, the entire Maiyumerak Mountains study area is not covered by all three image types (Fig. 6). Cloud-free IKONOS images covered 694.3 km² in the study area (the area covered by the 2018 WV-2 images).

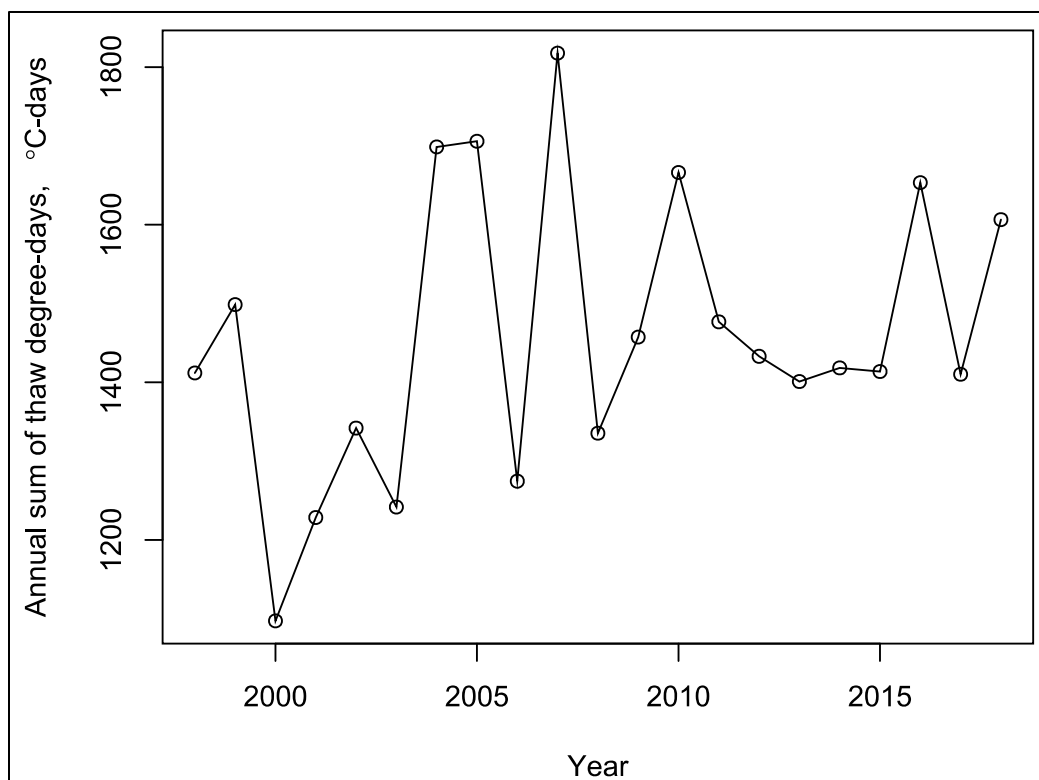


Figure 4. Annual sum of thaw degree-days vs. year at the Kelly RAWS.

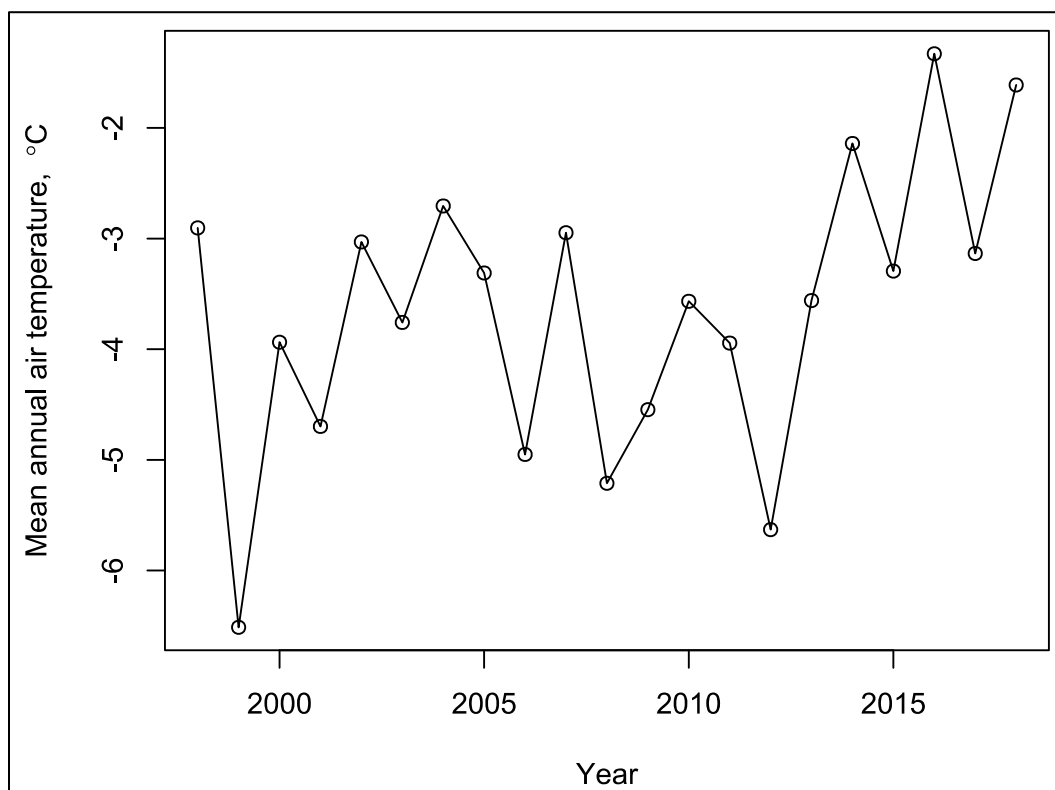


Figure 5. Mean annual air temperature at the Kelly RAWS.

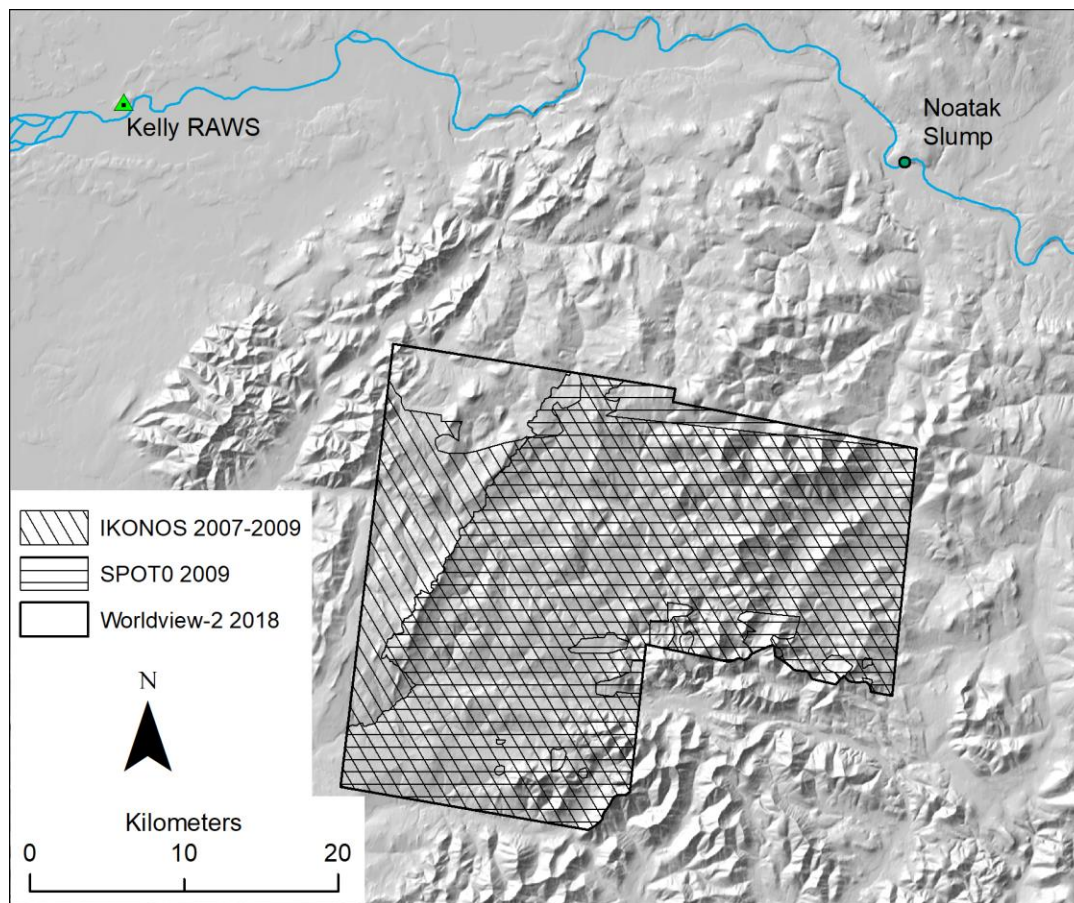


Figure 6. Study area location detail and image boundaries. The outer boundary shows the coverage of the 2018 Worldview-2 images. Hatching shows the coverage of the 2009 SPOT and 2007-2009 IKONOS images within the Worldview-2 boundary. The missing areas had clouds or cloud shadows. Kelly RAWS is the source of climatic data used in this report.

The study area has shrubby tundra vegetation (Table 1). ALD and RTS were discovered in the initial mapping in all the shrub types, but not the rocky alpine barrens.

The original mapping of ALD and RTS in the study area (Swanson 2014) was incorporated here without revision. It was based on the NPS IKONOS 2006-2009 image mosaic. This imagery was originally taken at a resolution of 4 m (multispectral blue, green, red, and near-infrared) and 1 m (panchromatic). It is available pan-sharpened to 1 m, and was orthorectified using the best available DEM at that time, the National Elevation Dataset at 60 m resolution. The study area here is covered by images taken in 2007 (9% of the mapped area of erosion features), 2008 (69.5%), and 2009 (21.5%).

Erosion features were mapped by a partially automated, 3-step process: 1) map bare-soil polygons by computing normalized difference vegetation index (NDVI), classify the NDVI images as vegetation or un-vegetated by thresholding the NDVI values, and convert the result to polygons; 2) manually create a point layer marking all ALD and RTS visible on the images, with the feature type as an attribute, and 3) join these two layers to extract the permafrost-related bare soils areas (ALD and

RTS) and eliminate non-target bare soil areas, such as river gravel bars and bedrock exposed on mountain ridges. Details of the mapping process are given in Swanson (2014) and the vital sign protocol (Swanson 2017a, b). Because the Worldview-2 multispectral data had sufficiently high resolution (2.2 m) for step one above of the mapping process, I used the multispectral data as-is (without pan-sharpening) to map the un-vegetated areas in step one. However, I used pan-sharpened images to visually identify the erosion features (step 2 above).

Table 1. Vegetation of the study area

Proportion of area, %		
Study Area ^A	Within ALD and RTS ^B	Vegetation type ^C
33	49	Upland Dwarf Birch-Tussock Shrub
16	3	Alpine Dryas Dwarf Shrub
11	23	Upland Birch-Ericaceous-Willow Low Shrub
11	0	Alpine Alkaline Barrens
8	9	Upland Sedge-Dryas Meadow
6	6	Upland Alder-Willow Tall Shrub
6	0	Alpine Acidic Barrens
4	9	Upland Willow Low Shrub
3	3	Alpine Ericaceous Dwarf Shrub

^AProportion of the entire study area in each vegetation type; only types covering more than 1% of the study area are shown.

^BProportion of area within mapped polygons of ALD and RTS from the previous (IKONOS 2007-2009) mapping.

^CVegetation types from Jorgenson et al. (2009).

Results

The Noatak Slump

The Noatak Slump grew in area by 370 m² between 11 July 2016 and 6 July 2018 (Figs. 7 and 8). This was less than 1% of the total area in 2018 of 42,913 m² (about 4.3 ha). The maximum total scarp retreat over the two years was 8 m. This was by far the slowest growth rate since monitoring began in 2008. The floor of the slump was still mostly bare of vegetation in 2018 and thus susceptible to erosion by water. However, the most prominent debris-flow channel that was visible in 2016 was still apparent in 2018, and no obvious new channels had formed. These channels mark the course of the debris flows that led from the zone of water-saturated mud that was formerly present below the active scarp (Swanson and Nolan 2018). This saturated zone was probably very small or absent in 2016-2018, judging from the slow rate of growth and lack of new debris flows.

Maiyumerak Mountains ALD area

In the area covered by both IKONOS (2007-2009) and SPOT (2009) imagery, The count of ALD and area of bare soil exposed by ALD as mapped on the SPOT images dropped to about half of what was mapped on the IKONOS imagery (Table 2, Fig. 9). While some of the drop in area of bare soil in ALD could be attributed to the lower resolution of the SPOT images (i.e., failure to detect some ALD on the SPOT), inspection of the images confirms that the ALD were indeed growing-over rapidly with vegetation during this period, and at least some of the drop in bare ALD area is due to re-vegetation. The count of RTS and the bare soil area of RTS increased slightly from the IKONOS to SPOT.

In the somewhat larger area covered by both IKONOS (2007-2009) and Worldview-2 (2018) images, the number of ALD and area of bare soil they exposed dropped greatly between 2007-2009 and 2018 (Table 3; Figs. 9 and 10). In this case, the fewer detections of ALD at the later date cannot be attributed to coarser image resolution, because the latter date actually had higher-resolution data. Most of the ALD mapped in 2007-2009 had re-vegetated completely by 2018 (Fig. 1).

The number of RTS was nearly the same in 2018 as in 2007-2009. The bare soil area of RTS dropped substantially between the 2007-2009 and 2018, but not as precipitously as the area of ALD, and by 2018 ALD and RTS covered similar areas.

The majority of ALD present in 2018 were new: they were in locations where no ALD was present in 2007-2009 (Table 4, Fig. 1). About a quarter of the total area of ALD in 2018 was portions of old 2007-2009 ALD that had failed to re-vegetate completely. The RTS present in 2018 included 1) new features, 2) RTS that formed from an ALD mapped in 2007-2009, and 3) RTS that were still active from an RTS present in 2007-2009. Of the three origins, RTS that formed from ALD visible in 2007-2009 occupied the largest area. Fig. 11 is an example of an ALD from 2007 that continued to grow as an RTS until 2018.

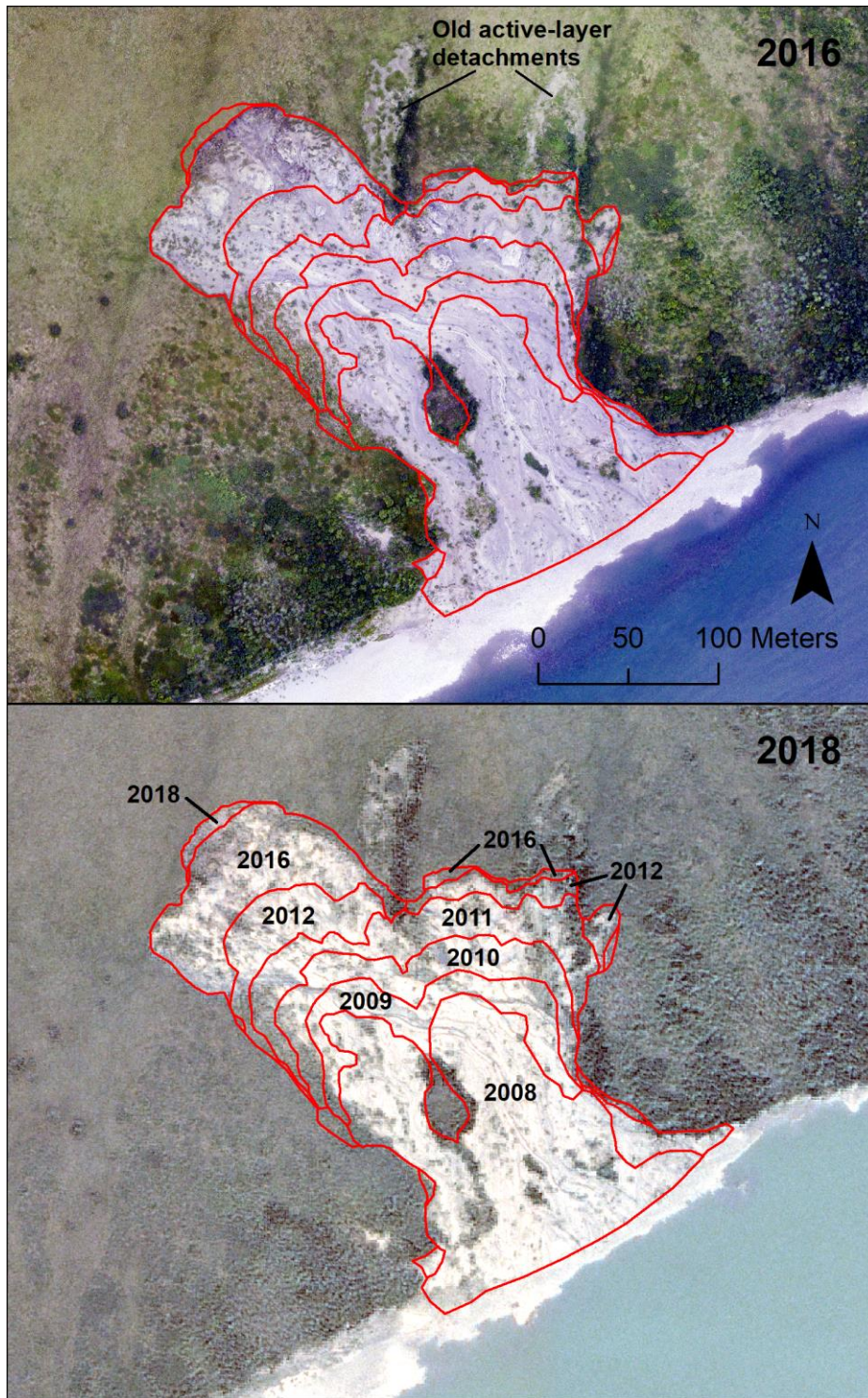


Figure 7. The Noatak Slump in 2016 (above) and 2018 (below). The 2016 image is an orthorectified mosaic from digital aerial photographs, the lower a Worldview-3 satellite image, both in natural color. Perimeters of the slump in various years are shown in red and labeled by year on the lower image. Between 2016 and 2018 there was only a small area of new growth, on the northwest edge of the slump. The slope is to the southeast toward the river. The old active-layer detachments that probably initiated the slump are labeled on the upper image. Center of the slump is near longitude -161.092° , latitude 67.948° .

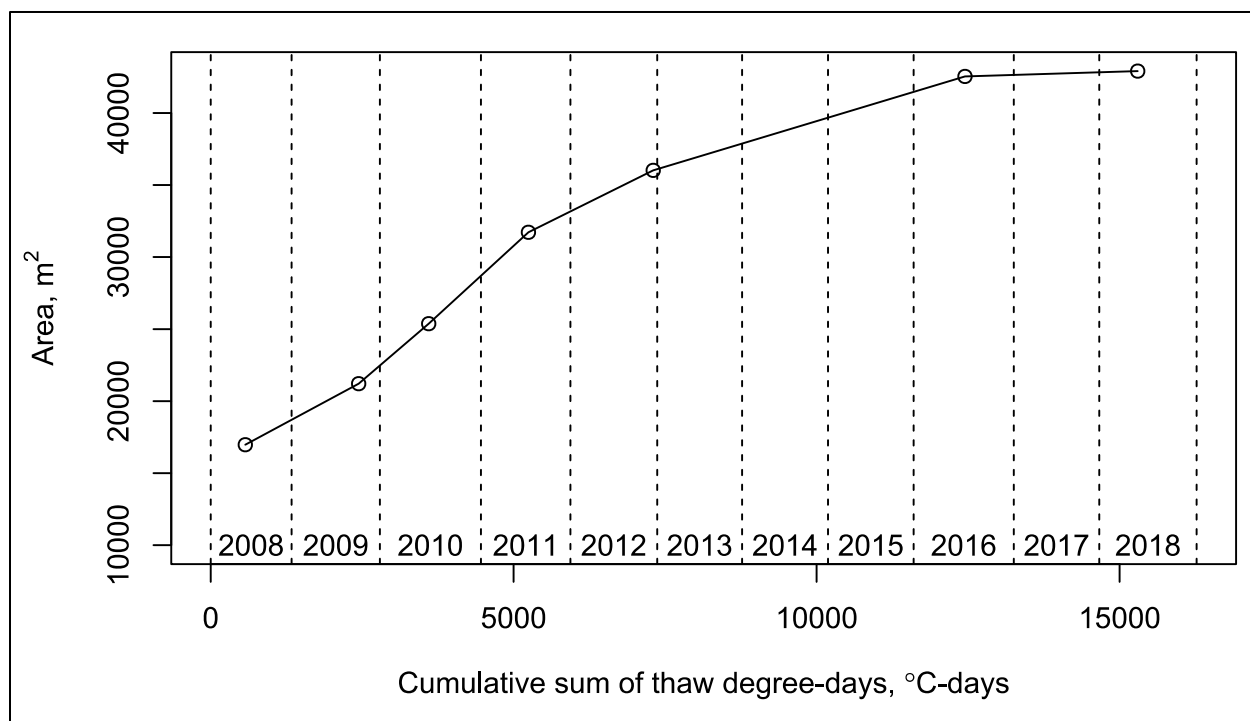


Figure 8. Growth in area of the Noatak Slump. “Time” on the x-axis is expressed as the cumulative sum of thaw degree-days, starting in January 2008. The slump area is plotted versus the degree-day sum on the date of the image used for area measurement. Dashed lines separate the different thaw seasons, which are labeled by year along the bottom of the plot.

Table 2. Count and area of erosion features in the area covered by IKONOS (2007-2009) and SPOT (2009)

Image,Year	Feature ^A	Count	Area ^B , m ²
IKONOS, 2007-2009	ALD	136	219,208
IKONOS, 2007-2009	RTS	24	75,151
SPOT, 2009	ALD	73	98,271
SPOT, 2009	RTS	29	82,491

^AALD – active-layer detachment, RTS retrogressive thaw slump

^BArea of bare soil exposed

Table 3. Count and area of erosion features in the area covered by IKONOS (2007-2009) and Worldview-2 (2018)

Image,Year	Feature ^A	Count	Area ^B , m ²
IKONOS, 2007-2009	ALD	152	245,796
IKONOS, 2007-2009	RTS	24	75,151
Worldview-2, 2018	ALD	26	9,060
Worldview-2, 2018	RTS	26	10,455

^AALD – active-layer detachment, RTS retrogressive thaw slump

^BArea of bare soil exposed

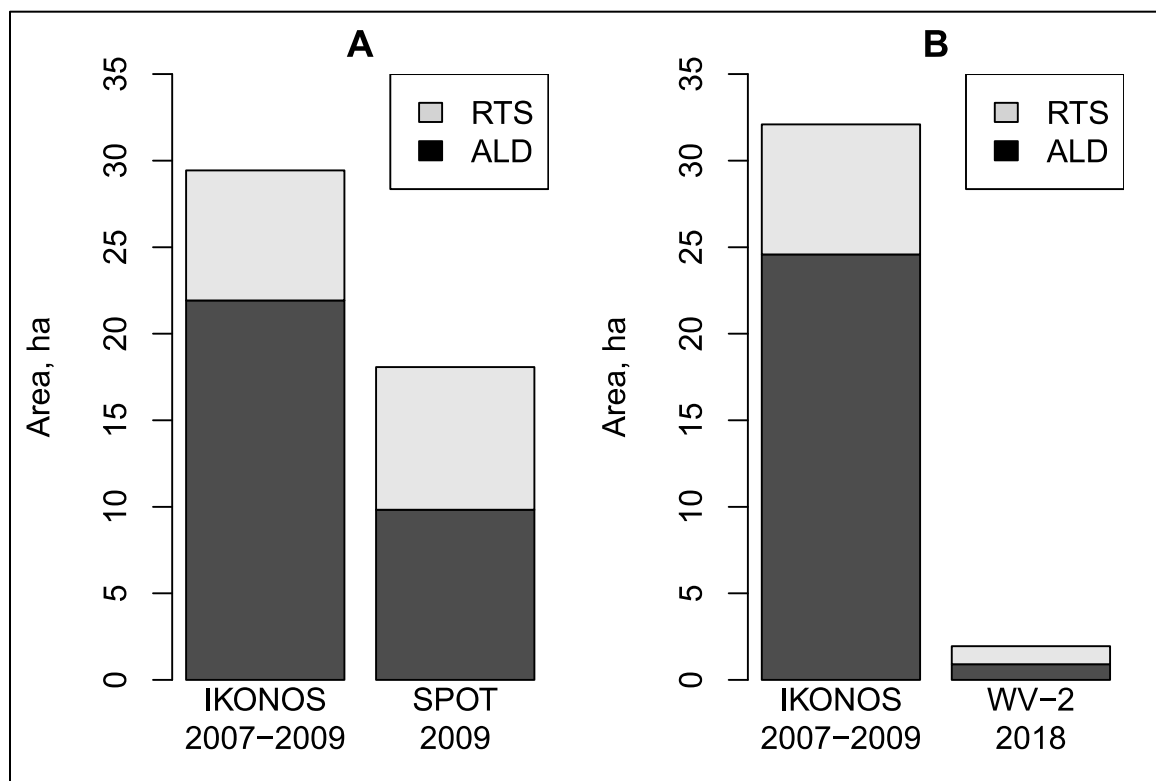


Figure 9. Change in bare-soil area of erosion features between image dates. (A) Comparison of IKONOS 2008-2009 and SPOT 2009 images; (B) comparison of IKONOS 2007-2009 and Worldview-2 2018 images. ALD- active-layer detachments, RTS – retrogressive thaw slumps. Due to clouds, the area of common coverage between IKONOS and SPOT was different from and smaller than the common area of IKONOS and Worldview-2 (WV-2).

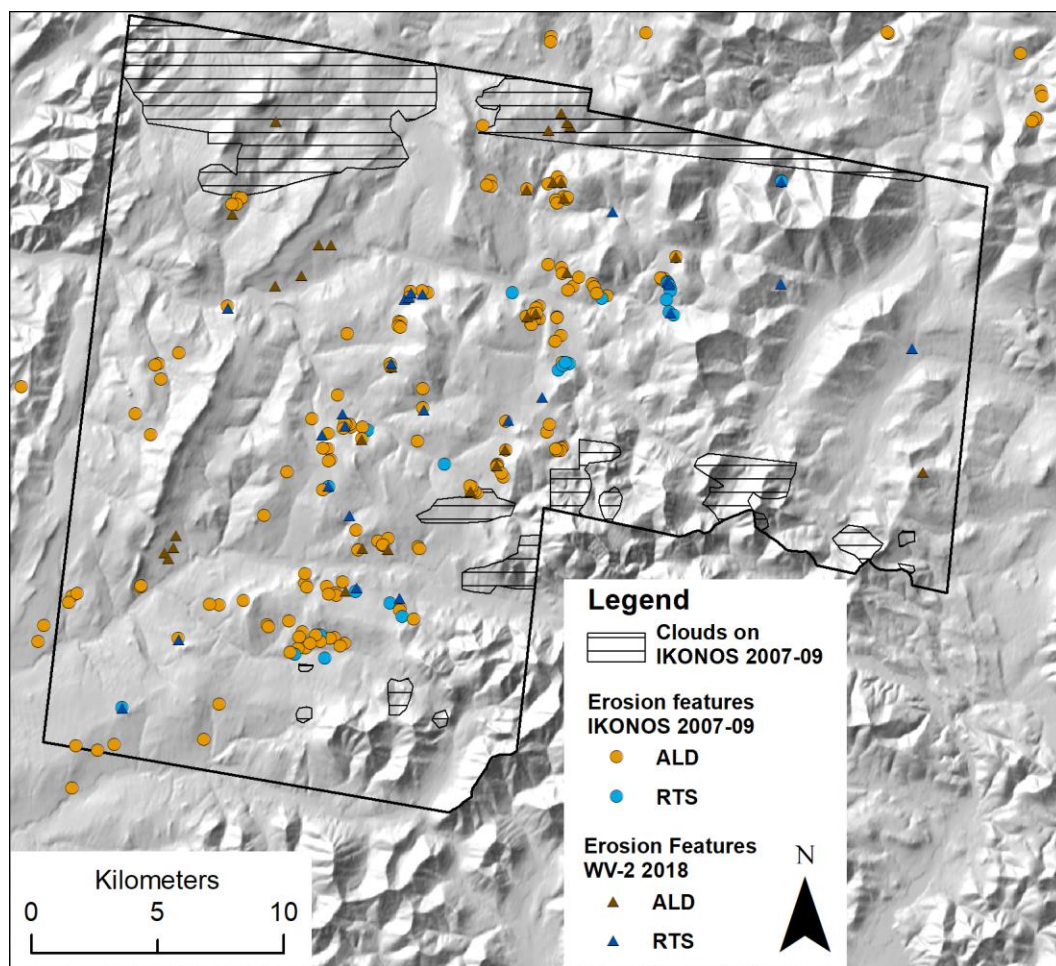


Figure 10. Map of bare-soil erosion feature locations in the study area in 2007-2009 and in 2018.

Table 4. Origin of erosion features observed in 2018^A

2018 Feature ^B	2007-09 Feature ^C	Count	Sum of Area, m ²
ALD	None	19	7917
ALD	ALD	11	2454
RTS	None	10	2819
RTS	ALD	9	5375
RTS	RTS	7	2260

^AALD – active-layer detachment, RTS retrogressive thaw slump

^BFeatures of the given type in the year 2018

^CNone – no feature was present (the area was undisturbed) on 2007-2009 images; ALD – an active layer detachment was present in 2007-2009; RTS – a retrogressive thaw slump was visible in 2007-2009.

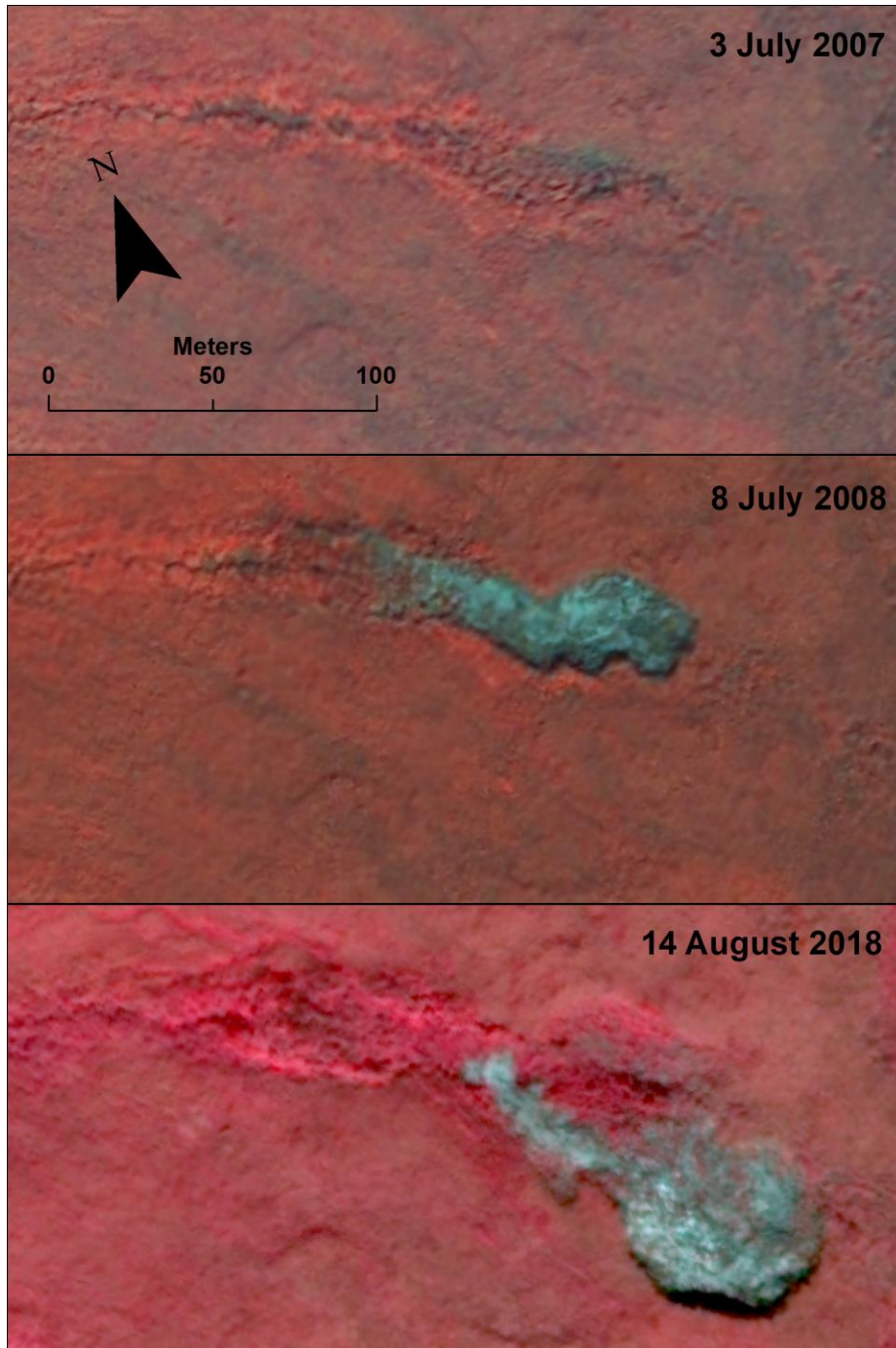


Figure 11. An active-layer detachment (ALD) that formed in 2007 and then continued to grow as an RTS. The slope is downhill to the left. As a result of overlap between adjacent scenes in our 2007-2009 IKONOS satellite mosaic, we have a close time series from July 2007 (top) and July 2008 (middle), followed by a Worldview-2 image in August 2018. All are in color-infrared color scheme, which shows green vegetation as red. The ground surface was undisturbed in July 2007. The 80 m-long ALD visible in July 2008 probably formed in late July or August of 2007 (because in 2008 prior to July 8 there had probably not yet been enough thaw). By 2018 the original ALD was mostly revegetated, but erosion continued by retrogressive thaw slumping from the southwestern side of the ALD, and it advanced 70 m in 10 years. Location near longitude -161.729° , latitude 67.589° .

Discussion and Conclusions

The Noatak Slump

After a decade of rapid growth, the Noatak Slump appears to have nearly stopped growing. Nonetheless, much of the floor and slopes of the slump remain bare of vegetation, which leaves them susceptible to erosion by water. However, an inactive slump, even if still lacking vegetation, is much less susceptible to erosion than an active slump. The reason is that on an inactive slump, the sediment on the floor of the slump is dry and compact, and for sediment transport to occur it must be entrained by moving water. In contrast, when this slump was active there was a zone of water-saturated sediment near the active escarpment that was unstable and readily flowed downslope (Swanson 2012, Swanson and Nolan 2018). Unless thaw and scarp movement are reactivated, in the foreseeable future the Noatak Slump will shed eroded sediment at a gradually declining rate as vegetation is re-established, and this rate will be much slower than the tens of thousands of cubic meters of material that were lost annually during the active-growth phase of this slump prior to 2016 (Swanson 2013).

Maiyumerak Mountains Slope Failures

The area of bare soil exposed by slope failures in the Maiyumerak Mountains study area was much lower in 2018 than in 2007-2009. The 2007-2009 mapping effort came soon after the major ALD event that occurred in 2004 (Balser 2015), and it captured many of these features before they re-vegetated (Swanson 2014). The comparatively small area of ALD found in 2018 by the present study confirms our subjective impressions gained from flying in ARCN over the past decade: that no new slope failure event comparable to 2004 had occurred as of 2018.

Many of the RTS present today were initiated by bare soil exposed by ALD from the 2004 event. However, their area has declined to a small fraction of what was present in 2007-2009. This agrees with the results of our intensive monitoring of selected RTS (Swanson and Nolan 2018), which showed that many RTS began growing in the mid 2000 decade (see also Balser 2014) and grew rapidly for several years, but then slowed or ceased growth in the mid-2010 decade.

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