Permafrost thaw-related slope failures in Alaska’s Arctic National Parks, c. 1980–2019

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Abstract
Active-layer detachments (ALD) and retrogressive thaw slumps (RTS) are landslides that occur as a result of thaw in permafrost regions. I mapped the extent of bare soil exposed in these thaw-related slope failures in four study areas with continuous permafrost in Alaska’s Arctic National Parks, on mosaics of aerial photographs from 1977–1985 (sampling episode 1), satellite images from 2006–2009 (sampling episode 2), and satellite images from 2018–2019 (sampling episode 3). In all four study areas the count of ALD and RTS, and the area of bare soil they exposed, was greater during the first or second sampling episode than the third sampling episode, in spite of record high mean annual temperatures in 2014–2019. One study area had frozen debris lobes (FDL) in addition to ALD and RTS. In that study area the bare ground exposed by destabilization and rapid movement of FDL was greatest in the third sampling episode, probably as a result of deep thaw and talik formation. The destabilization of FDL in episode 3 was probably a long-term consequence of warming and permafrost loss, while the observed pulses of ALD and RTS in episodes 1 and 2 were closely tied to short-term deep thaw events in areas where the underlying permafrost remained stable.

KEYWORDS
landslide, mass movement, permafrost, remote sensing

1 | INTRODUCTION

Permafrost thaw can lead to mass movement of material on slopes and exposure of bare soil to erosion by water. Two important types of thaw-induced slope failures in northern Alaska are active-layer detachments (ALD) and retrogressive thaw slumps (RTS).1–3 ALD are small landslides that occur over a period of days to weeks in a single thaw season.4,5 A layer of thawed material slides downhill on wet mud over the underlying frozen ground. The slide leaves an elongated region of bare soil exposed on a slope, which can lead to erosion of soil into streams.6,7 RTS occur where a steep face advances into ice-rich permafrost as material thaws, falls or slumps onto the adjacent more gentle slope, and then is transported away by water erosion, sliding, or viscous flow.8,9 RTS can persist and grow for many years. RTS often occur on escarpments produced by shoreline or fluvial erosion and may shed large amounts of sediment into the adjacent water body.5,10,11 Another type of permafrost-related mass movement in northern Alaska is frozen debris lobes (FDL). These are frozen bodies of colluvium that move downslope slowly (usually <10 m yr⁻¹) while remaining mostly vegetated.12,13 FDL occasionally lose much of their vegetation cover and move much faster (30 m yr⁻¹ or more14), apparently due to thaw-related processes.13,15,16 All three of these mass movement types have threatened infrastructure in Alaska.13,17
Permafrost degradation and the resulting thermokarst caused by recent climate warming have been well documented in Alaska, but data on thaw-related slope failures are limited. Spatial time-series analysis of thaw-related slope failures over extensive areas have been conducted in northwestern Canada, revealing increases in the activity of RTS in recent decades. These studies emphasized RTS rather than ALD, presumably because the latter are smaller and shorter lived, and therefore more difficult to map. In Alaska we have monitored the growth of selected RTS, but temporal trends in thaw-related slope failures over extensive geographic areas remain mostly unquantified. Knowledge of the trends in areas disturbed by thaw-related slope failures is needed to understand the effects of permafrost thaw, for purposes ranging from protection of local infrastructure and water quality to global carbon balance modeling.

Concerns about the changing state of permafrost led the National Park Service Arctic Inventory and Monitoring Network (ARCN, Figure 1) to include permafrost as a monitoring “Vital Sign.” ARCN permafrost monitoring includes several projects, one of which is the repeat mapping of thaw-related erosion features, such as ALD and RTS, over extensive areas to determine if there are any trends in their abundance. We monitored the area of bare soil exposed as a result of slope failures, rather than the full extent of affected areas, because bare soil areas represent the most extreme disturbance caused by thaw of permafrost, and they are relatively easy to map because they contrast strongly with adjacent vegetated areas. Thus, we were able to use a semi-automated mapping method that is feasible over large areas. Our monitoring protocol calls for revisiting selected areas at approximately 10-year intervals.

I initially mapped ALD and RTS across all of ARCN (82,000 km²) using high-resolution satellite images from 2006 to 2009 (Figure 1). I located hundreds of ALD and RTS, many of which were apparently initiated in 2004 by unusual weather (high early thaw-season temperatures, intense rainfall events in May, early loss of the annual snowpack, and record high annual sum of thawing degree-days). Subjective observations based on flights over ARCN by the author and colleagues since that time suggest that no new events comparable to the one in 2004 have occurred, and most ALD from that era have revegetated. Intensive monitoring of selected RTS suggest that they have also become less active since 2006–2009. However, in the field and on satellite images we have recently observed dramatic new slope failures produced by the destabilization and rapid downslope movement of FDL, apparently as a result of deep thaw. Thus, I added bare areas exposed on destabilized FDL to the list of mapped and monitored thaw-related erosion features.

The purpose of the present study is to compare the abundance of thaw-related erosion features from 2006–2009 with both earlier and more recent times. I selected four subareas and remapped thaw-related erosion features on scanned and orthorectified color-infrared

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**FIGURE 1** Study area locations. Numbers 1–4 are the four study areas. Letters refer to National Park Units: N – Noatak National Preserve, K – Kobuk Valley National Park, G – Gates of the Arctic National Park and preserve. The inset map shows the location of the study area in relation to the state of Alaska and the five parks of the NPS Arctic inventory and monitoring network. Locations of thaw-related erosional features from a comprehensive inventory are shown; these are referred to as “episode 2” in the present study [Colour figure can be viewed at wileyonlinelibrary.com]
aerial photographs from c. 1980 and on high-resolution satellite imagery from 2018–2019. The three time periods are referred to chronologically as sampling episodes 1, 2, and 3 (Table 1).

### 1.1 Study area

ARCN includes five National Park Service units in northern Alaska (Figure 1). The terrain ranges from broad lowlands near sea level to mountains above 2000 m in elevation, with mostly continuous permafrost and tundra vegetation.\(^2\)\(^,\)\(^27\)\(^,\)\(^28\) Boreal forest and discontinuous permafrost are present in the southern portions of the noncoastal parks.

The four study areas were chosen for remapping based on the availability and cost of suitable imagery from 2018–2019, in areas known to be susceptible to slope failures from the ARCN-wide map\(^2\) (episode 2, 2006–2009) (Figure 1). I manually digitized clouds and cloud shadows on all images, and subtracted these from the study areas. Thus, only areas that were clear in all three sampling episodes were included. The size, elevations, and mean annual temperatures of the study areas are summarized in Table 2.

Study area 1 is an area of low mountains in the southwestern Noatak National Preserve with tundra vegetation. This study area had a dense concentration of ALD and a few RTS in the episode 2 inventory.

Study area 2 comprises gently sloping lowlands and low rounded mountains with tundra vegetation in the upper Noatak River basin. This area had many RTS in our episode 2 inventory, and many of our intensive RTS monitoring sites\(^3\) were located there.

Study area 3 is an area of low mountains in the north-central Noatak National Preserve with tundra vegetation. This study area had a dense concentration of ALD and a few RTS in the episode 2 inventory.

Study area 4 is an area of low mountains (though somewhat more rugged than the other study areas) on the south side of the Brooks Range in Gates of the Arctic National Park. It has mostly tundra vegetation, with open white spruce (\(Picea glauca\)) forest locally present up to about 750 m elevation. Both ALD and RTS were mapped there in the episode 2 inventory. Area 4 also has numerous FDL.\(^13\)\(^,\)\(^29\)

Modeled 1981–2020 mean annual air temperatures in the study areas ranged from \(-5\) to \(-8\) °C (Table 2). Modeled mean annual ground temperatures for the 2000–2009 decade in the study areas were mostly \(-3\) to \(-8\) °C, with the warmest locations in study area 4 above \(-3\) °C\(^30\) (Table 2). Observations at ARCN climate monitoring stations and nearby National Weather Service stations showed that mean annual ground and air temperatures for the period 2014–2019 were about \(2\) °C above the 30-year pre-2014 averages.\(^31\) Taliks (unfrozen areas in permafrost) are expected to develop as the climate continues to warm in the current century\(^30\) (Figure 2). In addition to the more common ground ice types (wedges and segregated ice lenses), Pleistocene glacial ice has been identified in parts of ARCN (Figure 2).

Long-term temperature records are summarized using annual sums of thaw- and freeze-degree days in Figure 3, from weather

### Table 1

| Sampling episode | Study areas | Image source | Image years | Image resolution |
|------------------|-------------|--------------|-------------|-----------------|
| 1                | 1, 2, 3, and 4 | Alaska high-altitude aerial photographs, color-infrared, scale 1:60,000 | 1977–1979, 1981, 1985 | Scanned at 25 μm (1,000 dpi); 1.5 m orthorectified |
| 2                | All of the NPS Arctic inventory and monitoring network | IKONOS multispectral satellite images | 2006–2009 | 4 m multispectral, 1 m pansharpened and orthorectified |
| 3                | 1 and 3 | Worldview-2 multispectral satellite images | 2018 (study area 1), 2019 (study area 3) | 2.2 m multispectral, 0.6 m panchromatic, orthorectified |
| 3                | 2 and 4 | SPOT6 (study area 4) and SPOT7 (study area 2) multispectral satellite images | 2019 | 6 m multispectral, 1.5 m pansharpened and orthorectified |

### Table 2

| Study area | Size (km²) | Mean annual air temperature 1981–2010 (°C) | Mean decadal ground temperature 2000–2009 (°C) | Elevation (m) |
|------------|------------|------------------------------------------|----------------------------------------|---------------|
|            |            | 10%-ile | Median | 90%-ile | 10%-ile | Median | 90%-ile | 10%-ile | Median | 90%-ile |
| 1          | 664        | −7.2    | −6.6   | −5.6    | −6.1     | −4.6    | −3.2    | 347     | 513     | 788     |
| 2          | 1,722      | −7.9    | −7.7   | −7.4    | −6.3     | −5.2    | −4.3    | 406     | 521     | 939     |
| 3          | 363        | −8.3    | −8.1   | −7.5    | −7.8     | −6.5    | −5.7    | 428     | 580     | 798     |
| 4          | 1,078      | −6.7    | −6.1   | −5.5    | −5.5     | −4.3    | −2.5    | 550     | 858     | 1,130   |

\(^a\) Medians, 10th percentiles, and 90th percentiles are summaries of spatial (not temporal) variation in pixel values from raster maps of mean annual air temperature,\(^49\) mean decadal ground temperature,\(^30\) and elevation.\(^30\)
stations near the study area: Kotzebue, Bettles, and Kelly River (Figure 1). Kelly River station is at an inland location nearer to the study areas than Kotzebue, but it has a shorter period of record. Sampling episode 1 occurred within a few years of the abrupt Alaska-wide shift to higher temperatures that occurred in 1976. Episode 2 occurred during and after a series of unusually warm years beginning in 2004. Episode 3 followed a series of exceptionally warm years that began in 2014 (Figure 3).

Bedrock geology in the study areas is a mixture of Paleozoic sedimentary and metasedimentary rocks: sandstone, conglomerate, shale, phyllite, and limestone. Area 4 also has schist bedrock. The ALD, RTS, and FDL in the study area are in slope deposits derived from these bedrock types and from glacial deposits. Study area 2 has extensive areas of lowlands with late Pleistocene glacial deposits, and many of the RTS are located there.

Wildfires can result in thaw of permafrost and slope failures. Fires have been recorded in study areas 1, 2, and 3 but cover minor areas. Areas burned by year (since the start of records in 1949) were: study area 1, 0.2 km² (1977); study area 2, 2.9 km² (2011) and 0.8 km² (2013); study area 3, 2.6 km² (2010) and 5.6 km² (2012); and study area 4, no area burned.

2 | METHODS

Erosion features were mapped on high-resolution multispectral images from three distinct time periods, referred to here as “episodes” (Table 1). Episode 1 consists of the earliest color-infrared imagery available for the study area, an Alaska-wide aerial photography effort that occurred around 1980. Episode 2 consists of the first high-resolution multispectral satellite images available for the study area, which were taken in 2006–2009. Episode 3 consists of high-resolution multispectral satellite images from 2018 and 2019. I composed a mosaic of available images from each episode so that any specific location was covered by only one image per episode. Thus, the presence of several years of images within a single sampling episode does not imply multiple samples of the same area within an episode; each location was mapped on just one image date per episode.

I mapped the erosion features by a partially automated process that took advantage of the human eye’s ability to recognize ALD, RTS, and FDL, while assigning the painstaking work of delineating the bare soil areas to the computer. The steps were as follows (Figure 4). (1) I manually created a geographic point layer marking all patches of bare ground in ALD, RTS, and destabilized FDL visible on the images, with the feature type as an attribute. This was accomplished by systematically searching the imagery at a scale of 1:10,000 or larger. (2) I computed the normalized difference vegetation index (NDVI) from high-resolution multispectral imagery. A median filter using a circle with a radius of 3 m was applied to the NDVI image, to reduce speckling. (3) I classified the images as vegetated or unvegetated by thresholding the NDVI values. The threshold value was chosen manually for each image so that bare and vegetated areas were properly separated. (4) I converted the classified NDVI image to polygons representing bare or vegetated areas. (5) I joined the points from step 1 to the polygons from step 4 to separate the thaw-related bare soils areas from nontarget bare soil areas such as river gravel bars and bedrock exposed on mountain ridges. Minor hand-editing of the resulting bare-soil polygon layer was occasionally required, usually where an
erosion feature was contiguous with a nontarget low-NDVI area such as a water body or gravel river floodplain. More details of the mapping process are available in the ARCN monitoring protocol.24,25

This mapping method delineates only bare soil areas and not the entire area affected by slope failure, or 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 have resulted from the slope failures. The NDVI calculations were made on pan-sharpened IKONOS and SPOT images. The Worldview-2 multispectral data had sufficiently high resolution (2.2 m) without pan-sharpening; however, I used pan-sharpened images to visually identify the erosion features (in mapping step 1 above). NDVI was computed directly from the AHAP (1.5 m resolution) color-infrared 3-band color scans.

I summarized both the area of bare ground in features of each type and the total count of individual features. An “individual feature”

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**FIGURE 3** Annual sums of (a) thawing degree-days, (b) freezing degree-days, and (b) May–September precipitation at Kotzebue and Bettles, Alaska, and the Kelly River remote automated weather station52 (see Figure 1 for their locations; precipitation data are missing for Kelly). Annual sums of freezing and thawing degree-days were computed from monthly means to avoid problems due to occasional days of missing data.53 All months had 5 days or less of missing data.52 Annual sums are for hydrologic years (October–September, named for the later of the two years), to avoid splitting the thaw and freeze seasons. Bars show the timing of the sampling episodes (see Table 2). The dashed bar for part of episode 1 illustrates that most of the study areas were covered by 1977–1981 aerial photographs, with only a minor part of area 4 covered by 1985 photographs.
was defined as all bare areas resulting from a contiguous slide event (ALD), or from growth along a contiguous escarpment (RTS), or from the disintegration of a single frozen debris lobe (FDL). I also noted which features persisted between episodes. These consisted of ALD that failed to revegetate completely, ALD that became RTS that were active enough to continue to produce bare ground, and RTS that

**FIGURE 4** Mapping method for thaw-related erosion features, illustrated with an example from sampling episode 2 and IKONOS satellite imagery. A – Active-layer detachments visible on color-infrared (CIR) satellite images were manually marked by digitizing points (shown with white squares). B – An NDVI image was computed from the CIR image, displayed in grayscale from low (black) to high (white) NDVI. C – The NDVI image displayed as black below a selected threshold (bare areas) and white above the threshold (vegetated areas). D – The NDVI image from step C, converted to polygons, and intersected with the points digitized in step A. Only polygons containing a point or within 20 m of a point were retained. Nontarget bare areas (river gravel bars, rocky bare hilltops) were thus excluded. Located in study area 2 near longitude −163.880°, latitude 67.540° [Colour figure can be viewed at wileyonlinelibrary.com]
continued to grow, or were reactivated within the same footprint as a previous RTS.

I initially mapped ALD and RTS that formed on the surface of otherwise vegetated FDL. In study area 4, several FDL became unstable to the point that much of their vegetation cover was lost, and the resulting bare areas were not typical ALD or RTS. The bare-soil areas on these FDL were labeled as “destabilized FDL” so that their area could be compared between episodes.

The imagery used in the present study is for the most part the only high-resolution imagery available for the study time periods, and ground verification data are absent in this remote region. Thus, there are no independent data available to determine what portion of the change in number or area of slope failures between episodes may be due to varying detectability of erosion features on the different imagery types and on the different dates within an imagery type. In support of the idea that the observed trends are real and not sampling artifacts are that (a) all image types were color-infrared multispectral with resolution of 2.2 m or finer (Table 1), which was adequate to distinguish the features of interest. (b) Each episode was represented by an image mosaic where each location was covered by only one image. Thus, each episode is a snapshot from a single point in time. Multiple image dates within an episode (which were required to give complete coverage of all four study areas) did not provide additional opportunities to locate more erosion features. And (c) as will be show below, all four study areas showed the same trend between episodes 2 and 3 (a decline in the number and area of ALD and RTS), in spite of the fact that two different sensors (Worldview-2 and SPOT) were used in two different years (2018 and 2019) for episode 3.

3 | RESULTS

In study area 1 (664 km²), both the count of erosion features and the area they occupied were much greater in sampling episode 2 (2007–2009) than either episode 1 (1979) or episode 3 (2018) (Table 3, Figure 5a,b). ALD dominated the area and count of features in episode 2. The count and area covered by erosion features in episode 1 were 25% and 20%, respectively, of the totals for episode 2. Just one RTS was recorded in episode 1, with an area too small to be visible on the barplot. About half of the ALD area in episode 1 was within the perimeter of a 1977 wildfire, in spite of the latter covering only a tiny proportion of the study area (0.03%). No other erosion features in any study area fell within mapped burn perimeters on the Alaska Fire Service fire history database35 or within fire scars visible in the imagery. The count and area of erosion features in area 1 dropped markedly from episode 2 to 3.

Study area 2 (1,922 km²) was dominated by RTS during all three episodes (Table 3, Figures 5c,d and 6). Both the count and area of erosion features was again greatest in episode 2. There was about half as much eroded area in episode 3 as episode 2, and somewhat less yet in episode 1.

Study area 3 (363 km²) showed a fairly similar total count and area of erosion features in episodes 1 and 2 (Table 3, Figure 7a,b). Nearly half of the relatively large area of RTS in episode 1 was from a single large complex of RTS and ALD. Outside of this slump complex, area 3 was dominated by ALD (Figure 8). Few erosion features were found in this area in episode 3.

Study area 4 (1,078 km²) had numerous ALD in episode 1, and they declined in number and area through episodes 2 and 3 (Table 3, Figure 7c,d). Study area 4 was the only one with FDL. Four of these FDL appeared to destabilize, lose much of their vegetation cover, and move at rates of about 30 m yr⁻¹ (Figure 9). Bare ground was present on these four FDL in all three sampling episodes, but distinctly more bare ground was exposed on these FDL in sampling episode 3 (Figure 7d). All four of the destabilized FDL had RTS in their upper part and long narrow debris flows extending downslope, usually in the trough along the margin of the FDL (Figure 9, year 2008). Additional evidence of flow and sliding included large transverse cracks in the

| Study area | Feature | Sample episode 1 | Sample episode 2 | Sample episode 3 |
|------------|---------|------------------|------------------|------------------|
|            |         | Count | Area (ha) | Count | Area (ha) | Count | Area (ha) |
| 1          | Total   | 38     | 6.4      | 171   | 31.8     | 52     | 1.9      |
| 1          | ALD     | 37     | 6.2      | 147   | 24.2     | 26     | 0.9      |
| 1          | RTS     | 1      | 0.1      | 24    | 7.5      | 26     | 1.0      |
| 2          | Total   | 30     | 19.9     | 105   | 51.5     | 43     | 27.6     |
| 2          | ALD     | 1      | 0.1      | 25    | 3.0      | 4      | 0.4      |
| 2          | RTS     | 29     | 19.8     | 80    | 48.5     | 39     | 27.2     |
| 3          | Total   | 95     | 10.4     | 109   | 10.6     | 16     | 1.1      |
| 3          | ALD     | 77     | 5.5      | 103   | 10.3     | 15     | 1.0      |
| 3          | RTS     | 18     | 4.8      | 6     | 0.3      | 1      | 0.1      |
| 4          | Total   | 436    | 83.9     | 193   | 39.4     | 48     | 42.5     |
| 4          | ALD     | 411    | 59.1     | 120   | 13.1     | 23     | 3.3      |
| 4          | RTS     | 21     | 14.2     | 69    | 13.2     | 21     | 5.0      |
| 4          | FDL     | 4      | 10.6     | 4     | 13.2     | 4      | 34.3     |

TABLE 3 | Count and area of erosional features in the four study areas and three sampling episodes
middle of the FDL, and movement of large rafts of vegetated debris (Figure 9, year 2011).

RTS data from all four study areas were pooled together to summarize the persistence through time of individual features (Figure 10). The spike in RTS area in episode 2 was due both to the enlargement of features that were present in episode 1 and the appearance of new RTS (Figure 10). The decline of RTS area in episode 3 was due both to the revegetation of the RTS that were new in episode 2 and to the fact that the area of new RTS in episode 3 was relatively small.

ALD data from all four study areas were pooled together to summarize the persistence through time of individual features (Table 4). Nearly all of the ALD observed in episode 1 had revegetated by episode 2: of the 526 ALD mapped in episode 1, just two still had mappable bare ground in episode 2, with negligible area (Table 4). One small episode-2 ALD appeared to have formed in the footprint of an episode-1 ALD. The length of time separating episodes 1 and 2 was 27–31 years (except 22–23 years for a few features in study area 4). More ALD persisted across the shorter time interval (9–13 years) that separated episodes 2 and 3: 32 of the ALD mapped in episode 3 were ALD from episode 2 that had not yet completely revegetated. These persistent ALD occupied just 6% of the 50.6 ha covered by the 392 ALD identified in episode 2 (i.e., 94% of the episode-2 ALD area had revegetated). However, owing to the rarity of new ALD in episode 3 (n = 36), these persisting ALD represented an important fraction of the total ALD present in episode 3. A small number of ALD from both episodes 1 and 2 converted to RTS and persisted into the following episode (Table 4).

4 | DISCUSSION

ALD initiation is generally associated with warm summers, often in conjunction with heavy rainfall. RTS initiation is also generally associated with warm summers. RTS may be triggered by an ALD, if the ALD exposes sufficiently ice-rich material. There were temperature anomalies prior to both sampling episodes 1 and 2 that can

FIGURE 5 Thaw-related erosion features during the three sampling episodes in study area 1 (A – count of features and B – area of features) and study area 2 (C – count of features and D – area of features). RTS – retrogressive thaw slumps, ALD – active layer detachments.
explain the observed erosion features. A major climatic shift to warmer conditions in Alaska in 1976 resulted in a stepwise increase of 1–2°C in mean annual temperatures that persisted for the rest of the century.22 Both Kotzebue and Bettles set new all-time records for the largest annual sum of thawing degree-days in 1977, the first year of episode 1 sampling (Kotzebue set another record high in 1978; Figure 3a). Many of the slope failures observed in episode 1 could have been triggered by this late 1970s temperature increase. In particular, this could explain the great abundance of ALD in area 4 during episode 1. Summer precipitation totals were not anomalously high at these weather stations in the 1970s through 1981 (Figure 3c; recall that episode 1 maps were based mainly on photos from 1977–1981). However, the lack of anomalous events in the precipitation record from these stations, located approximately 100–250 km from the study areas, does not rule out the possibility that local heavy precipitation events may have been a factor in triggering some of the ALD mapped in episode 1.

The abundance of both ALD and RTS in sampling episode 2 (the late 2000s decade) has also been linked to a weather anomaly: the unusually warm weather and heavy precipitation in 2004.1,26 The annual thawing degree-day total for 2004 at Kotzebue beat the 1978 all-time record mentioned previously, and Kelly also set an all-time high, albeit with a short period of record beginning in 1998 (Figure 3a). Kelly experienced record early onset of thawing conditions and two heavy precipitation events in May 2004.1 The record high for annual thawing degree-days was set again in 2007 at Bettles and Kelly (Figure 3a); this warmth may have initiated some of the failures that were recorded in episode 2 (which included imagery from 2006 to 2009).

The decline in area by sampling episode 3 of individual RTS detected in episode 2 agrees with our detailed measurements of RTS that showed declining growth rates through the 2000s.3 The growth rate of an individual RTS may slow through time, independent of weather, as the slump encounters less ice-rich material or lower

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**FIGURE 6** Development of retrogressive thaw slumps (RTS) in a single area during the three sampling episodes. The image year is indicated on each frame. In 1977 (sampling episode 1) there were multiple active RTS in this area (1). In 2008 (sampling episode 2) all of the slumps active in 1977 had grown over with vegetation, which appears coarse-textured on the image due to shrubs. The outlines of the earlier slumps show that they grew little beyond their 1977 extents. Several new slumps had formed, overlapping (2) or next to (3) earlier slumps. Two small new slumps initiated by point (4). In 2019 (sampling episode 3) the large slumps (2) and (3) continued to grow while the small incipient slumps at (4) failed to develop. This location is from study area 2 near longitude −156.820°, latitude 67.962°. [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 7  Thaw-related erosion features during the three sampling episodes in study area 3 (A – count of features and B – area of features) and study area 4 (C – count of features and D – area of features). DFDL – destabilized frozen debris lobes, RTS – retrogressive thaw slumps, ALD – active layer detachments. [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 8  Example of active-layer detachments (ALD) in a single location during the three sampling episodes. The image year is indicated on each frame. The terrain slopes downhill to the south. In 1977 (sampling episode 1) there was one recent ALD (1). In 2006 (sampling episode 2) the 1977 ALD was completely revegetated and three new ALD had recently formed (2). In 2019 (sampling episode 3) all previous ALD had revegetated. This location is from study area 3, near longitude −157.904°, latitude 68.251°, the same area illustrated in Figure 4. [Colour figure can be viewed at wileyonlinelibrary.com]
The appearance of new RTS is more closely linked to weather\(^1\) and new RTS declined precipitously from episode 2 to 3, as did the area of new ALD, which as discussed above are closely tied to summer weather. The decline in ALD and RTS activity from episodes 2 to 3 occurred in spite of the record high mean annual air temperatures during 2014–2019\(^{21,38}\) (Figure 3). It is possible that the sites that were most vulnerable to failure did so in the late 2000s (episode 2), and summers were not warm and wet enough to trigger failure at new locations prior to episode 3. While mean annual temperatures in 2014–2019 were at record high levels in the study area, the greatest warming was in the winter, and summers (as shown by thawing degree-day sums, Figure 3a) were actually similar to the preceding decade.

If many of the ALD observed in episode 2 occurred in the 2004 event\(^{2,26}\), they were 14 or 15 years old at the time of our episode 3 sampling, when they had largely revegetated. In fact, some of these ALD already showed signs of revegetating on the later images of episode 2 (2006–2009).\(^2\) While revegetation of ALD in my study area was largely complete in a decade or two, the occurrence of just one new ALD within the footprint of a previous ALD across the approximately 40 years of this study suggests that more than 40 years are required for ALD to recur in the same exact location. Presumably many ALD were triggered by thaw of the ice-rich permafrost in the intermediate layer, which lies just below the active layer.\(^{39}\) Removal of vegetation and the original active layer in the slide exposed the intermediate layer to thaw and loss of ice as it became the new active layer. This thaw usually exhausted the ice-rich permafrost, and the slope stabilized. Ecosystem succession from an initial bare state causes thinning of the active layer and aggradation of ground ice into the newly formed intermediate layer.\(^{40}\) Our results suggest that more than 40 years are required for enough ice to accumulate for a new slide event. The few ALD that converted to RTS represent the subset

**FIGURE 9** Destabilization of a frozen debris lobe (FDL). The year of the image is indicated in each frame, and the terrain generally slopes downhill to the right (east). In 1981 (sampling episode 1) the lobe was nearly completely vegetated (1). In 2008 (sampling episode 2) it had begun to destabilize, with the formation of multiple small retrogressive thaw slumps that span the upper part of the lobe (2), transverse cracks forming (3), and material flowing in a narrow lobe at the front (4). In 2011 (not a sampling episode) large rafts of vegetated material (5) slid downslope 50–60 m since 2008. The narrow lobe of newly deposited material from 2008 was unchanged, but elsewhere the front of the disturbed mass in 2011 had moved about 75 m since 2008. In 2019 (sampling episode 3) vegetation had been lost over much of the lobe (6) and the farthest point on the active front was 280 m from where it was in 2011, giving an average rate of about 35 m yr\(^{-1}\). The lobe is in study area 4, centered near longitude –151.896°, latitude 67.748°. [Colour figure can be viewed at wileyonlinelibrary.com]
of cases where a sufficient thickness of ground ice was present to support continued thaw and sliding after the initial ALD event.

Multiple studies have shown a recent increase in the activity of slope failures from permafrost thaw, especially RTS, that has been linked to climate change.9,11,22,41–45 All of these studies relied on visual recognition of slump perimeters, and the increase in slump activity was detected by a change in the rate of area growth or the rate of appearance of new features. My study differed in that I mapped only the unvegetated portions of slope failures, and thus an erosion feature could grow over with vegetation and thus become smaller or drop out entirely from the subsequent inventory. My results represent the net result of the competing processes of slope disturbance and revegetation. They show that the ecological impacts brought on by thaw-related slope failures can rise and fall in intensity, even under generally warming conditions.

Knowledge of ground-ice occurrence, in addition to climate data, is needed to predict when and where thaw-related instability will occur in the future. Buried relict Pleistocene glacial ice has been observed at multiple locations in the lowlands of the central and eastern Noatak National Preserve and locally in Gates of the Arctic National Park and Preserve (Figure 2). If warming were to progress to the point that active layers failed to refreeze and progressively thickening taliks formed over glacial ice masses, then retrogressive thaw slumping would become widespread wherever glacial ice is present and proceed until the supply of ice is exhausted. The full extent of glacial ice in this area is unknown, but in the places where glacial ice has been observed in ARCN (Figure 2), modeling30 suggests that permafrost will generally remain stable in spite of the 3–5°C of warming expected in the current century. However, even in the areas where the permafrost beneath remains generally stable, active-layer thickening due to warming is likely to set off more bouts of ALD and RTS (similar to what we observed in sampling episode 2) wherever sufficient ground ice is present.

The observed increase in FDL disintegration in episode 3 runs counter to the trends in other thaw-related erosion features. Factors contributing to destabilization and rapid movement of FDL include13,16: (a) RTS on or above the FDL, which can increase shear stress by sediment loading, and meltwater from the RTS can reduce shear strength in the FDL; (b) longitudinal and transverse cracks that allow entry of water deep into the lobe, possibly to the basal shear...
zone; and (c) general loss of vegetation cover, which allows deeper thaw penetration and subsequent loss of strength. All of these characteristic features of destabilized FDL were visible on the FDL in our study area 4 (Figure 9). The factors leading to destabilization of FDL are self-reinforcing; faster movement leads to cracking and disruption of the surface soil and vegetation, which facilitate more water entry to the shear zone and deeper thaw. FDL movement rates are sensitive to the temperature, water content, and pore water pressure throughout the thickness of the lobe, but especially in the basal shear zone where most of the motion occurs.15,46 The basal shear zone lies well below the surface, about 20 m deep in one intensively studied FDL.46 Penetration of increasing temperatures to these depths requires years, while outright thaw could take decades.16 Thus, destabilization of FDL should generally increase with increasing temperatures, but the timing and rate of destabilization are likely to lag surface conditions and be unique to each FDL. This behavior is in sharp contrast to ALD, where multiple slides appear together in a single thaw season as an immediate response to anomalous weather conditions or surface disturbance by fire. Thus, the destabilization of FDL in episode 3 was probably a long-term consequence of warming, while the observed pulses of ALD and RTS were closely tied to anomalous warm summers.

These results illustrate important differences between permafrost degradation due to (a) fundamental destabilization of permafrost that accompanies a rise in mean annual ground temperatures above 0 °C, versus (b) thickening of the active layer while the permafrost below remains stable.47 RTS and ALD are thaw-related slope failures that can occur in either situation, but in my study area they have as yet apparently only occurred as a result of a thickening active layer over generally stable permafrost. Prior to 2014, most of my four study areas had mean annual air temperatures below −6 °C and modeled mean annual ground temperatures at the base of the active layer below −3 °C (Table 2).29 This implies that, even with the recent (post-2013) increase of +2 °C in air and ground temperatures,21 permafrost below the active layer generally remained stable. Thus, deep thaw events triggered slope failures (episode 2) that were followed by a period of stability (episode 3). RTS frequently re-occur in the same place in the continuous permafrost zone, indicating that massive ice bodies survived previous slumping episodes and persisted under a reformed active layer.39,41,43

The situation is fundamentally different if the mean annual ground temperature at the base of the seasonally freezing layer moves above 0 °C and a persistent talik develops. This is probably the case with the observed destabilized FDL. The FDL occur in the warmest locations of study area 4, where mean annual air temperatures historically were close to −5 °C and modeled ground temperatures were close to −2 °C (Table 2). Ground temperatures were −1–1 °C below the zone of annual fluctuation during 2013–2015 in a vegetated FDL in a setting very similar to mine, about 90 km east of the lobes in study area 4.15 Temperature modeling of this lobe16 suggested that disturbance of the surface soil and vegetation of the lobe would produce a persistent talik with mean annual temperatures above +2 °C. Complete thaw of a frozen lobe that is tens of meters thick would probably take decades,16 but even partial thaw with extensive cracking and penetration of water into the shear zone could destabilize much of an FDL and lead to the behavior we observed (Figure 9).

FDL are widespread in the valleys in the southern half of Gates of the Arctic National Park,13,29 within the area where modeling30 predicts formation of persistent taliks during the current century (shaded gray in Figure 2). As mentioned previously, mean annual ground and air temperatures for the period 2014–2019 were about 2 °C above the 30-year pre-2014 averages,31 approximately the predicted amount of change in ground temperatures for the 2050s, based on moderate emission scenarios from a composite of five global climate models.30 Whether the recent 2 °C positive temperature shift will persist in the near future is unknown, but even the warming that has occurred to date may have put other FDL in this region at risk of destabilization like the one shown in Figure 9.

5 | CONCLUSIONS

ALD occurred episodically in association with deep thaw events, and revegetation was nearly complete within a decade or two. Even under the generally warming conditions of the past half century, there were periods of ALD activity (prior to sampling episodes 1 and 2), followed by relative quiescence and revegetation (prior to sampling episode 3). The time prior to sampling episode 3 also produced few new RTS, and most of the bare ground area in RTS present in episode 3 was from slumps that persisted from earlier times. Continued growth of older RTS did not keep pace with revegetation, and thus the area of bare ground exposed in RTS in episode 3 was also the least of the three episodes. In spite of increasing mean annual temperatures, ground temperatures were low enough over most of the study area to maintain the underlying continuous permafrost, and no new extreme thaw events sufficient to cause initiation of numerous new ALD and RTS occurred after episode 2. However, in the warmest parts of the study area, ground temperatures were high enough for recent warming coupled with surface disturbance to lead to deeper thaw of permafrost, which resulted in the destabilization of FDL.

Permafrost thaw in mountainous regions is likely to create a variety of new slope failures, because thaw can reduce material strength directly, and indirectly by allowing water to enter.38 Where climate warming results in active-layer thickening alone, we can expect the familiar ALD and RTS to occur where sufficient ground ice is present. Where deeper permafrost destabilization and talik formation occur, we are likely to see ALD and RTS, along with more deep-seated slope failures, such as the disintegration of FDL observed in this study.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the United States National Park Service Integrated Resource
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