National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Mapping of Erosion Features Related to Thaw of Permafrost in Bering Land Bridge National Preserve, Cape Krusenstern National Monument, and Kobuk Valley National Park

Natural Resource Data Series NPS/ARCN/NRDS—2010/122

ON THE COVER

A typical active-layer detachment in Cape Krusenstern National Monument, visible on a 20 Aug 2006 IKONOS satellite image with a color-infrared color scheme. Movement was from left to right toward the small stream visible as a narrow line. Grayish areas are bare soil, reddish areas are graminoid- and low-shrub dominated tundra, and yellow is willow scrub in fall colors. (163.502° W, 67.705° N, image 20060830_561_01200001)

Mapping of Erosion Features Related to Thaw of Permafrost in Bering Land Bridge National Preserve, Cape Krusenstern National Monument, and Kobuk Valley National Park

Natural Resource Data Series NPS/ARCN/NRDS—2010/122

David K. Swanson

National Park Service
Fairbanks Administrative Center
4175 Geist Road
Fairbanks, Alaska 99709

December 2010

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Fort Collins, Colorado

The National Park Service, Natural Resource Program Center publishes a range of reports that address natural resource topics 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 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.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

This report is available from the National Park Service, Arctic Inventory and Monitoring Network (http://science.nature.nps.gov/im/units/arcn/) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/NRPM).

Please cite this publication as:

Swanson, D. K. 2010. Mapping of erosion features related to thaw of permafrost in Bering Land Bridge National Preserve, Cape Krusenstern National Monument, and Kobuk Valley National Park. Natural Resource Data Series NPS/ARCN/NRDS—2010/122. National Park Service, Fort Collins, Colorado.

NPS 182/106253, 183/106253, 187/106253, December, 2010

Abstract

A systematic survey was made of three National Park Service units in northern Alaska for active-layer detachments (ALDs) and retrogressive thaw slumps (RTS) using high-resolution satellite imagery from 2006 and 2008. ALDs and RTS develop by localized thaw of permafrost, and have the potential to expose significant areas of soil to erosion. I identified 22 ALDs in Bering Land Bridge National Preserve, 22 in Cape Krusenstern National Monument, and 14 in Kobuk Valley National Park. These ALDs are typically 10 to 30 m wide and up to 300 m long, and on the average expose about 1000 sq m of bare soil each, amounting to a total area of about 6 ha in the 3 NPS units. The ALDs occur on long, well vegetated slopes of moderate steepness and are restricted to specific physiographic areas. These ALDs probably formed by deep thaw during the exceptionally warm summer of 2004. No true retrogressive thaw slumps were found in the study area.

Introduction

Thaw of permafrost can lead to subsidence, mass movement of material on slopes, and exposure of bare soil to erosion by water. While localized thaw and refreezing of permafrost occurs under a stable cold arctic climate, climate change has been cited as a cause of recent increased thaw of permafrost in Alaska (Jorgenson et al., 2006). Concerns about the state of permafrost in the future led the National Park Service Arctic Inventory and Monitoring Network (ARCN, the five NPS units in northern and western Alaska) to include permafrost as a monitoring “vital sign” (Lawler et al., 2009). Thaw-related slumping and associated soil erosion may have increased in ARCN in recent years (Balser et al., 2007), and an important component of ARCN’s permafrost vital sign monitoring involves locating and mapping subsidence and erosion features related to permafrost thaw.

Two important erosion features related to permafrost thaw are active-layer detachments (ALDs) and retrogressive thaw slumps (RTS). ALDs are small landslides that occur on vegetated slopes. (Fig. 1). A surface layer about 1 m thick slides as a unit held together by the root mat, and accumulates as a winkled mass on the footslope. ALDs are typically 10 to 30 meters wide and up to several hundred meters long. The slide leaves an elongated region of bare soil exposed on a

Fig. 1. A typical active-layer detachment in CAKR, visible on a 20 Aug 2006 IKONOS satellite image with a color-infrared color scheme. Movement was from left to right toward the small stream visible as a narrow line. Grayish areas are bare soil, reddish areas are graminoid- and low-shrub dominated tundra, and yellow is willow scrub in fall colors. Note the mostly bare upper part (A) and accumulation of sod and vegetation at the foot (B). The willow-rich strip at (C) may represent an earlier ALD that has re-vegetated. (163.502° W, 67.705° N, image 20060830_561_01200001)

slope, which can lead to erosion of sediment into streams (Bowden et al., 2008; Lamoureux and Lafrenière, 2009). ALDs tend to occur in clusters, where soil and slope conditions are favorable, after periods of unusually warm summer weather or possibly high rainfall (Carter and Galloway, 1981; Lewkowicz and Harris, 2005). They apparently occur after thaw of the ice-rich layer that is often present in the upper permafrost (approximately 1 m below the surface), which produces a mud slurry that lubricates the downslope flow of an elongate strip of surface soil and vegetation (Lewkowicz and Harris, 2005).

Retrogressive thaw slumps occur where a cut-bank in ice-rich permafrost advances into undisturbed ground as material thaws in the steep bank, falls or slumps onto the adjacent more gentle slope, and then is transported away by water erosion or sliding (Burn and Lewkowicz, 1990). RTS are deeper than ALDs and the eroding cut-bank is typically 2 to 10 m high. RTS often begin as escarpments produced by marine, lakeshore, or riverbank erosion and then advance away from the shore by thaw and slumping, sometimes shedding large amounts of sediment into the adjacent water body. Very ice-rich material of substantial thickness (e.g. several meters) and lateral extent is needed to produce a RTS.

Retrogressive thaw slumps are one of many phenomena produced by the action of thermokarst, which is subsidence caused by the thaw of ground ice (Czudek and Demek, 1970; Jorgenson and Osterkamp, 2005). RTS result in the exposure of extensive areas of bare soil, and thus they may be mapped using the unique spectral properties of bare soil. Other thermokarst processes result in subsidence while the vegetation mat remains intact, or they occur along lakeshores and the resulting subsided areas end up under water, or they produce unstable eroding banks so narrow (typically 10 m or less) that they are not readily mapped as polygon features at the mapping scale used here.

The newly acquired nearly complete coverage of ARCN by high-resolution satellite imagery has allowed the NPS to make a comprehensive survey of erosion features caused by permafrost thaw in the Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), and Kobuk Valley National Park (KOVA)(Fig. 2). I combined automated mapping methods with visual recognition of geomorphic features to make a comprehensive map of ALDs and RTS in these NPS units. The purpose of this report is to present the results of mapping efforts to date. Mapping continues in the other ARCN NPS units (Noatak National Preserve, NOAT, and Gates of the Arctic National Park and Preserve, GAAR).

Methods

Study Area

The study area consists of three National Park Service units that are largely within the continuous permafrost zone, where permafrost covers 90% or more of the landscape (Jorgenson et al., 2008; Fig. 2). Permafrost is very ice-rich and subject to thermokarst in lowland areas throughout the study area, while ice contents are negligible in high mountain areas where bedrock is near the surface. Massive ground ice probably consists mainly of wedge ice. Wedge ice forms in a polygonal pattern (in map view) due to water freezing in thermal contraction cracks; the wedge form of the ice is visible in cross-section (Lachenbruch, 1963). Locally in BELA are Pleistocene "yedoma" deposits that contain very large ice wedges. Yedoma deposits contain up to 90% ice by volume and can subside 20 m or more if thawed (Shur et al., 2009). The study area was largely free of glacial ice during the late Pleistocene (Péwé, 1975); thus moraines that contain relict glacial ice and are highly susceptible to thaw slumping (as in the Noatak valley: Balser et al., 2006; Swanson and Hill, 2010) are not widespread in the study area.

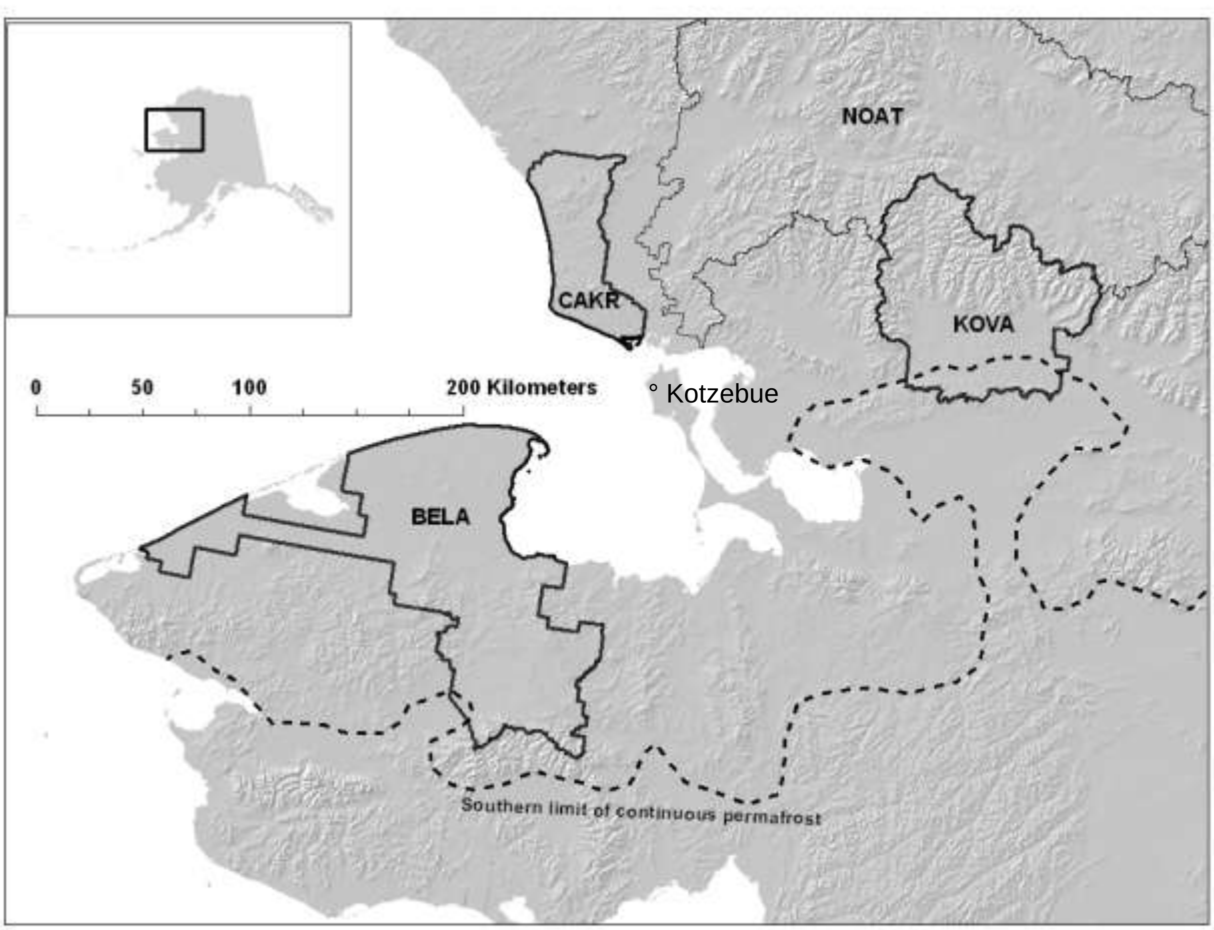

Figure 2. Location of BELA - Bering Land Bridge National Preserve, CAKR - Cape Krusenstern National Monument, and KOVA - Kobuk Valley National Park. The adjacent Noatak National Preserve (NOAT) is also shown. The approximate southern limit of continuous permafrost is from Jorgenson et al. (2008).

Mapping Methods

Exposed bare soil areas were delineated on IKONOS multispectral satellite imagery, (Geoeye, 2010). This imagery includes blue, green, red and near-infrared spectral bands with 4 m resolution, pan-sharpened to 1 m resolution. The images examined are from the leaf-on period (late June through early September) of 2006 and 2008. They were orthorectified with the best available digital elevation model, the National Elevation Dataset at 60 m resolution (USGS, 2006).

Erosion features were mapped by a 3-step process: 1) digitize bare-soil polygons by automated process, 2) manually create a point layer marking all thaw-related erosion features visible on imagery, with the feature type as an attribute, and 3) join these two layers to differentiate permafrost-related bare soils areas from non-target bare soil areas (such as river gravel bars) and transfer the type information to the polygons (Fig. 3).

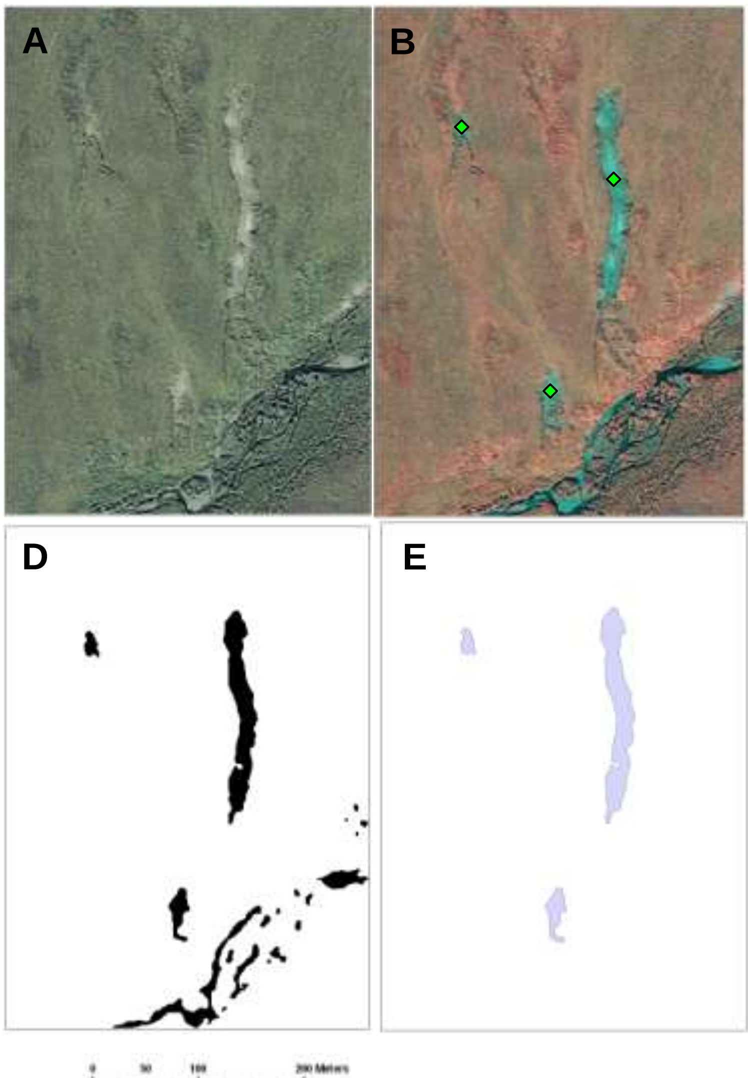

Figure 3. Mapping of erosion features related to permafrost thaw. A) IKONOS image in natural color. B) IKONOS image with color-infrared color scheme and 3 ALDs marked with points. C) NDVI of the IKONOS image. D) NDVI image thresholded to differentiate bare soil (black) from vegetated areas (white). E) Polygons produced by conversion of the thresholded image to a polygon layer and intersection with points in (B). (163.880° W, 67.540° N, image 20060819_053_00600000.

Delineation of bare-soil polygons

First, the normalized difference vegetation index (NDVI) was computed from the near infrared (NIR) and red spectral bands of the IKONOS imagery. NDVI is a measure of "greenness" that is closely related to leaf area and biomass (Tucker and Sellers, 1986). NDVI is computed as (NIR - red)/(NIR + red). It is high (near 1) in densely vegetated areas and zero or lower in unvegetated areas. A median filter over a circle with radius of 3 pixels was then applied to reduce speckling in the NDVI images while preserving features greater than 10 m across. Next, a threshold NDVI value was chosen subjectively for each image to separate vegetated and unvegetated areas; this value varied between 0 and -0.2 for the different images. Finally, the unvegetated areas were converted from raster (pixel) format to polygons (line-delineated).

Identification of permafrost-related erosion features

A point layer of permafrost-related erosion features was produced by systematic examination of the IKONOS images. Images were displayed in the color scheme of color-infrared aerial photographs to enhance visibility of unvegetated areas: band 4 (near infrared) was displayed as red, band 3 (red) as green, and band 2 (green) as blue (Fig. 3). The bare soil polygons produced by the previous step were also overlaid and turned on-and-off to aid in the location of bare soil areas. A 4 by 4 km grid was placed over each image, and each cell in the grid was searched at 1:20,000 scale for any potential erosion features, which were then examined at a larger scale (1:5,000 or larger) to verify and label them as ALD or RTS. Features with 2 or more disjunct patches of bare soil that were nonetheless part of a single feature (e.g. an ALD with a block of vegetation that slid partway down and separates the bare soil into two patches) were given multiple points with the same identifying number. The ecological subsection of each feature was also added as an attribute (Jorgenson, 2001; Swanson, 2001a, b).

Active-layer detachments produce strips of bare soil 10 to 30 m wide and up to several hundred meters long on slopes; they stand in sharp contrast to adjacent, densely vegetated areas. ALDs are distinguished from other bare soil areas by their shape, the presence of a deformed soil-vegetation mat at their downhill end, and orientation vertically up-down a slope. Features readily confused with ALDs include elongate snow beds (which lack the deformed vegetation-soil mat, are often oriented other than up-down the slope, and often have a snow patch in summer imagery), elongated eroded areas along small streams (which also lack the deformed vegetation mat, typically have pointed as opposed to blunt ends, and have a stream entering and exiting from their upper and lower ends), and elongate patches of scree or rubble (which again lack the deformed vegetation-soil mat and typically occur in a pattern related to bedrock outcrops).

The features of RTS that distinguish them from other unvegetated areas include: 1) generally equant shape with an escarpment along part of the perimeter, 2) location on slopes with fine-grained geologic materials (as opposed to terrain with coarse rubble or exposed bedrock), 3) evidence for transport of significant sediment from the RTS, in the form of an evacuation channel or debris fan (Lacelle et al., 2010). Many RTS occur along a river or lakeshore bluff that provided the initial exposure of ice to thaw.

Spatial join of polygon and point layers

Bare-soil polygons that either contained a thaw-feature point within them, or had a point fall within 20 m of their boundaries were identified by automated process and given the attributes of the point. All other bare-soil polygons were deleted. This spatial join eliminated the numerous bare polygons of other origins, such as river sandbars and bedrock outcrops. The area of each ALD or RTS was then computed; these areas do not include of the displaced vegetated mats typically present at the lower end of an ALD (e.g., Fig. 1).

Results

Active-layer Detachments

Twenty-two ALDs were identified in BELA, exposing a total bare soil area of about 28,800 m^2 (2.9 ha; BELA's total area is 1.1 million ha). The largest ALDs are about 20 m wide and 200 m long. All are located in the far southeastern part of the Preserve (Fig. 4) in the Bendeleben Mountains or Bendeleben Foothills subsections, which are composed of various igneous and metamorphic rocks. The greatest concentration of ALDs in BELA is in the Minnie Creek valley, where 10 occur in a 4-km (approximately 2.5-mile) section of the valley; these 10 ALDs cover about 1.4 ha within an area of about 500 ha.

Twenty-two active-layer detachments were also found in CAKR, exposing a total bare soil area of about 17,400 sq m (1.7 ha; CAKR has an area of about 0.3 million ha). The largest one is again about 20 m wide and 200 m long. All are in the Mulgrave Hills ecological subsection in the northern part of CAKR, an area of mostly vegetated low mountains composed primarily of non-carbonate sedimentary rocks (Fig. 5).

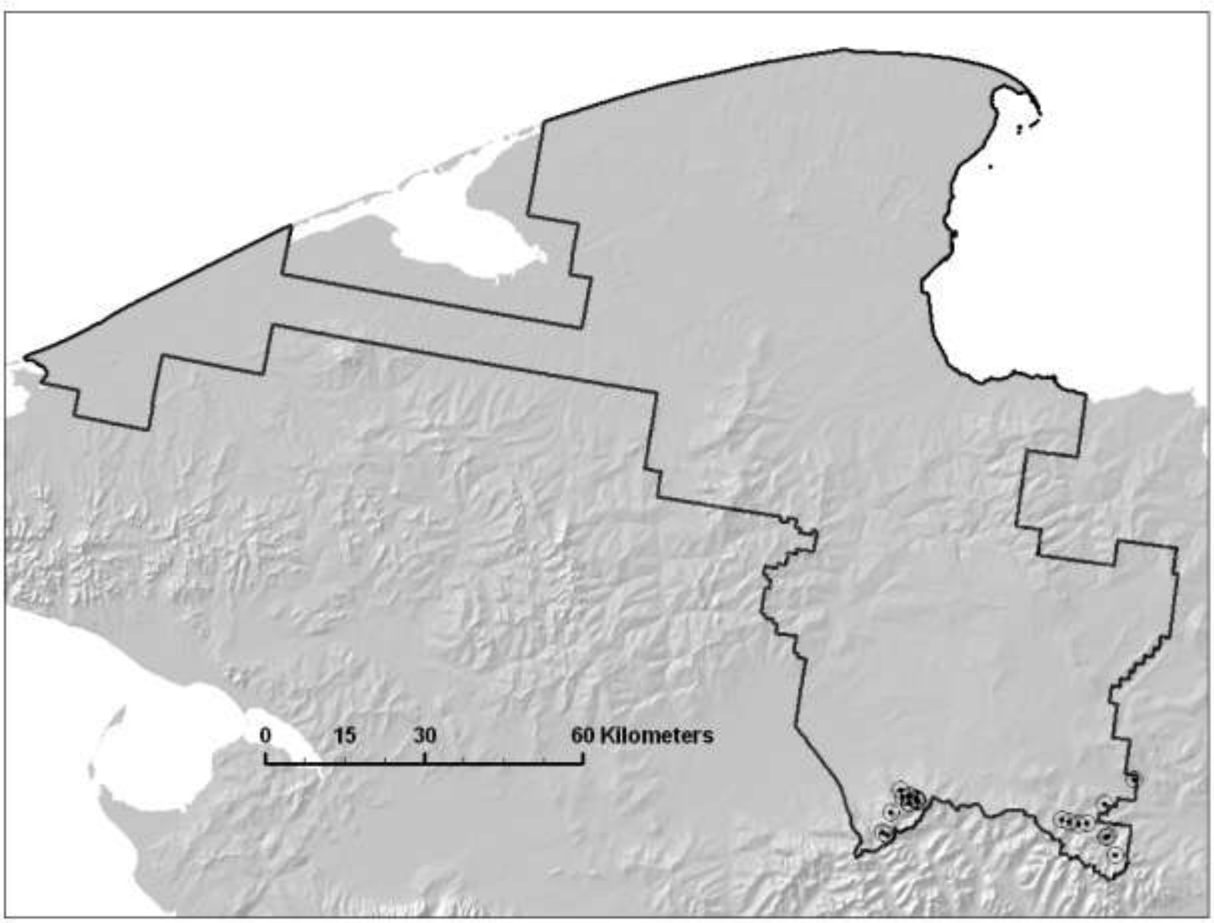

Figure 4. Active-layer detachments in Bering Land Bridge National Preserve, identified using 2006 IKONOS satellite imagery.

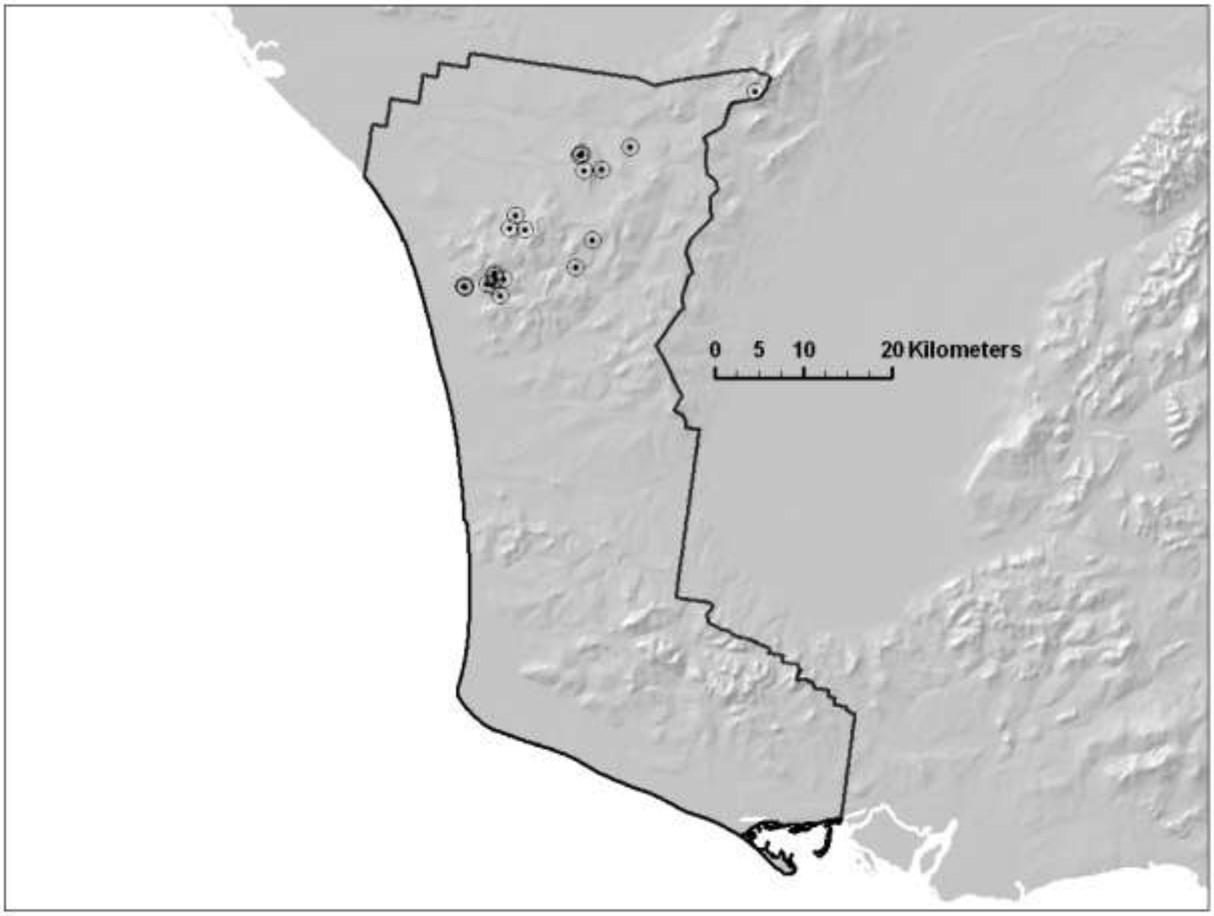

Figure 5. Active-layer detachments in Cape Krusenstern National Monument, identified using 2006 IKONOS satellite imagery.

Fourteen ALDs were found in KOVA, exposing a total bare soil area of about 16,200 sq m (1.6 ha; KOVA's area is about 0.7 million ha). The largest is about 300 m long and 20 m wide. All are in the mountains north of the Kobuk River (Fig. 6), mainly in the Salmon River Hills subsection (non-carbonate sedimentary rock), with a few in the Kunyanak Mountains (carbonate sedimentary rock) and the Akiak Mountains (schist) subsections.

The image dates are July, August, or September 2006 for the ALDs in BELA and CAKR, and these features appear fresh, without signs of revegetation (Fig. 1). The image dates are Aug 2008 for the ALDs in KOVA. Some of the KOVA ALDs show signs of vegetation re-establishment (Fig. 7).

Retrogressive Thaw Slumps

This survey failed to locate any true RTS in the three NPS units of the study area. Two relatively small, amphitheater-shaped features that have cut 50 to 80 m into steep river bluffs were located in KOVA, one along the Kobuk River near the mouth of Kavet Creek just northwest of the Great Kobuk Sand Dunes, and another along Niaktuvik Creek southeast of the Great Kobuk Sand Dunes. The combined area of these two features is under 1400 sq m (0.14 ha). For comparison, numerous individual RTS have been identified in NOAT that are over 1 ha in size (Balser et al.,

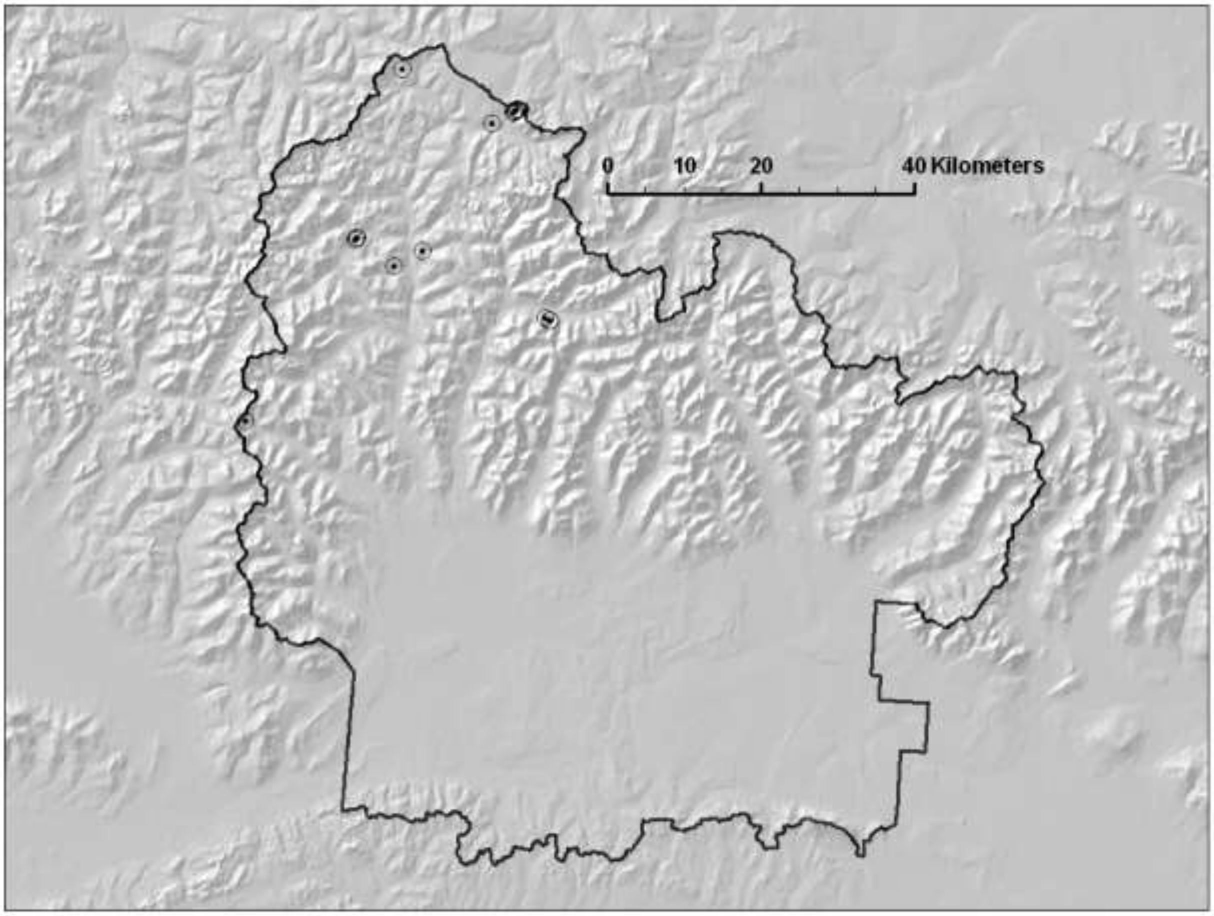

Figure 6. Active-layer detachments in Kobuk Valley National Park, identified using 2008 IKONOS satellite imagery.

2006; Swanson and Hill, 2010). Just outside of KOVA to the east are two larger amphitheater-shaped features - though still not classic RTS - that extend 100 to 150 m inland from Epiguruk Bluff on the south shore of the Kobuk River.

Thermokarst is widespread in the lowlands of the study area, but it has not produced true RTS and associated mappable areas of bare soil. Thermokarst features common in the area that have some similarities to RTS include: 1) steep eroding banks of ponds, lakes, and streams that are unstable due to the presence of ice-rich permafrost, but have not advanced any significant distance beyond the water line (Fig. 8). These features are usually less than 10 m wide, i.e. linear features at our scale of mapping, though especially high banks such as that depicted in Fig. 8 can be 20-30 m wide. 2) Sparsely vegetated thaw depressions with a persistent snow drift, often located along escarpments near ponds, lakes, and streams (Fig. 9). The snow drift probably leads to permafrost thaw by insulating the ground from winter chilling. These areas are sparsely vegetated due to the presence of snow well into the growing season, but they appear to be quite stable and their margins are well vegetated. 3) Steep, eroding banks of ponds, lakes, and streams that have a network of gullies resulting from disintegration of ice wedges (Fig. 10). These features represent significant local disintegration of permafrost and some soil erosion, but currently they result in relatively little exposed bare soil and thus are difficult to map by the methods used here. A combination of thaw of the ice wedge network and erosion due to concentration of running water along the wedge network allows the gullies to propagate from the initial escarpment (typically along a water body). However, the vegetation remains mostly intact over the ice-wedge polygon centers, helping to stabilize the area.

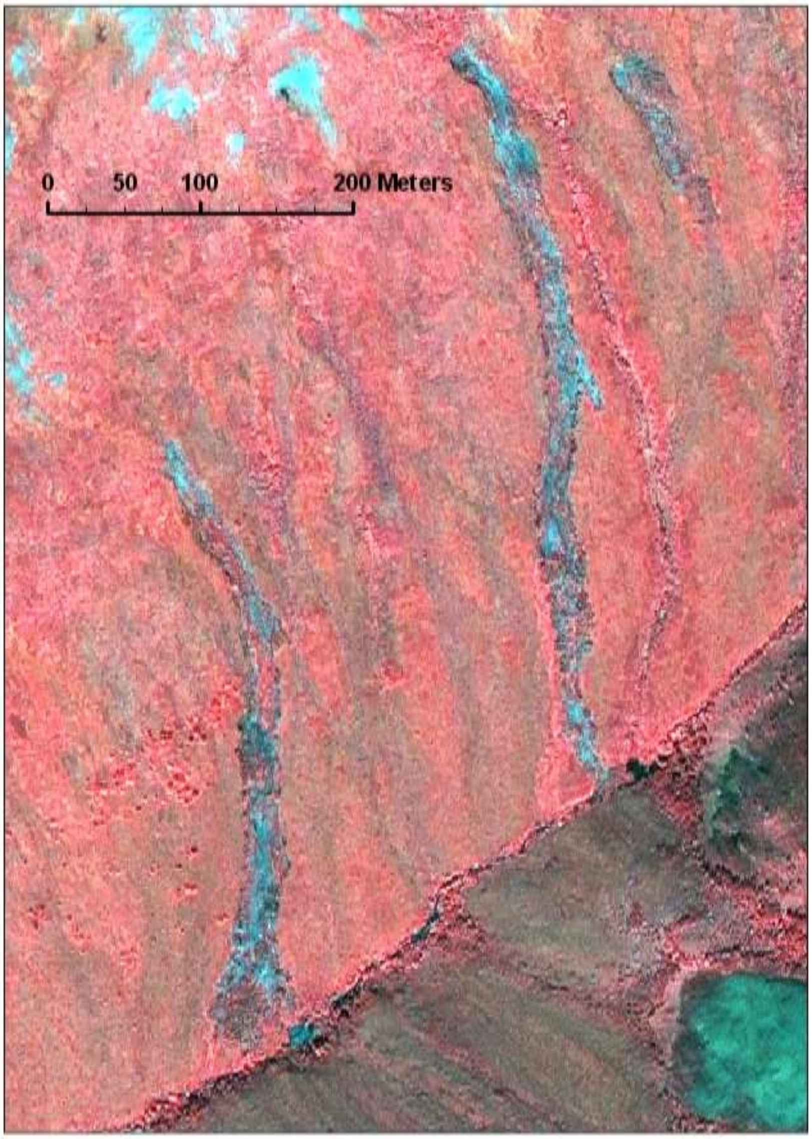

Figure 7. Active-layer detachments that have begun to re-vegetate in Kobuk Valley National Park. Reddish tones indicate green vegetation and gray is exposed bare soil.(159.517° W, 67.800° N, image 20080807_155_0350001)

Figure 8. Steep thermokarst bank near a lake in BELA. The bank on the lower left shore of the lake is sparsely vegetated and unstable due to permafrost thaw, but the escarpment ends at the water line and has not advanced inland. The amount of subsidence between the lake bottom and the undisturbed bank appears to be in excess of 10 m here, indicating the presence of very thick ice-rich “yedoma” deposits (Shur et al., 2009)(163.703° W, 65.757° N, image 20060705_228_0150001)

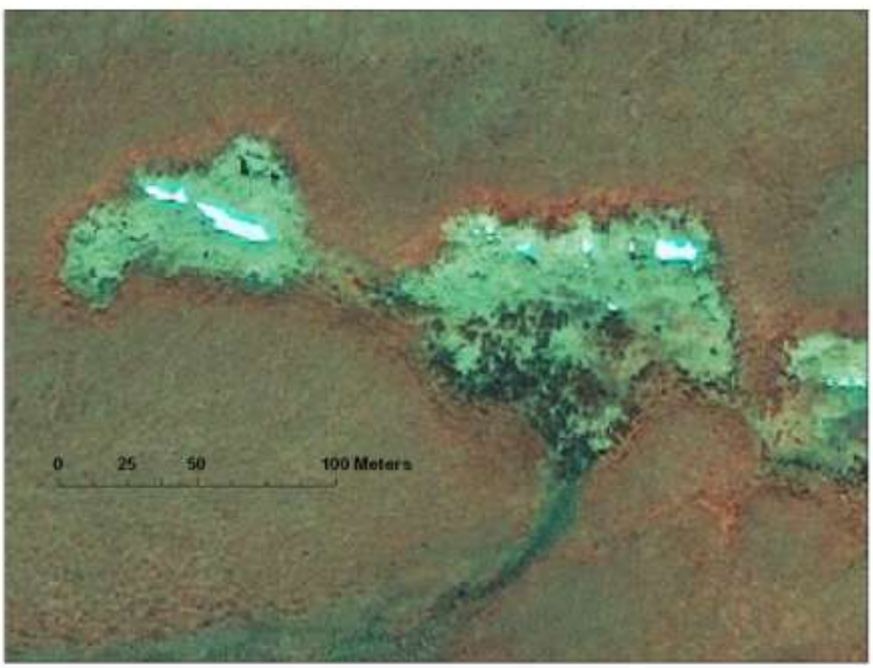

Figure 9. Depressions occupied by a persistent snow banks in BELA. These are thaw subsidence features that have the approximate size and shape of retrogressive thaw slumps, but sparseness of the vegetation is due to persistent snowbanks not rapid erosion (note remnant drifts on 5 July 2006), and they lack the typical morphology of a smooth floor leading up to a steep, unstable cut-bank. (163.355° W, 65.626° N, image 20060705_229_0250001)

Figure 10. Disintegration of ice wedge polygons near a lake in BELA. High-centered polygons have formed by melting of ice wedges, and gullies following the ice-wedge network have grown to the right, from the lake shore. Sparse vegetation (grayish tones) is probably due more to the persistence of snowbanks (note small remnant patches on 6 July 2006) than to rapid erosion, though some soil erosion is undoubtedly occurring, especially at the heads of the gullies. (164.787° W, 66.356° N, image 20060706_880_0160001)

Discussion

Active-layer Detachments

Active-layer detachments can move rapidly, up to 9 m hr^{-1}, and can develop fully in a few days to weeks within a single growing season (Carter and Galloway, 1981; Lewkowicz, 2007). They occur in late summer following exceptionally warm weather, possibly augmented by rainfall, which results in unusually deep thaw that liquefies the upper layer of permafrost (Carter and Galloway, 1981; Lewkowicz and Harris, 2005). To be effective, the triggering event probably must follow a period of pre-conditioning, years where ice builds up in the soil under colder conditions (Lewkowicz and Harris, 2005). Thus formation of ALDs can be synchronous over fairly large areas and coincident with regional warm weather events. The fresh appearance of the ALDs on 2006 imagery, with some signs of revegetation on 2008, suggests a triggering event in the years immediately prior to 2006. Weather data for Kotzebue shows that a trigger event probably occurred in the summer of 2004, when record or near-record high temperatures were recorded for all of the months May through August, and the sum of thawing degree-days was the highest ever recorded (Fig. 11).

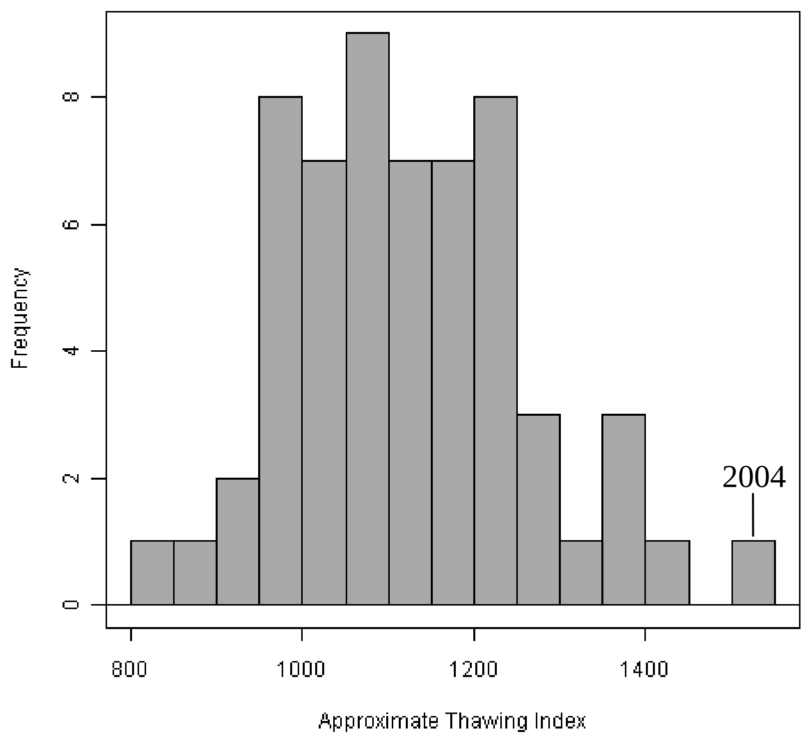

Figure 11. Approximate thawing index (sum of degrees-days above 0 °C for the calendar year, estimated from monthly means) for Kotzebue, Alaska, 1950 to 2009 (excepting 2 years of missing data). The year 2004 had the highest total ever recorded. Station KOTZEBUE WSO AIRPORT, 66° 52’ N, 162° 38’ W, 10 ft elevation (data from WRCC, 2010).

ALDs are clearly restricted to certain landscapes. They occur on well vegetated slopes of substantial length (in excess of 100 m). ALDs are absent from the extensive lowland landscapes in the study area, where slopes are flat except for short, steep slopes on the margins of lake basins and river terraces. ALDs are also absent where bedrock is exposed at the surface or surface materials are coarse-grained rubble with low ice content, though they can occur nearby in finer material. No ALDs were observed in the Igichuk Hills of southern CAKR, which are mostly limestone. Apparently weathering of this limestone does not produce material that is favorable for active-layer detachments.

We currently do not know if the number of ALDs recorded in this inventory is typical or exceptional from a historical point of view. ALDs were documented prior to 1980 (i.e. before the onset of recent warming) in Alaska (Carter and Galloway, 1981) and Canada (Lewkowicz, and Harris, 2005). Possible revegetated ALDs were observed in a few places (e.g., Fig. 1). Retrospective study of ALD frequency using historical imagery will be difficult in ARCN because we have just two prior image dates for most of our region, early 1950s (incomplete coverage) and approximately 1980. If the formation of ALDs is episodic and infrequent, and revegetation makes their age indeterminate after 5 to 10 years, then we might miss events using this historical photography. In the future we intend to monitor the landscapes in ARCN susceptible to ALDs at intervals of no greater than 10 years in order to capture future events.

Retrogressive Thaw Slumps

All of the classic RTS identified in ARCN to date are outside of the study area of this report, in NOAT and GAAR. According to Swanson and Hill (2010) and unpublished observations by A. Balser, they occur on rolling terrain that was glaciated in the Pleistocene and contains laterally extensive bodies of ground ice (probably relict late-Pleistocene glacial ice), with ice wedges also present above the glacial ice in some areas. The flat terrain with wedge ice (but lacking glacial ice) in the current study area has not been susceptible to RTS formation, and cut-banks temporarily stabilize at some rather steep slope angle, usually near a water body (Fig. 8); further progress of such a cut-bank depends on removal of sediment from the base of the slope by wave action or stream erosion. For the cut-bank to continue to advance in the fashion of a RTS, the material that falls from the cut-bank (known as the main scarp or headwall) must be transported away by sliding or flow, which in turn requires a slope below the main scarp and ideally also laterally continuous ice (e.g. glacial ice) on the floor underneath the sliding material. Typical RTS have a floor with slope of 2-10°, and some have evacuation channel below the slump with slope up to 25° (Lacelle et al. 2010; Swanson and Hill, 2010).

The ice-rich sediments of lowlands in our study area deserve continued monitoring in the event that they become less stable in the future due to climate change. Thermokarst in BELA, CAKR, and KOVA is most likely to manifest itself in forms other than RTS, such as the advance of lakeshore cutbanks (Fig. 8), vertical subsidence under nearly continuous vegetation, and thaw of ice wedges (Fig. 10). These processes change the topography without exposing extensive areas of bare soil that are can be mapped by the methods used here. ARCN has proposed to use detailed topographic maps produced by LIDAR to monitor these potential changes due to thaw of permafrost in the future. LIDAR mapping will be targeted to lowland areas with ice-rich permafrost that are most likely to change with climatic warming.

A very large RTS has developed over the past decade along the Selawik River about 60 km southeast of KOVA (Crosby, 2009). The ground ice conditions that led to the formation of this exceptionally deep slump (with a 25 m tall escarpment) remain unknown at the present, but the setting is broadly similar to the Kobuk River valley and there is some possibility that a similar feature could develop along the Kobuk River. Continued monitoring is recommended to detect the development of a similar or a less dramatic feature in the Kobuk River valley.

Literature Cited

Balser, A. W., M. N. Gooseff, J. B. Jones, W. B. Bowden, D. M. Sanzone, A. Allen, J. R. Larouche, 2006. Thermokarst characteristics and distribution in a transitional arctic biome: new discoveries and possible monitoring directions in a climate change scenario. American Geophysical Union, Fall Meeting 2006, abstract #C51B-0428.

Balser, A. W. W. B. Bowden, J. B. Jones, M. N. Gooseff, D. M. Sanzone, A. Bouchier, A. Allen, 2007. Thermokarst distribution in the Noatak Basin, Alaska: increased frequency and correlations with local and regional landscape variables. American Geophysical Union, Fall Meeting 2007, abstract #C32A-08.

Bowden, S. B., M. N. Gooseff, A. Balser, A. Green, B. J. Peterson, and J. Bradford, 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impact on headwater stream ecosystems. Journal of Geophysical Research 113, G02026, doi:10.1029/2007JG000470,2008.

Burn, C. R. and A. G. Lewkowicz. 1990. Retrogressive thaw slumps. Canadian landform examples – 17. The Canadian Geographer 34(3):273–276.

Carter, L. D., and J. P. Galloway. 1981. Earth flows along Henry Creek, Northern Alaska. Arctic, 34, 325-328

Crosby, B. T. 2009. Progressive Growth, Modulated Supply: How coupling and decoupling between an enormous retrogressive thaw slump and its depositional fan impacts sediment delivery to the Selawik River, Northwest Alaska. American Geophysical Union, Fall Meeting 2009, abstract #U41C-0043

Czudek, T. and J. Demek. 1970. Thermokarst in Siberia and its influence on the development of lowland relief. Quaternary Research 1:103–120.

Geoeye. 2010. Imagery sources. IKONOS. http://www.geoeye.com/CorpSite/products/imagery-sources/Default.aspx. Accessed 1 March 2010.

Jorgenson, M. T., Y. L. Shur, and E. R. Pullman. 2006. Abrupt increase in permafrost degradation in Alaska. Geophysical Research Letters 33:L02503.

Jorgenson, M. T. 2001. Ecological subsections of Bering Land Bridge National Preserve. Inventory and Monitoring Program, National Park Service, Alaska Region, Anchorage, Alaska.

Jorgenson, M. T. and T. E. Osterkamp. 2005. Response of boreal ecosystems to varying modes of permafrost degradation. Canadian Journal of Forest Research 35:2100-2111.

Jorgenson, T., K. Yoshikawa, , M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, G. Grosse, J. Brown, and B. Jones. 2008. Permafrost characteristics of Alaska. Proceedings of the Ninth International Conference on Permafrost. University of Alaska Fairbanks, Institute of Northern Engineering.

Lacelle, D., J. Bjornson, and B. Lauriol. 2010. Climatic and geomorphic factors affecting contemporary (1950-2004) activity of retrogressive thaw slumps on the Aklavik Plateau, Richardson Mountains, NWT, Canada. Permafrost and Periglacial Processes 21:1–15.

Lachenbruch, A. H. 1963. Contraction theory of ice-wedge polygons: a qualitative discussion. Pages 63-71 *in* Proceedings Permafrost International Conference, 11-15 November, 1963. National Research Council Publication 1287. National Academy of Sciences, Washington, D.C.

Lawler, J. P., S. D. Miller, D. M. Sanzone, J. Ver Hoef, and S. B. Young. 2009. Arctic network vital signs monitoring plan. Natural Resource Report NPS/ARCN/NRR-2009/088. U.S. Department of the Interior, National Park Service, Natural Resource Program Center, Ft. Collins, Colorado.

Lamoureaux, S. F., and M. J. Lafrenière. 2009. Fluvial impact of extensive active layer detachments, Cape Boundary, Melville Island, Canada. Arctic, Antarctic, and Alpine Research 41(1):59–68.

Lewkowicz, A. G. 2007. Dynamics of active-layer detachment failures, Fosheim Peninsula, Ellesmere Island, Nunavut, Canada. Permafrost and Periglacial Processes 18:89–103

Lewkowicz, A. G., and C. Harris. 2005. Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada. Permafrost and Periglacial Processes 16:115–130.

Péwé, T. L. 1975. Quaternary geology of Alaska. U.S. Geological Survey Professional Paper 835. U.S. Government Printing Office, Washington, D.C. 145 pp.

Shur, Y., M. Z. Kanevskiy, M. T. Jorgenson, D. Fortier, M. Dillon, E. Stephani, and M. Bray. 2009. Yedoma and thermokarst in the northern part of Seward Peninsula, Alaska. American Geophysical Union, Fall Meeting 2009, abstract #C41A–0443.

Swanson, D. K. 2001a. Ecological subsections of Cape Krusenstern National Monument. Inventory and Monitoring Program, National Park Service, Alaska Region, Anchorage, Alaska.

Swanson, D. K. 2001b. Ecological subsections of Kobuk Valley National Park. Inventory and Monitoring Program, National Park Service, Alaska Region, Anchorage, Alaska.

Swanson, D. K. and K. Hill. 2010. Monitoring of retrogressive thaw slumps in the Arctic Network, 2010 baseline data: Three-dimensional modeling with small-format aerial photographs. Natural Resource Data Series NPS/ARCN/NRDS—2010/123. National Park Service, Fort Collins, Colorado.

Tucker C. J., and P. J. Sellers 1986. Satellite remote sensing of primary production. International Journal of Remote Sensing 7(11):1395–1416.

US Geological Survey [USGS]. 2006. National elevation dataset. http://ned.usgs.gov/. Accessed 13 April 2010.

Western Regional Climate Center (WRCC). 2010. Western U.S. Climate Historical Summaries. http://www.wrcc.dri.edu/Climsum.html (accessed 2 April 2010).