Thermokarst distribution and relationships to landscape characteristics in the Feniak Lake region, Noatak National Preserve, Alaska

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1.0 ABSTRACT

Climate warming in the arctic is leading to loss of permafrost and wide-scale ecosystem alteration(ACIA 2004). Permafrost thaw often results in thermokarst, involving intensive and catastrophic loss of soil structure and subsidence(Jorgenson et al. 2008). Regional-scale distribution of thermokarst features is poorly documented throughout the arctic, and correlations with landscape variables are poorly understood(Osterkamp 2007). The Feniak Lake area, within the Noatak Basin in northwestern Alaska's Brooks Range mountains, harbors a transitional landscape from arctic and alpine tundra to boreal shrubland (Young 1974). Field investigations augmented by photogrammetric measurements in 2006 reveal patterns in the distribution of classifiable thermokarst failure types, and provide data on the physical and chemical impacts these features have on aquatic systems. Distinct thermokarst types show significant relationships with local landscape variables such as slope and vegetation, and with regional variables including lithology, surficial geology, glacial history and landcover. Frequency of thermokarst features has increased markedly within this study area in the past 25 years. Analysis of current and historical aerial photography shows a two fold increase in number of thermokarst features, and in total surface area of affected landscape. The majority of these previously unreported features occur in headwaters of Noatak River tributaries, where they can have marked impacts on small headwater streams which have less buffering capacity for disturbance. These results demonstrate that thermokarst, especially in headwater regions, has been vastly under-reported in the Noatak Basin. These findings also suggest that similar phenomena may be under-reported in other permafrost regions as well, due in part to the logistical difficulty of conducting quantitative surveys in remote areas with rugged topography. Significant associations among thermokarst types and landscape parameters suggest that a predictive model to identify thermokarst-susceptible terrain should be viable in the future.

2.0 INTRODUCTION

Average annual Arctic temperatures have risen ~1^{o}C in the past 50 years(ACIA 2004). Results from general circulation models (GCMs) further suggest that average annual temperatures in the Arctic will continue to increase, perhaps as much as 3-5^{o}C in coming decades (U.S. Arctic Research Commission Permafrost Task Force 2003, IPCC 2007). Regional warming and climate change are linked with permafrost degradation (Hinzman et al. 2005), including thermokarst formation (Jorgenson and Osterkamp 2005). While increased thaw has already been observed in Alaska through borehole monitoring programs (Osterkamp 2003), melt-derived pond drainage (Yoshikawa and Hinzman 2003), and serendipitous discovery of large thermokarst features in remote landscapes, quantified, regional-scale spatial data for frequency, distribution and correlation with landscape parameters are virtually absent (Gooseff et al. 2009).

Thermokarst (soil structural failure and mass wasting following permafrost thaw) releases stored carbon and nutrients as well as sediment load into aquatic systems (Bowden et al. 2008). Up to 40% of global carbon storage is in arctic and sub-arctic frozen soils (Billings 1987, Shaver et al. 2000) These nutrients, carbon efflux and sediment load alter aquatic ecology, feed into regional and global climate change processes, and permanently alter the character of the terrestrial ecosystem on which they form (Peterson et al. 1993, Mack et al. 2004, Schuur et al. 2007).

There are many distinct, classifiable modes of thermokarst formation, driven by regional and site-specific variables (Jorgenson and Osterkamp 2005). Some types have been prominently reported (Hinzman et al. 2005, Walter et al. 2006), but these represent a minority of the total number of features on the landscape. Well-reported thermokarst tends toward very large, singular features (retrogressive thaw slumps, glacial thermokarst)(Jorgenson and Osterkamp 2005) associated with lake margin collapse; features identified with comparative ease using coarse-scale satellite imagery and airphotos (Lewkowicz 1999). In the Feniak Lake study area, these large features are outnumbered roughly 4 to 1 by smaller features, including thermokarst gullies and active layer detachment slides (ALDSs). Volumetrically, preliminary analysis suggests that these smaller features average 12,500 m^2 in area and displace 37,500 m^3 each, whereas the larger features average 22,000 m^2 in area and displace 200,000 m^3 of soil each. These results suggest that the smaller, overlooked features comprise a comparable displaced soil volume and twice the disturbed surface area of the larger, better known features. Yet, these smaller thermokarst features are virtually unreported and unaccounted-for in landscape ecological studies, regional-scale models and GCMs.

2.1 Feniak Lake Study Area

Thermokarst distribution was surveyed for a 3600 km^2 area (60 km x 60 km) centered on Feniak Lake in the Noatak National Preserve, Brooks Range, Alaska (68^o 15’N, 158^o 20’W). The study area includes the eastern DeLong Mountains of the Brooks Range, moving south through periglacial landforms in the Aniuk Lowlands, to the mainstem Noatak River at the valley bottom (Young 1974). Upland substrates include non-carbonate, carbonate and ultramafic lithologies (Jorgenson et al. 2001), and are typically overlain by colluvial deposits, soliflucted hillslopes, glacial till and outwash primarily of early Itkillik Age (roughly 50,000 years BP) (Hamilton in press). Upland land cover is predominantly arctic and alpine tundra, including dry scrub (IID1,2,3), open low scrub (tussock and shrub tussock tundra)(IIC2), and open and closed tall scrub (primarily lakeshore and riparian willow and alder)(IIB1,2)(land cover names and codes from (Viereck et al. 1992)). Watertracks with wet sedge meadow (IIIA3a) are common on hillslopes in headwater areas, and are comprised of both diffuse-flow and channelized-flow varieties. Unvegetated bedrock exposures commonly span upland ridges and peaks (Hamilton 2009). Valley bottoms have non-carbonate and carbonate substrates (Jorgenson et al. 2001) as glaciolacustrine, alluvial, outwash and periglacial deposits primarily of late Itkillik age (roughly 20,000 years BP)(Hamilton 2009, in press). Valley bottom land cover is similar to that of the uplands, but with minimal exposed bedrock and a higher proportion of scrub and tussock tundra classes. Tussock formation is common and pronounced in the Aniuk lowlands.

3.0 METHODS

Our survey canvassed the landscape by helicopter, flying 300 – 600 m above ground level. Thermokarst features were noted by type with GPS locations and oblique photographs, and ground visits were made to a subset of representative thermokarst features. Physical parameters measured for each feature included length, width, depth at headwall, aspect and ambient slope. Length, depth and width were measured with an electronic, laser rangefinder/inclinometer. Aspect and slope were obtained with a Brunton compass / inclinometer. It should be noted that the available DEM data (USGS 60 m NED) were too coarse to provide reliable slope and aspect data at the scale of the features in this study, and all values used were therefore field-measured. Vegetation and landcover within and adjacent to each feature were assessed with a species list within a 10m radius from arbitrarily selected points, with landcover designations following Level IV of the Alaska Vegetation Classification (Viereck et al. 1992). For the purposes of spatial analyses, landcover was condensed into simpler classes roughly corresponding to Alaska Vegetation Classification Level III categories.

To complement the initial field survey, a series of airphoto lines were defined on the basis of the field results (Figure 1). Low altitude, vertical aerial photography was flown by TerraTerpret Inc. on September 1, 2006 at elevations of 2286 m and 3048 m above target, producing photos with 40 cm and 100 cm pixel resolution respectively. These natural color, digital photographs were collected with a Nikon D2X 35mm format camera, with 20% endlap between adjacent frames.

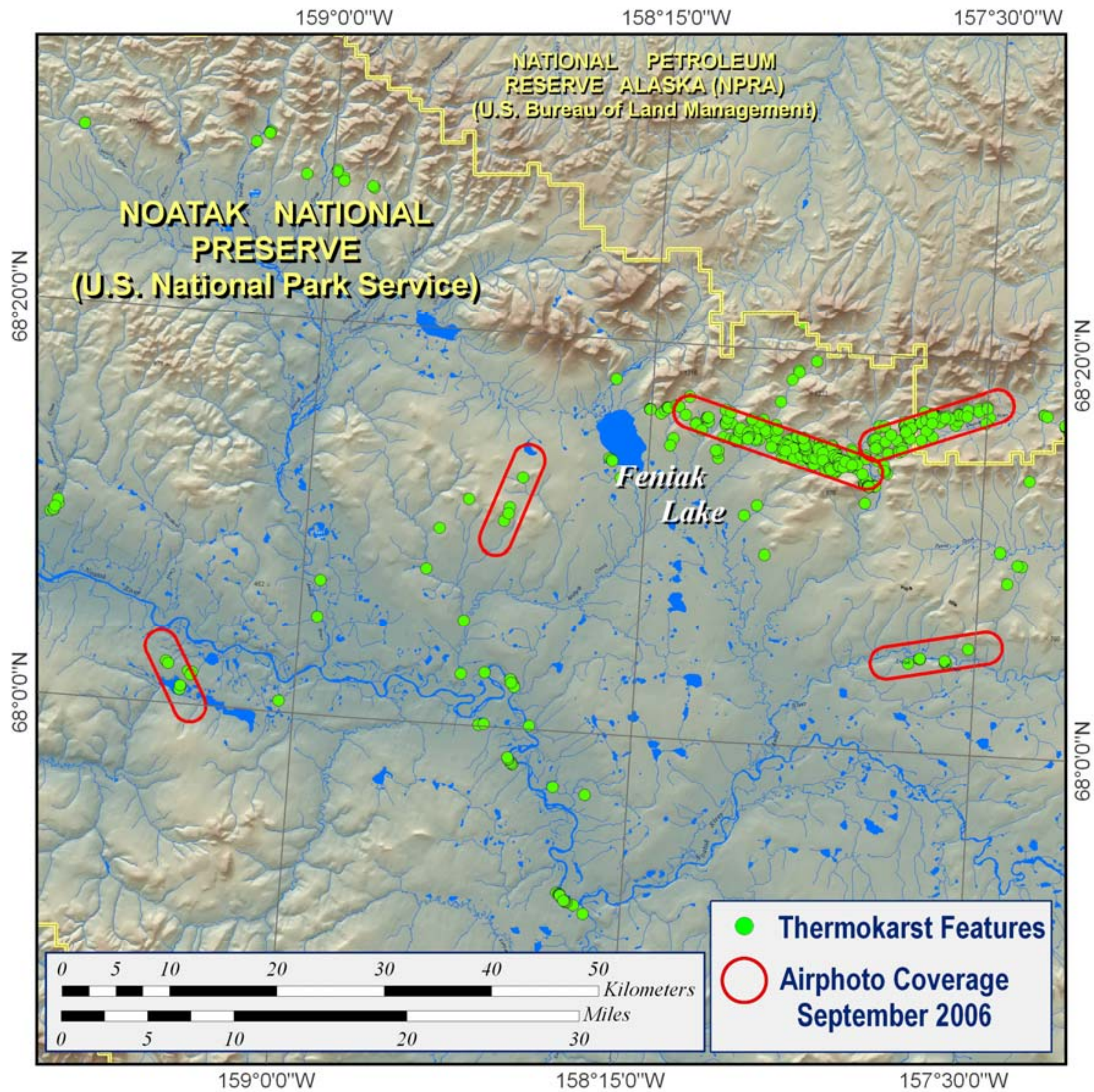


Figure 1. Map of Feniak Lake study area thermokarsts and airphoto acquisitions.

Historic photographic data for the area were obtained from the Alaska High-Altitude Photography program (AHAP) archives at the Geophysical Institute at the University of Alaska Fairbanks. These 9" format, color-infrared airphoto lines have roughly 40% endlap, were taken between 1978 and 1986, and constitute one iteration of full coverage of the study area for that timeframe. The original film sheets were scanned at 1800 dpi, corresponding to roughly 1 m ground resolution (original photography was flown at roughly 1:63,360 scale).

Paucity of existing framework spatial data for the Noatak National Preserve and lack of high-accuracy ground control necessitated an innovative means of georectification of airphoto data. For each airphoto line, individual frames were stitched into a single airphoto panorama using the 'PTGui' panorama stitching tool (http://www.ptgui.com/). PTGui uses a hybrid of manual and automated control point selection techniques among frames, and was found to be the only product of many tested that delivered reliable results in a time-effective manner, and was the only utility with full documentation of its processing steps and algorithms. Resulting cylindrically-projected airphoto panoramas were georectified manually using ERDAS Imagine 9.0. Primary ground control for control point selection consisted of Landsat ETM+ data, geocoded and provided as public domain through the Global Land Cover Facility at the University of Maryland. Data from the USGS National Hydrographic Dataset and National Elevation Dataset were also consulted to strengthen control point selection decisions. AHAP lines were rectified first because they are intermediate in scale between Landsat and TerraTerpret data, have broader coverage and therefore more control point opportunities, and have less orographic distortion as they were flown at a higher altitude. Each airphoto line was saturated with 150 – 350 control points, and rectified with non-linear rubber sheeting. Spatial accuracy of this technique was evaluated using a set of GPS derived ground control points from field data, and from visual interpretation against the Landsat imagery. This method yielded average results estimated at better than 7 m, and which were locally within 3 m in most areas. TerraTerpret airphoto lines were coregistered to AHAP lines using the same numbers of control points and rubber sheeting techniques. An accuracy assessment using a separate set of 100 control points estimated 4m accuracy on average among coregistered AHAP and TerraTerpret airphoto lines.

Thermokarst features were mapped from georectified aerial photography solely by manual interpretation and examination. Several automated classification and thresholding techniques that were tested to identify thermokarst features, but spectral and radiometric variability of both the landscape and of individual thermokarst features in the photography resulted in widespread errors. Automated techniques were ultimately abandoned, and manual mapping was done on a 1 km x 1 km grid cell basis throughout the entire extent of the airphoto coverage. Each feature location was recorded along with thermokarst failure mode and year identified (2006 for TerraTerpret photos, years from 1978-1986 for AHAP photos).

All thermokarst features (from both field reconnaissance and airphoto analysis) were combined into a single ArcGIS GeoDatabase, and linked with ancillary field data for features where ground visits were made. The resulting database was used in all subsequent spatial overlay analyses characterizing thermokarst distribution in the Feniak Lake area, and correlation with landscape parameters.

4.0 RESULTS

4.1 Frequency

Comparison of airphoto results between AHAP and TerraTerpret photography shows a nearly two-fold increased frequency (263 : 127) of thermokarst features within the airphoto analysis window (a subregion within the Feniak Lake study area) in the roughly 25 years from the 1980s to 2006. The tally of active features in the overall Feniak Lake study area was 503 thermokarst features as of 2006. By thermokarst mode, the predominant features were active layer detachment slides (389), followed by retrogressive thaw slumps (79), thermokarst gullies (28), and glacial thermokarsts (7).

Airphoto analysis also suggests a more distant history of thermokarst development, though the evidence is only circumstantial. Many landscape features were discernible which were similar in size, shape and landscape location to current, active thermokarst features, but which were instead vegetated with a different land cover type than the surrounding landscape. Figure 2 shows an example of active thermokarst features becoming revegetated between AHAP and TerraTerpret airphoto acquisitions. We believe that many landscape features of similar description are revegetated thermokarst failures from earlier episodes of permafrost thaw. It is not known how many revegetated thermokarst features exist in this area, or what proportion they may be to the overall tally of thermokarst features. Timing is likewise entirely speculative; 'old' thermokarsts could represent past change at the decadal scale, or over centuries. It is also unknown whether such features tend to initiate episodically, due to seasonal climate or acute weather events, or whether they develop in a slow and steady progression, gradually increasing in number through time.

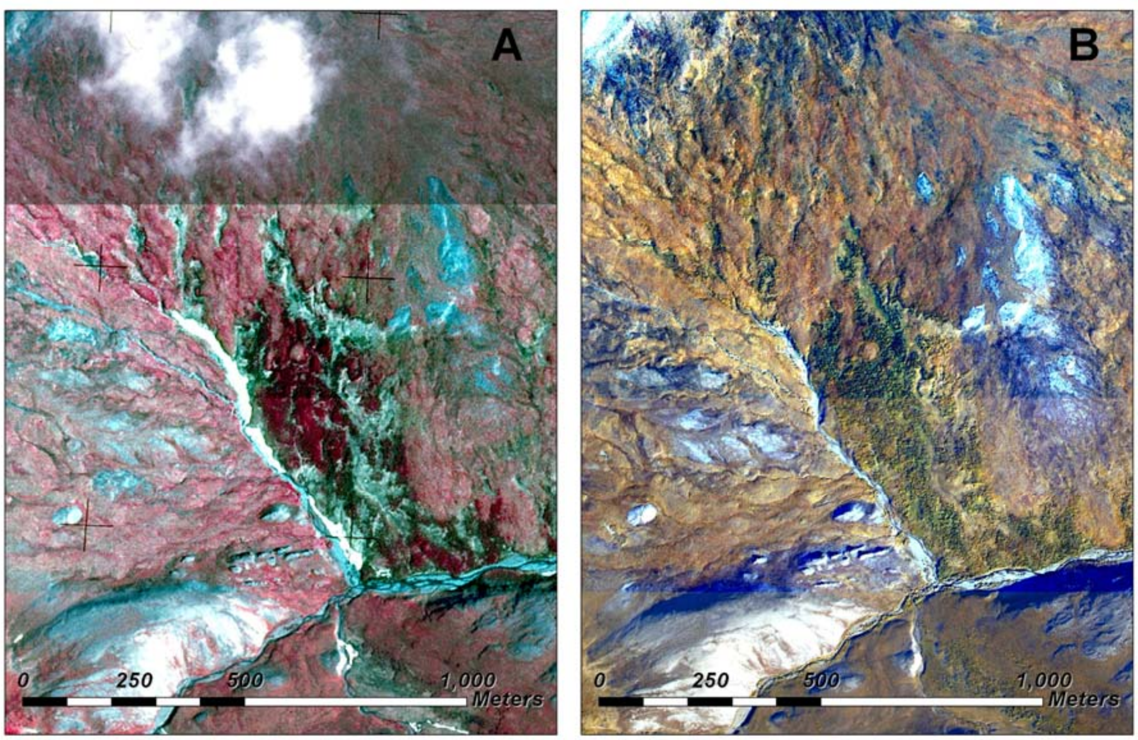


Figure 2. Thermokarst revegetation. A. Color-infrared airphoto, July 1985. B. Natural color airphoto, September 2006. Note the general re-vegetation and the expansion of shrub cover.

4.2 Distribution

Thermokarst features, when considered by mode, showed strong correlations with several physical and ecological landscape parameters. Ambient slope showed an especially strong association, and local landcover was 100% consistent within modes for the 35 thermokarst features which were surveyed on the ground in 2006 (Table 1).

Table 1. Landscape Associations for the 35 thermokarst features which were ground-surveyed in 2006.

Mode	Slope° mean (std)	Landcover
Active Layer Detachment Slides	4.69 (1.58)	Wet Sedge Meadow[1] (class IIIA3b*)
Retrogressive Thaw Slumps	9.45 (3.44)	Low Shrub/Shrub-tussock tundra (class IIIA3b*)
Thermokarst Gullies	5.10 (3.29)	Wet Sedge Meadow[2] (class IIIA3b*)

[1] = Wet Sedge Meadow with diffuse surface flow
[2] = Wet Sedge Meadow with channelized flow in watertracks
* Land cover classes from The Alaska Vegetation Classification, (Viereck et al. 1992)

Thermokarst features occurred exclusively on a suite of non-carbonate lithologies (lithology as mapped by (Jorgenson et al. 2001)) within the study area (Table 2, Figure 4), . A possible reason for this is the differences in soil development typical of carbonate, and especially of ultramafic lithologies. Chi-square testing indicates that thermokarst features are generally not distributed evenly among lithologies (Table 3). The possible exception is the retrogressive thaw slump, which generally occurs on lake and river margins and is tied to landform more than lithology. It is interesting to note that the results suggest glacial thermokarsts are even distributed among lithologies, when they are by definition obligate to a particular landscape surface (containing relic massive ice). The relatively small sample size (n=8) for glacial thermokarsts may account for this result.

Landcover characteristics are also consistent by thermokarst mode. Retrogressive Thaw Slumps were found only on low shrub and shrub tussock landscapes. It is not known whether this landcover is directly associated with thermokarst-prone conditions, or whether it is merely coincident with thaw slumps as the predominant landcover of river banks and lake margins, where thaw slumps occur. Active Layer Detachment Slides were only observed within the discrete boundaries of diffuse-flow watertracks containing wet sedge meadow.

Table 2. Thermokarst distribution by Lithology. (note that “Sedimentary Noncarbonate” is the primary constituent of “Sedimentary Complex”, and the two categories are nearly identical for the purposes of this analysis)

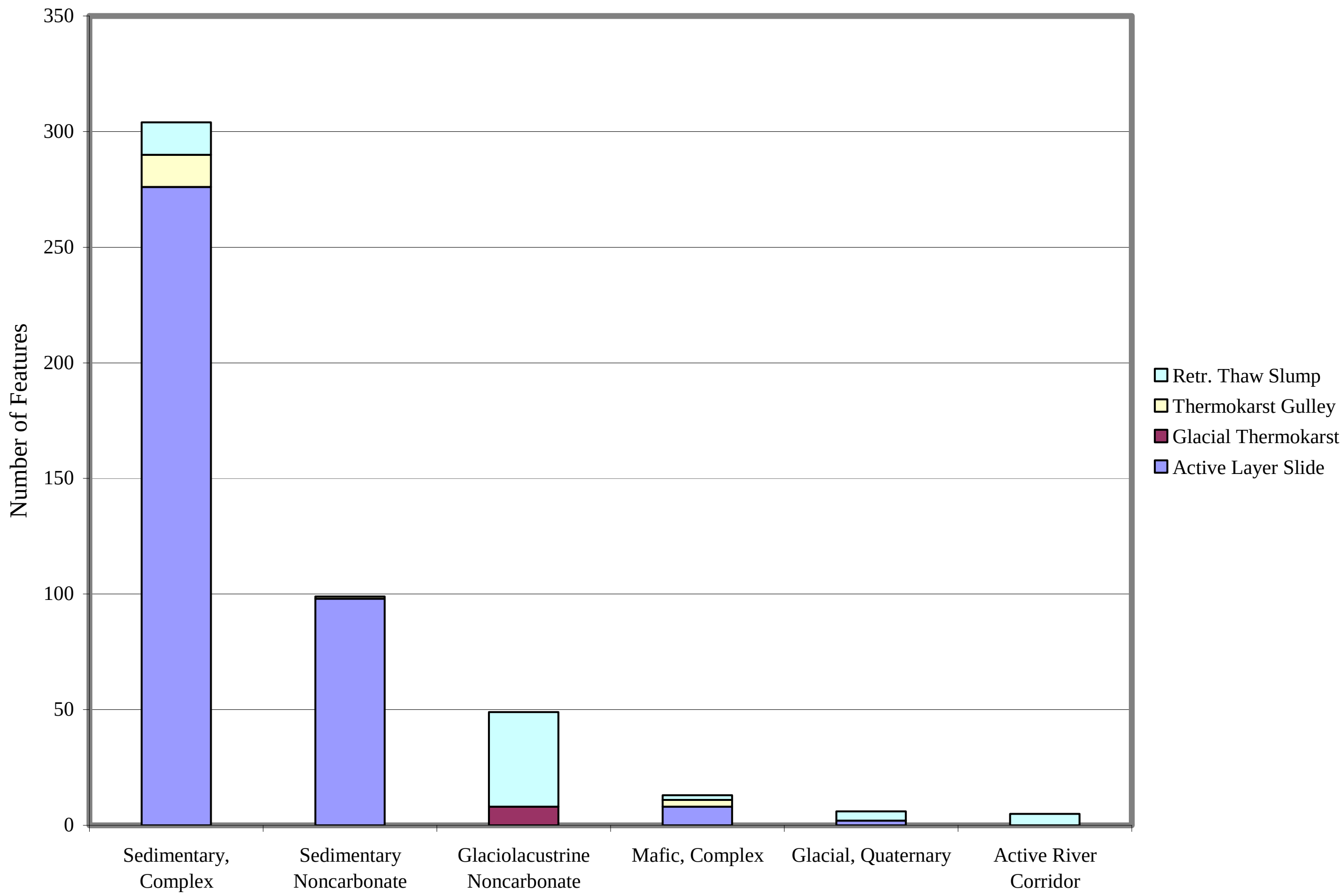
	Thermokarst Mode				
Lithology	Active Layer Slides	Glacial Thermokarsts	Thermokarst Gullies	Retrogressive Thaw Slumps	Total
Carbonate	-	-	-	-	-
Sedimentary Complex	276	-	14	14	304
Sedimentary Noncarbonate	98	-	1	-	99
Glaciolacustrine Noncarbonate	-	8	-	41	49
Mafic, Complex	8	-	3	2	13
Glacial, Quaternary	2	-	-	4	6
Active River Corridor	-	-	-	5	5
Total	384	8	18	66	**476**

Table 3. Chi-square test of thermokarst distribution by lithology.

Thermokarst Mode	**p-value**	**Chi Square**
All Modes Combined	4.34969E-88	417.7852
Active Layer Slides	5.72771E-76	534.8152
Retrogressive Thaw Slumps	0.0574	* 21.18506
Thermokarst Gullies	9.57082E-05	35.49318
Glacial Thermokarsts	0.1737	# 12.58812

* significant at 0.05
# sample size = 8
$\alpha = 0.05$

Figure 4. Thermokarst Distribution by Lithology. Lithology from (Jorgenson et al. 2001).



5.0 DISCUSSION

While evidence clearly shows that thermokarst frequency has dramatically increased in specific areas around Feniak Lake since 1980, the overall rate of thermokarst development for the region is uncertain. It is possible that thermokarst activity has simply increased dramatically in recent decades, or that thermokarst frequency has remained roughly constant, but that feature development has shifted among specific local areas.

Carbonate soils often retain a smaller proportion of silt-sized particles due to the tendency of carbonates to dissolve and leach away. This changes the drainage characteristics of soils, and consequently the permafrost characteristics. It is possible that these soils have less tendency to develop the ice-rich transition zone at the top of the permafrost table which is usually the zone of thaw and primary failure, especially for Active Layer Detachment Slides. Ultramafic lithologies, having comparatively little or even no soil development, do not typically harbor ice-rich soils which result in thermokarst upon thawing.

Recent work in arctic Canada has shown that ALDS features are commonly triggered by an extended period of hot, sunny weather which transmits excess heat deeper through the active layer mobilizing ice-rich transition-zone soils (Lamoureux and Lafreniere 2009). In the Feniak Lake area, it may be that wetter conditions in watertracks promote a more ice-rich transition zone closer to the surface, making watertracks more susceptible to failure from increased thaw depth. Thermokarst Gullies also occur exclusively in watertracks, though in watertracks with channelized flow. Thermokarst gullies are associated with melting at the interface of segregation ice (an ice lens or wedge) and adjacent frozen soils. Channelized water from the surface dips beneath the vegetation and rapidly perpetuates the melting, forming a tunnel where ice and ice-rich silts have melted and mobilized downstream. Channelized surface flow, typical of watertracks, is a prerequisite for thermokarst gully formation, and therefore a partial predictor of thermokarst-vulnerable conditions(Jorgenson and Osterkamp 2005).

Glacial Thermokarsts are associated with relic glacial ice in lowlands(Hamilton in press). All those found in the Feniak Lake region were on late Itkillik Age (roughly 25,000 year old) surfaces consisting of glacial till with interspersed masses of buried, relic glacial ice. These features tend to be the largest of all modes found in this area, and seem to occur in dramatic, episodic events of one to several years which, through time, contribute to the initiation and expansion of thaw lakes. The largest observed in 2006 displaced an estimated 225,000m^3 of relic ice and ice-rich till into the adjacent lake.

6.0 CONCLUSIONS

Thermokarst formation has increased markedly in the Feniak Lake area in the past 25 years. Impacts range from local to global, and are relevant both to global change questions and to local ecological conditions. Continued climate change, especially more frequent periods of hot, sunny summer weather, are likely to further increase the incidence of thermokarst formation in the Noatak Basin and elsewhere. The close associations observed among thermokarst modes and landscape characteristics suggest a useful predictive model and thermokarst risk map for future monitoring, and to estimate the possible future extent and impact of thermokarst formation in a continued climate change scenario.

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