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Sediment and Nutrient Delivery from Thermokarst Features in the Foothills of the North Slope, Alaska: Potential Impacts on Headwater Stream Ecosystems

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Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems

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[1] Permafrost is a defining characteristic of the Arctic environment. However, climate warming is thawing permafrost in many areas leading to failures in soil structure called thermokarst. An extensive survey of a 600 km^2 area in and around the Toolik Lake Natural Research Area (TLNRA) revealed at least 34 thermokarst features, two thirds of which were new since ~1980 when a high resolution aerial survey of the area was done. Most of these thermokarst features were associated with headwater streams or lakes. We have measured significantly increased sediment and nutrient loading from thermokarst features to streams in two well-studied locations near the TLNRA. One small thermokarst gully that formed in 2003 on the Toolik River in a 0.9 km^2 subcatchment delivered more sediment to the river than is normally delivered in 18 years from 132 km^2 in the adjacent upper Kuparuk River basin (a long-term monitoring reference site). Ammonium, nitrate, and phosphate concentrations downstream from a thermokarst feature on Imnavait Creek increased significantly compared to upstream reference concentrations and the increased concentrations persisted over the period of sampling (1999–2005). The downstream concentrations were similar to those we have used in a long-term experimental manipulation of the Kuparuk River and that have significantly altered the structure and function of that river. A subsampling of other thermokarst features from the extensive regional survey showed that concentrations of ammonium, nitrate, and phosphate were always higher downstream of the thermokarst features. Our previous research has shown that even minor increases in nutrient loading stimulate primary and secondary production. However, increased sediment loading could interfere with benthic communities and change the responses to increased nutrient delivery. Although the terrestrial area impacted by thermokarsts is limited, the aquatic habitat altered by these failures can be extensive. If warming in the Arctic foothills accelerates thermokarst formation, there may be substantial and wide-spread impacts on arctic stream ecosystems that are currently poorly understood.

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1. Introduction

[2] Recent summaries of international research clearly document the past and future extent of climate warming in the Arctic [e.g., *Chapin et al.*, 2000; *International Protocol on Climate Change*, 2001; *U.S. Arctic Research Commission Permafrost Task Force*, 2003; *Bigelow et al.*, 2003; *Jia et al.*, 2003; *Arctic Climate Impact Assessment* (*ACIA*), 2004]. The *Arctic Climate Impact Assessment* (*ACIA*), [2004], for example, reports that in the decades between 1954 and 2003 annual average temperatures in the Arctic rose ~1°C and that average winter temperatures increased 2–4°C. Results from general circulation models (GCMs) differ somewhat regarding future trends, but for the models and scenarios selected for the ACIA report, average

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annual temperatures in the Arctic are expected to increase by 3–5°C and winter temperatures may increase by 4–7°C. These models also suggest that the rising temperatures will be accompanied by increased precipitation mostly as rain; 20% more over the Arctic as a whole and up to 30% more in coastal areas during the winter and autumn.

[3] These are important changes that will have large impacts on Arctic systems. Of particular interest to this study is the projection that large areas of permafrost will thaw [*ACIA*, 2004; *Walker*, 2007]. Permafrost across the Arctic has already warmed by up to 4°C [*Zhang et al.*, 1997; *Osterkamp and Romanovsky*, 1999; *Pollack et al.*, 2003; *Frauenfeld et al.*, 2004; *Oelke and Zhang*, 2004; *Osterkamp and Jorgenson*, 2006], though a few locations have not warmed or have even cooled [*Osterkamp*, 2007]. *Osterkamp* [2007] concluded that in the area of interest to this study (the North Slope of the Brooks Range, Alaska) the warming has been on the order of 1 to 4°C, with most of the warming in the winter and little change in the summer. Projections are that 10–20% of the area currently occupied by permafrost will thaw in the next 100 years, shifting the permafrost boundary 100s of kilometers north and increasing the fragmentation of discontinuous permafrost [*Lunardini*, 1996; *ACIA*, 2004].

[4] It is well recognized that permafrost thawing will lead to increased development of thermokarst features, with potentially severe impacts on civil infrastructure; e.g., roads, railways, and buildings [*International Protocol on Climate Change*, 2001; *Nelson et al.*, 2002; *U.S. Arctic Research Commission Permafrost Task Force*, 2003; *ACIA*, 2004]. However, the impacts of increased thermokarst activity on aquatic ecosystems and resources are less well known [*Rouse et al.*, 1997; *Hobbie et al.*, 1999; *Harding et al.*, 2002; *Jorgenson et al.*, 2006; *Huntington et al.*, 2007].

[5] Some previous work on the ecological impacts of thermokarst features in Alaska has been done, including central Alaska [*Osterkamp et al.*, 2000; *Jorgenson et al.*, 2001; *Jones et al.*, 2005; *Petrone et al.*, 2006], the Seward Peninsula [*Lloyd et al.*, 2003; *Yoshikawa and Hinzman*, 2003], and the North Slope coastal plain [*Walker and Walker*, 1991; *Walker and Everett*, 1991; *Yoshikawa and Hinzman*, 2003; *Smith et al.*, 2005; *Jorgenson et al.*, 2006]. None of this previous work focuses on the direct impacts of thermokarsts on aquatic resources and little of the work focuses on the foothills province of the North Slope, likely because few thermokarst had been previously observed and documented in the foothills areas of the Brooks Range.

[6] The most directly relevant work is that of *Jones et al.* [2005], who found that nitrogen export exceeded nitrogen deposition in three boreal forest watersheds in interior Alaska that were underlain by discontinuous permafrost. The imbalance in favor of export was greatest for the two watersheds with the least permafrost. *Petrone et al.* [2006] followed up on this work and found that permafrost controls the depth of subsurface flow paths, which subsequently influences the biogeochemical composition of runoff. They concluded that the net flux of most of the solutes they measured (except DOC) was lower from the watersheds with the highest percentage of permafrost compared to those with moderate or low levels of permafrost. While these studies do not address thermokarst effects directly, they do indicate that where permafrost has thawed (or at least is discontinuous) solute fluxes may be higher than in areas where permafrost is intact. This is important because increased nutrient loading from thermokarst features to arctic streams might stimulate biological production [e.g., *Bowden et al.*, 1992; *Finlay and Bowden*, 1994; *Arscott et al.*, 1998; *Stream Bryophyte Group*, 1999].

[7] There is even less information available about sediment inputs to aquatic systems from thermokarsts. Thermokarst activity in hilly regions has the potential to deliver large amounts of sediments to streams through mass wasting [*Lewkowicz and Kokelj*, 2002; *Lewkowicz and Harris*, 2005a, 2005b; *Lewkowicz*, 2007], which may have serious negative impacts on stream communities. The effects of increased sediment loading combined with high or low nutrient loading on community structure and production in Arctic streams are poorly understood.

[8] The purpose of this paper is to summarize data we have collected on sediment and nutrient loadings from two thermokarst features in the vicinity of the Toolik Lake Research Natural Area (TLNRA) in the foothills regions of the Brooks Range on the North Slope of Arctic Alaska. While the TLNRA is a well-studied area, little of this research has focused explicitly on thermokarst features or their effects on stream ecosystems. Nevertheless, the stream research from the TLNRA [e.g., *Peterson et al.*, 1985, 1986, 1993; *Slavik et al.*, 2004] provides a valuable point of reference for understanding how thermokarst might affect the basic ecology of streams and lakes in the foothills region of the Brooks Range. This study was motivated by our observation that over the last few years there seems to have been an increase in the number of thermokarst features in the TLRNA and vicinity, which we hypothesized might have important impacts on stream ecosystems in this region.

2. Methods

2.1. General Study Area

[9] This research was conducted in the vicinity of the Toolik Field Station (TFS, N68° 38′, W149° 36′), which is approximately 255 km north of the Arctic Circle and at an average elevation of 720 m above sea level in the foothills province of the Brooks Range (Figure 1). The glacial history of the TFS region has been described recently by *Hamilton* [2003], who concluded that the complex deposits in this area are the product of drift from at least four separate glacial intervals. The earliest two glacial advances date from the late Tertiary to early Pleistocene times. The next younger period of glaciation appears to have occurred in the middle Quaternary (Middle Pleistocene, about 780,000 to 125,000 years B.P.). The most recent period of glaciation included two advances (Itkillik I and II) that were interpreted to have occurred in two and three phases, respectively. The Itkillik II phases were contemporaneous with the late Wisconsin advances of North America.

[10] According to *Walker et al.* [2002] the study area is in the warmest of the Arctic subzones (Subzone E), defined by the low shrubs dwarf birch (*Betula nana*) and several species of willows (*Salix* spp.). The dominant vegetation community is tussock tundra, defined by tussock-forming grass *Eriophorum vaginatum*. Vegetation and soils in the study area have developed in response to interactions among the glacial legacy described above, topography,

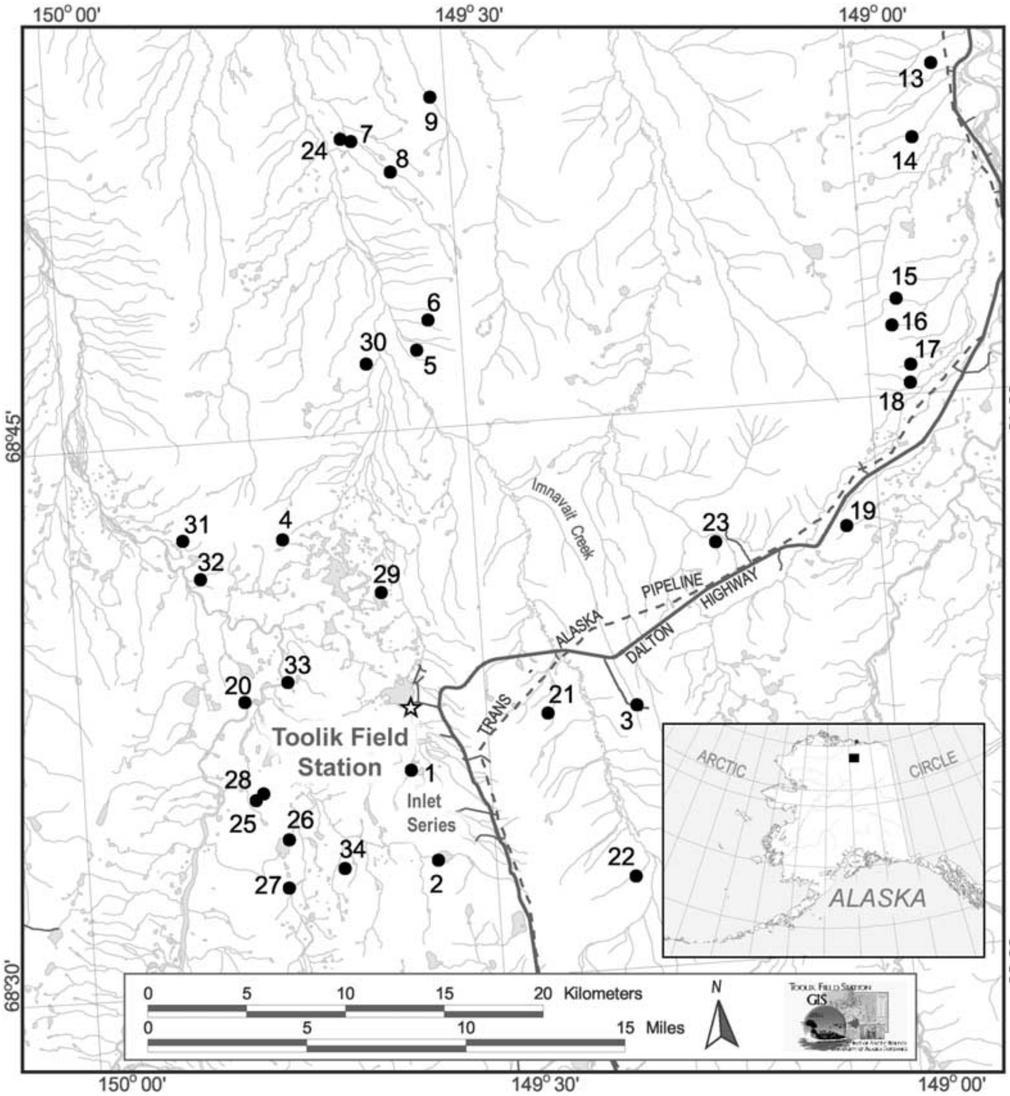

Figure 1. Location of the study area. The numbered sites correspond to the thermokarst features identified in Table 1.

and climate [*Epstein et al.*, 2004]. The plant and soil associations can be broadly divided into acidic versus nonacidic landscapes based on differences in organic matter accumulation and weathering processes. Topography and aspect influence local temperature and moisture regimes, which further define plant and soil communities. The diverse plant and soil communities in this area have been described in detail by [*Walker et al.*, 1989a, 1989b; *Ping et al.*, 1998; *Bockheim et al.*, 1998; *van der Welle et al.*, 2003].

[11] Mean annual temperatures range from −7 to −11°C [*Walker et al.*, 1989a, 1989b] with summer highs of 10 to 18°C and winter lows of −30 to −40°C [*Kriet et al.*, 1992]. Mean annual precipitation ranges from 140 to 267 mm [*Walker et al.*, 1989a, 1989b] with 30–40% falling as snow between September and May [*McNamara et al.*, 1997].

[12] The results we report here are based on observations of thermokarst features in the vicinity of TFS. We focus in particular on a thermokarst feature that formed on or about 28 July 2003 in the headwaters of the Toolik River (#23 in Table 1, N68.6921916°, W149.2047272°). The mode of permafrost degradation associated with this thermokarst feature fits the description of a *thermokarst gully* as defined by *Jorgenson and Osterkamp* [2005]. The thermokarst gully straddled a water track with the top of the feature defined by a headwall ~2.5 m high and running ~400 m to the confluence with the Toolik River. Additional information was obtained from an older thermokarst feature classified as a *thaw slump*, that formed in association with a road crossing over Imnavait Creek (#3 in Table 1, N68.6201189°, W149.3156288°). This feature is about 9.4 km south-southwest from the Toolik River feature.

2.2. Spatial Surveys

[13] We performed two different types of spatial survey. Annually from 2004 through 2006 we used survey-grade GPS (Trimble 5700 receiver with Trimble TSCe controller) to obtain a perimeter and several transects across the Toolik River thermokarst, to monitor growth and development of this feature. GPS data were post-processed with Trimble Geomatics Office software, using Toolik Field Station's

Table 1. Characteristics and Locations of Thermokarsts in the Region of the Toolik Field Station, North Slope, Alaska as Surveyed on 28 June 2005 and 11 August 2006[a]

ID	Code	Year Observed	Mode[b]	AHAP Comparison	Possibly >20–25y old	Slope[c] (d)	Slope[d] (d)	Apect[c] (d)	Aspect[d] (d)	Elevation[c] (m)	Elevation[d] (m)	Latitude (dd.dddd)	Longitude (ddd.dddd)
1	T70	2005	Thaw Slump	1978	yes	2		24		755		68.5971N	149.5978W
2	T69	2005	Thaw Slump	1978	yes	3		58		805		68.5552N	149.5721W
3	T68	<1999	Thaw Slump	1982	yes	7		283		882		68.6201N	149.3156W
4	T67	2005	Thermokarst Gulley	1982	no	1		135		765		68.7065N	149.7378W
5	T36	2005	Thermokarst Gulley	1979	unlikely	2	2	315	304	596	587	68.7892N	149.5569W
6	T66	2005	Thaw Slump	1979	no	1		247		612		68.8027N	149.5404W
7	T37C	2005	Thermokarst Gulley	1982	no	1	3	281	314	516	538	68.8868N	149.6212W
8	T37A	2005	Thermokarst Gulley	1979	no	1	3	304	316	549	542	68.8717N	149.5745W
9	T65	2005	Thaw Slump	1982	yes	1		14		531		68.9047N	149.5195W
10	T64	2005	Thaw Slump	1982	no	1		18		396		69.0567N	148.5481W
11	T63	2005	Thaw Slump	1982	no	2		22		412		69.0186N	148.8628W
12	T62	2005	Thaw Slump	1982	no	4		111		437		68.9926N	148.8376W
13	T61	2005	Thaw Slump	1982	no	2		91		444		68.9039N	148.8947W
14	T60	2005	Thaw Slump	1979	no	1		89		470		68.8707N	148.9249W
15	T59	2005	Thaw Slump	1979	no	5		164		599		68.7974N	148.9599W
16	T58	2005	Thaw Slump	1979	no	5		103		624		68.7853N	148.9672W
17	T57	2005	Thaw Slump	1979	no	2		38		547		68.7667N	148.9479W
18	T56	2005	Thaw Slump	1978	no	4		135		537		68.7584N	148.9499W
19	T55	2005	Thaw Slump	1982	no	5	10	106	125	669	670	68.6951N	149.0418W
20	T40	<2001	Thaw Slump	1982	no	1	4	148	153	627	637	68.6332N	149.7967W
21	T54	2005	Thermokarst Gulley	1982	no	2		337		838		68.6192N	149.4251W
22	T53	2005	Thermokarst Gulley	1978	unlikely	3		342		916		68.5419N	149.3315W
23	T42	2003	Thermokarst Gulley	1982	no	4	3	34	33	783	786	68.6921N	149.2047W
24	T38	2006	Polygonal Thermokarst Mounds	1982	yes	0	0	0	0	510	519	68.8882N	149.6339W
25	T52	2006	Thaw Slump	1978	maybe	4		315		654		68.5878N	149.7906W
26	T51	2006	Thaw Slump	1978	yes	1		297		726		68.5691N	149.7530W
27	T50	2006	Thaw Slump	1978	no	1		135		761		68.5469N	149.7566W
28	T41	2006	Thermokarst Gulley	1978	no	15	10	295	296	690	691	68.5908N	149.7807W
29	T39	2006	Glacial Thermokarst	1982	no	6	10	207	190	716	727	68.6793N	149.6202W
30	T49	2006	Thermokarst Gulley	1979	no	1		101		593		68.7845N	149.6203W
31	T48	2006	Thaw Slump	1982	no	1		126		578		68.7088N	149.8609W
32	T47	2006	Thaw Slump	1982	yes	2		225		587		68.6907N	149.8418W
33	T46	2006	Thaw Slump	1982	no	3		290		631		68.6409N	149.7422W
34	T45	2006	Thermokarst Gulley	1978	yes	4		334		821		68.5543N	149.6870W

[a]Latitude and longitude are in decimal degrees referenced to datum NAD83 Alaska. The unit "d" is degrees of slope, aspect, latitude or longitude. Images from the Alaska High-Altitude Photography (AHAP) program were taken in different years, as noted. Column 6 reports the likelihood that the features observed between 1999 and 2006 were present in ∼1980 based on an examination of the AHAP images.

[b]Modes follow *Jorgenson and Osterkamp* [2005].

[c]Estimated from USGS Digital Elevation Model (DEM) data developed at 1:63,360 scale, National Elevation Dataset (NED).

[d]Measured in situ. Slope: Brunton Analog Inclinometer, Aspect: Brunton compass (from true N, declination 24.5E), Elevation: Garmin eTrex Legend, meters HAE.

permanent Trimble NetRS base station. Final edits were performed in ArcGIS.

[14] On 28 June 2005 we conducted a low-altitude survey covering roughly 600 km^2 north from the TFS. The purpose of this survey was to determine whether active thermokarst features were rare or common features in the foothills around TFS. The survey involved visual searching at low altitude (<200 m above ground level) from a helicopter. We recorded approximate (uncorrected) GPS locations and general characteristics of identified thermokarst features. The survey was extended slightly on a similar flight, on 11 August 2006. We compared the 2005 and 2006 observations to high-resolution, false-color infrared imagery of the area obtained for the Alaska High-Altitude Photography (AHAP) program during the late 1970s and early 1980s. The AHAP imagery was obtained at ∼1:63,360 scale (inch to the mile) with ∼1.5 m pixels and digitized from the original photographs using a high resolution scanner. For each feature that we observed in 2005–2006 we determined by inspection whether we could reliably detect the feature in the ∼1980 imagery.

2.3. Total Suspended Sediment Concentration

[15] To determine changes in suspended sediment dynamics due to thermokarst development, we measured total suspended solids (TSS) along the water track that ran through the middle of the Toolik River thermokarst. Triplicate samples were taken above and below the thermokarst on 9 July 2004. At the same time, duplicate samples were taken above and below the point at which the water track merged with the Toolik River. Total suspended solids were analyzed using standard methods (USGS method I-3765). For each sample, up to 3 L of water were filtered in the field through a predried (105°C) and preweighed 47 mm diameter glass fiber filter (GF/F). Samples were returned immediately to the laboratory at TFS, redried to 105°C, and reweighed to four decimal places. TSS was calculated as the difference in filter mass before and after filtration divided by the volume filtered (mg/L).

2.4. Nutrient Concentrations

[16] Water samples were taken on 4 August 2004 and 27 June 2007 from a first-order stream (water track) that

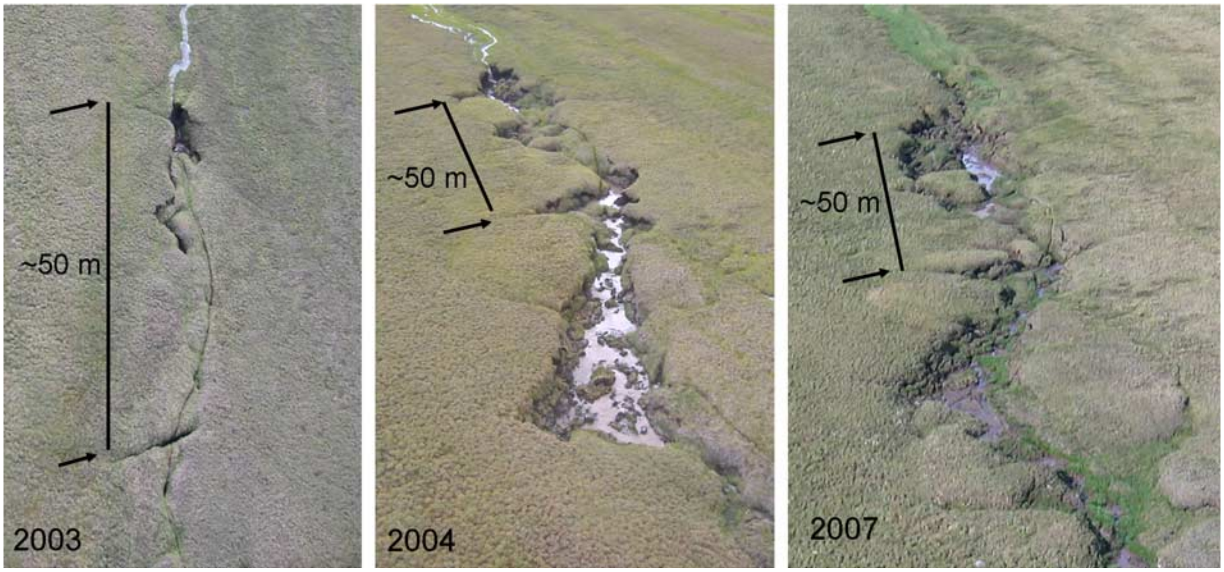

Figure 2. Images of the thermokarst in the headwaters of the Toolik River shortly after it formed in 2003 and in 2004 and 2007. Note how the feature grows rapidly from 2003 to 2004 and how the edge features collapse and "soften" between 2004 and 2007.

flowed through the Toolik River thermokarst. Samples were taken at a reference location in the stream above the thermokarst (undisturbed), within the thermokarst feature, and at three locations downstream of the thermokarst (30 m, 150 m, and 300 m above the confluence with the Toolik River). Similar samples have been taken annually between 1999 and 2005 (except for 2000) above and below the thermokarst in the headwaters of Imnavait Creek. This record provides a longer-term comparison to the Toolik River thermokarst.

[17] Water samples for nutrient analyses were filtered in the field through 0.45 μm pore size, cellulose-acetate filters. Separate samples were taken for each analyte. Samples for phosphate and ammonium analyses were taken to the lab at TFS for immediate analysis. Samples for nitrate analyses were frozen and shipped back to the Ecosystems Center in Woods Hole, Massachusetts for analysis within six months of collection. Nitrate samples taken for the 2007 thermokarst survey were analyzed at the University of Alaska – Fairbanks within three weeks of collection. We analyzed phosphate manually by the molybdate blue method [*Murphy and Riley*, 1962]. We measured ammonium manually by the fluorometric method of *Kérouel and Aminot* [1997] as modified for manual use by *Holmes et al.* [1999]. Nitrate was measured on a Lachat autoanalyzer by the cadmium reduction method (method 4500-NO3-E as by *Eaton et al.* [2005]).

3. Results

3.1. General Observations

[18] Regular observations of environmental conditions at and around TFS began in the mid-1970s shortly after the Alyeska oil pipeline construction was completed. In recent years we have noted the formation of several new thermokarst features near the TLRNA. One of these new thermokarsts (Figures 2 and 3) formed on or about 28 July 2003 in the headwaters of the Toolik River immediately after a period of heavy rainfall. The failure was caused by the collapse of the roof of an open tunnel, ~2 m wide and ~1 m tall, buried ~1 m under the tundra surface on a gentle hillslope in an area characterized by *Hamilton* [2003] as ice-rich silt deposited during the oldest (Sagavanirktok River) period of glaciation.

3.2. Spatial Survey - Intensive

[19] Annual surveys of the thermokarst on the Toolik River showed that the disturbed area grew substantially since its inception in July 2003 (Figure 2). It was not possible in 2003 to mount an effort to quantify the dimensions of this thermokarst feature, but we did note that it was roughly 10 m wide and 400 m long. By 2004 we more accurately established the maximum width to be 13.1 m width and length to be 457.5 m. By 2005 the feature was 17.1 m maximum wide by 459.5 m long with an area (determined by GPS) of 1603 m^2 and by 2006 it was 19.8 m wide (maximum) by 475.0 m long with an area of 2324 m^2. By 2007 the thermokarst feature had expanded to a maximum width of 22.9 m, a length of 495.4 m, and an area of 3410 m^2. Much of this expansion occurred as a consequence of lateral retreat along the feature's edge with slumping of the edge material into the gulley. This difference in the form of the edge is clear from a comparison the 2004 and 2007 images in Figure 2. Thus in the three year period from 2005 to 2007 alone, the feature widened, lengthened, and more than doubled in area.

[20] We noted that this thermokarst feature lies on the eastern boundary of a subtle surface flow path down the southern (north facing) hillslope leading to the Toolik River. This flow path is discernable from changes in the vegetation composition and "greenness" (e.g., Figure 2) and is also evident in Synthetic Aperture Radar imagery (SAR) from the area (Figure 4). An aircraft-based, orthorectified C-band SAR backscatter image with 5 m post spacing, acquired the year before the thermokarst feature appeared, shows very

Figure 3. Characteristics of the tunnel in the permafrost that ultimately created the thermokarst gully on the Toolik River. The upper panel shows the tunnel near the headwall of the thermokarst, shortly after the thermokarst formed in late July 2003. Note the well-formed streambed, scalloping on the roof of the tunnel, and ice wedge in the right center of this image. The lower panel shows a remnant of this same feature approximately 50 m downstream.

high backscatter for the flow path in which the thermokarst is situated. Observation of that flow path and adjacent landscapes strongly suggests that several centimeters of standing water combined with well-hydrated, vegetative tissue structures produced much higher backscatter compared to the surrounding landscape [*Ulaby et al.*, 1982]. The flow path is comprised primarily of Wet Sedge Meadow Tundra (IIIA3a) with a low shrub component [*Viereck et al.*, 1992]. It is clear that this thermokarst failure occurred along the contact between the Wet Sedge Meadow Tundra flow path to the west and the drier hillslope Tussock Tundra (IIIA2d) to the east [*Viereck et al.*, 1992].

3.3. Total Suspended Sediment Concentration

[21] The TSS levels below the Toolik River thermokarst were more than two orders of magnitude higher than just above the thermokarst (Figure 5). One year after the initial failure, sediment delivery from the thermokarst was sufficient to raise the TSS concentrations in the Toolik River from background levels of 1.2 and 2.0 mg L^{-1} (n = 2) to 25.0 and 26.0 mg L^{-1} (n = 2) under moderate flow conditions (30 L s^{-1}).

3.4. Nutrient Concentration

[22] We collected nutrient samples from several locations above, within, and below the Imnavait Cr. thermokarst, annually from 1999 to 2005 (Figure 6). The background ammonium concentrations above the thermokarst at the Imnavait site were 0.15 ± 0.03 μM while background nitrate concentrations were 0.33 ± 0.23 μM and the background phosphorus concentrations were very low at 0.04 ± 0.01 μM. By comparison, the peak ammonium concentrations below the thermokarst at the Imnavait site were 1.1 ± 0.5 μM) while peak nitrate concentrations were 3.5 ± 1.1 μM. The pattern of higher nutrient concentrations downstream of the thermokarst persisted over the period of record (1999 to 2005, Figure 7). The ammonium concentrations we measured were among the highest we have measured anywhere in the region and the phosphate concentrations were similar to the target levels we have used for our long-term experimental fertilization of the Kuparuk River [*Peterson et al.*, 1993; *Slavik et al.*, 2004].

[23] On 4 August 2004 and 27 July 2007 we sampled water from above and within or below selected thermokarst features in or near the TLNRA (Table 2). The mean values for ammonium, nitrate, and phosphate were uniformly higher below the thermokarst features than above them. Although there was considerable variability, phosphate concentrations were 4× higher below thermokarsts than above them, nitrate concentrations were 24× higher, and ammonium concentrations were 40× higher. The differences in phosphate and ammonium were significant at the $P < 0.05$ level while differences in nitrate were significant at $P = 0.07$.

3.5. Spatial Survey - Extensive

[24] Our extensive aerial surveys on 28 June 2005 and 11 August 2006 revealed that thermokarsts are common in the area around TFS. We identified 34 thermokarsts in an area of roughly 600 km^2 north, west and east of TFS (Table 1 and Figure 1). Most of these thermokarsts were associated with drainages and several were thermokarst gullies, apparently initiated by tunnel collapses as in the case of the thermokarst on the Toolik River. Two such thermokarsts (7 and 8, Table 1) on a tributary to the Kuparuk River were at least five times larger than the Toolik River thermokarst. It was not possible to say with assurance how old these features were at the time we observed them.

[25] However, determine if the formation of thermokarst features was a relatively recent phenomenon, we noted whether each thermokarst feature we observed between 1999 and 2006 could be reliably identified in high-resolution aerial photographs taken in this area as part of the Alaska High-Altitude Photography (AHAP) program in the late 1970s and early 1980s. We found that 8 of the features that we observed in 1999–2006 were clearly present in the ∼1980 images. However, 23 of the features that we observed in 1999–2006 were clearly not present in ∼1980. A total of 3 of the features we observed in 1999–2006 may

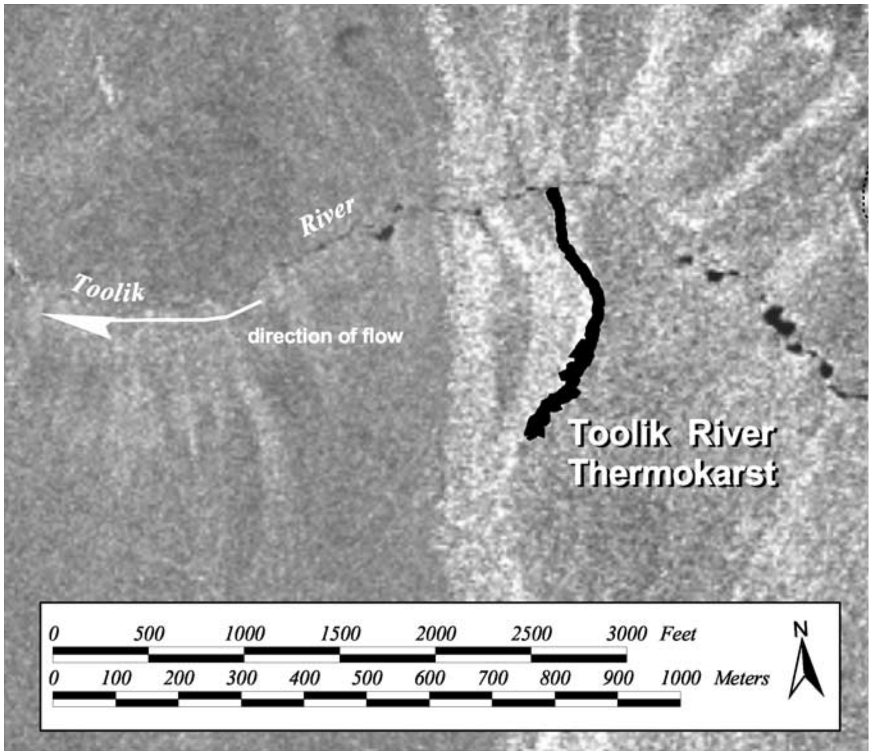

Figure 4. Location of the thermokarst on the Toolik River in relation to surface moisture distribution in soils and vegetation as identified by Synthetic Aperture Radar (SAR) imagery.

or may not have been present in ~1980; the resolution of the AHAP imagery was insufficient to determine with assurance. Thus at least 68% (23 of 34) of the features we observed in 1999–2006 were new since ~1980.

4. Discussion

[26] Polar regions are particularly sensitive to climate change. Recent studies suggest that the hydrologic regime of polar watersheds is already responding to climate change [*Stone et al.*, 2002; *Serreze et al.*, 2002; *Peterson et al.*, 2002; *McClelland et al.*, 2004; *Wu et al.*, 2005; *Jorgenson et al.*, 2006], resulting in warmer soil and active layer temperatures [*Zhang et al.*, 1997; *Osterkamp*, 2007]. Modeling exercises suggest that increased air temperatures will increase active layer depths across the Arctic tundra landscape [*Kane et al.*, 1991; *Hinzman and Kane*, 1992; *Lunardini*, 1996] and evidence from borehole measurements supports these predictions [*Osterkamp and Romanovsky*, 1999; *Pollack et al.*, 2003; *Osterkamp*, 2007].

[27] Watershed hydrology, stream ecology and geomorphology in Arctic regions are strongly controlled by permafrost, ice, and snow [*Prowse*, 2001a, 2001b; *Prowse and Culp*, 2003]. Because watershed morphology and hydrologic response are tightly coupled, changes in watershed morphology due to thawing permafrost will undoubtedly cause changes in the hydrologic response, in addition to the direct hydrologic changes in a new climate. For example, *McNamara et al.* [1997, 1998] showed that permafrost, snow, and ice strongly control the timing, magnitude, and sources of streamflow during rainstorms and snowmelt in the Kuparuk River basin. In addition, *McNamara et al.* [1999] analyzed channel networks obtained from a digital elevation model and field mapping in the Imnavait Creek watershed to show that permafrost has restricted the erosional development of the basin. Thus there is great potential for alteration to these 'geomorphically immature' channel networks, due to enhanced sediment loads from hillslope thermokarst features.

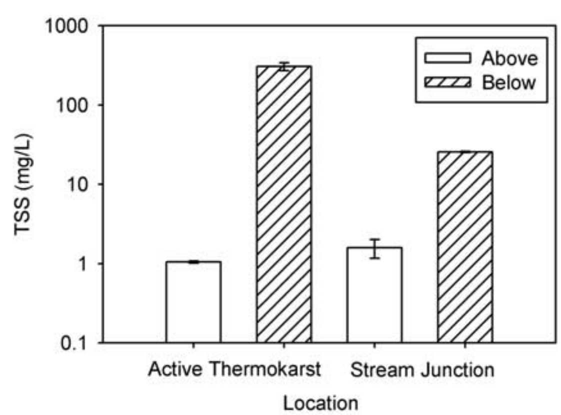

Figure 5. Total suspended sediment concentrations in the small drainage above and below the thermokarst near the Toolik River and above and below the point that this drainage entered the Toolik River. Note the log scale on the TSS concentration axis. The reported values are the means and range of values for n = 3 thermokarst samples and n = 2 junction samples.

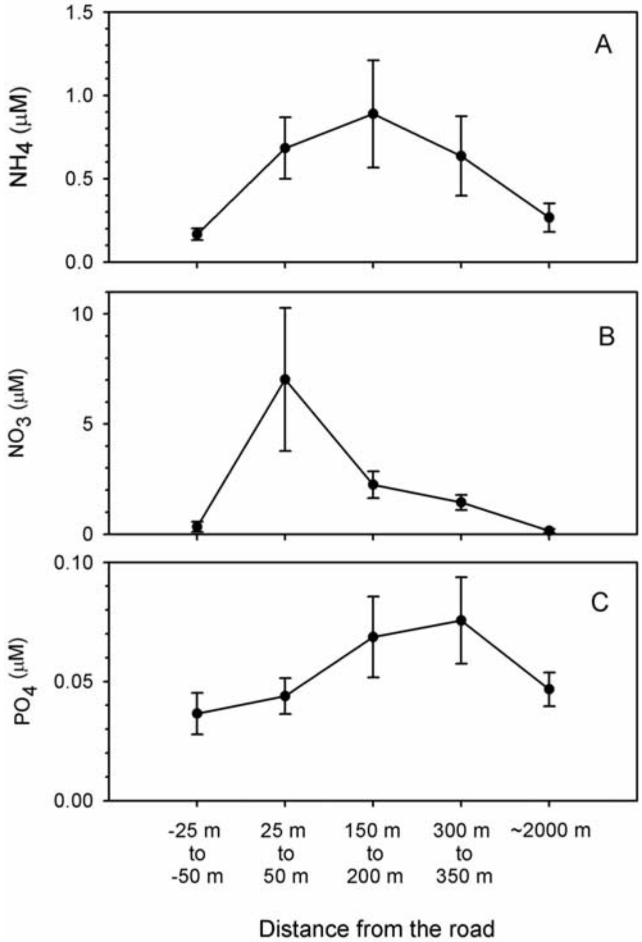

Figure 6. Concentrations of (a) ammonium, (b) nitrate, and (c) phosphate above and at several locations downstream from the road crossing over the thermokarst on Imnavait Creek. These data are means of two sampling dates in 1999 and one sampling date each in 2001 through 2005. No sample was taken in 2000. The error bars are ±1 SE for n = 7 except for upstream reference samples (−25 m to −50 m) in 2003 and 2005 (n = 5) and 2004 (n = 4).

[28] Thermokarst features form due to a positive subsurface energy balance that thaws subsurface permafrost and ground ice [*Lewkowicz and Harris*, 2005b; *Lewkowicz*, 2007]. The increased energy input to the soils is often due to a modification to the surface conditions of the land, e.g., reduced albedo, or a disturbance. The two thermokarst features on which we focused in this study resulted from different processes. The Toolik River thermokarst formed naturally, as subsurface ice was progressively eroded, possibly due to either a change in the surface albedo resulting from a local game trail (clearly visible in Figure 2, 2003 and identifiable in the 2004 and 2007 images) or possibly due to a change in water track flow paths. The thermokarst near Imnavait Creek, however is the result of an anthropogenic disturbance, the construction of a small road at the site. Regardless of origin, under a warming climate in the Arctic it is likely that small disturbances to surface soils and vegetation may promote accelerated subsurface warming that could lead to thermokarst development.

[29] It is instructive to consider the impact of the Toolik River thermokarst feature in the context of the background levels of sediment generation and transport in the Kuparuk River. *Kriet et al.* [1992] measured water and sediment yield from the Kuparuk River over 3 years (1978 to 1980) that were very different hydrologically, including one of the wettest years on record (1980). They made these measurements at a point that was only ∼5 km from the thermokarst feature on the Toolik River that is the main focus of this paper. *Kriet et al.* [1992] measured discharge that ranged from 0.3 to 28.3 m^3 s^{-1} with sediment concentrations ranging from 0.4 to 35 mg L^{-1}. Average water yields over the 3 years (late May to mid-August) were 15.7, 29.7 and 33.2 cm with specific sediment yields of 0.5, 1.1 and 3.5 t km^{-2} (metric ton per km squared) for an average of 1.7 t km^2 or 224 t for the entire 132 km^2 upper Kuparuk

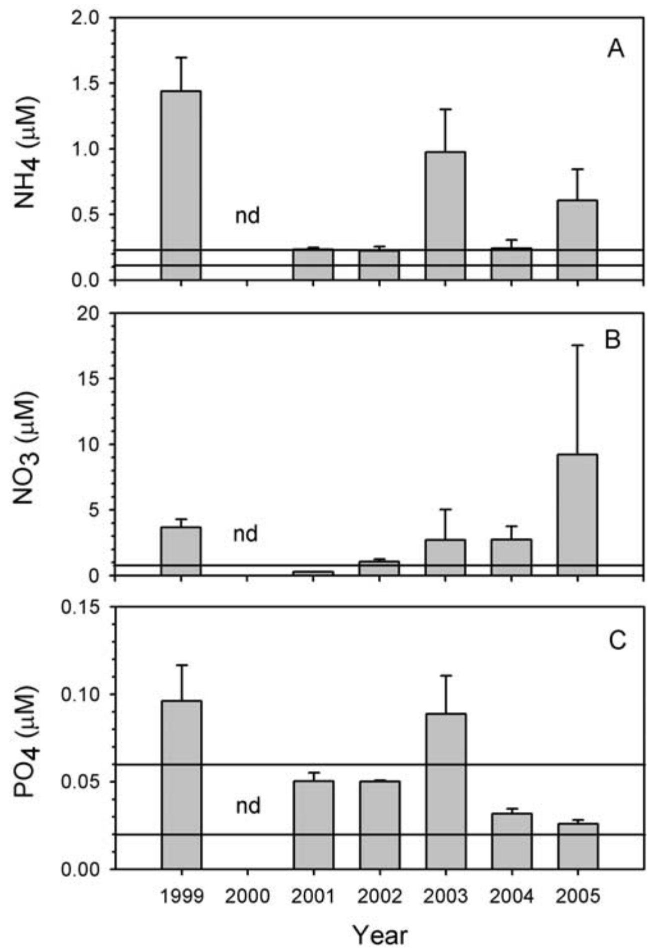

Figure 7. Concentrations of (a) ammonium, (b) nitrate, and (c) phosphate within the stream reaches most impacted by the thermokarst on Imnavait Creek. The bars are the mean values for the stations between 25 m and 350 m as reported in Figure 6, by year. No samples were collected in 2000 (nd). The error bars are ±1 SE. The horizontal lines indicated the 95% confidence intervals for the mean reference values measured in Imnavait Creek. The 95% confidence interval for reference nitrate values included zero and so there is only one (upper) boundary line. The exceptions are the same as indicated in Figure 6.

Table 2. Comparison of Nutrient Levels Above and Below Selected Thermokarst Features (Identified in Table 1) Sampled in Two Years (2004 and 2007)[a]

Table 1 Code	Year Sampled	Location	NH_4, μM	NO_3, μM	PO_4, μM
2	2007	above	0.13	0.09	0.05
2	2007	below	3.87	0.84	0.08
5	2007	above	0.16	0.10	0.04
5	2007	below	0.43	0.11	0.18
8	2007	above	0.13	0.04	0.06
8	2007	below	0.31	1.94	0.06
23	2007	above	0.17	0.15	0.05
23	2007	below	15.87	33.55	0.13
26	2007	above	0.09	0.58	0.03
26	2007	below	0.74	10.35	0.10
28	2007	above	0.10	0.51	0.02
28	2007	below	13.67	6.58	0.09
21	2004	above	0.28	0.23	0.05
21	2004	below	11.30	0.70	0.62
23	2004	above	0.23	0.57	0.04
23	2004	below	4.89	0.48	0.12
		above	0.16 (0.02)	0.28 (0.08)	0.04 (0.004)
		below	6.38 (2.24)	6.82 (4.03)	0.17 (0.065)
		P(different)	0.01	0.07	0.02
		ratio	40	24	4

[a] The significance of differences between the samples taken above and below the thermokarst features was tested with a non-parametric sign-test.

River basin. For comparison, we estimate that 2000 m^3 of soil was displaced at the thermokarst feature on the Toolik River in the first 2–3 years that it existed (an area of at least 2000 m^2 with an average depth estimated to be at least 1 m). If this material had a density of, say, 2 t m^{-3} (not unusual for a silty soil) it would have yielded 4000 t of sediments (less minor volumes of organic matter and boulders). Thus over a period of 2–3 years this single thermokarst feature in a small (90 ha or 0.9 km^{-2}) subwatershed on the Toolik River delivered 18× more sediment than would normally be delivered by the entire 132 km^{-2} upper Kuparuk River over the same time period. It is noteworthy as well that 2000 m^3 of soil displaced into the Toolik River, which is 5 to 10 m wide at this point, would be sufficient to cover 20–40 km of the river with sediment to a thickness of 1 cm.

[30] These calculations illustrate that an apparently minor disruption on the land, particularly in headwater locations, could potentially deliver very large quantities of sediment to otherwise relatively stable streams. Despite the fact that the thermokarst features we observed in the area of the TLNRA were relatively small and dispersed, sediment loading from these disturbance features in hilly terrain could have important impacts on stream ecosystems in the foothills region, and further downstream.

[31] While sediment loading might interfere with benthic stream communities, nutrient additions from thermokarst features might enhance benthic production. The concentrations of phosphorus and nitrogen we measured in water draining from the two thermokarst features that were the focus of this project were as high or higher than levels achieved during any of our experimental fertilizations. This long-term (20+ years) research on the structure and function of tundra foothill, mountain, and spring streams on the North Slope of Alaska [*Peterson et al.*, 1986, 1993; *Slavik et al.*, 2004] provides a useful point of reference for comparison to stream reaches that may be impacted by runoff from thermokarsts. In our previous work we have shown that long-term, low-level increases in phosphorus alone can have important influences on benthic autotrophic and macroinvertebrate community structure [*Hiltner and Hershey*, 1992; *Hinterleitner-Anderson et al.*, 1992; *Miller et al.*, 1992; *Huryn et al.*, 2005] and significantly increases primary and macroinvertebrate production [*Bowden et al.*, 1992, 1994; *Finlay and Bowden*, 1994; *Arscott et al.*, 1998; *Bowden*, 1999; *Benstead et al.*, 2005]. The influence on fish production is less clear [*Deegan and Peterson*, 1992; *Deegan et al.*, 1997, 1999]. Phosphorus fertilization also alters other nutrient dynamics [*Peterson et al.*, 1985, 1997, 2001; *Harvey et al.*, 1998] and increases organic matter decomposition [*Peterson et al.*, 1986; *Harvey et al.*, 1997; *Benstead et al.*, 2005].

[32] However, the nutrient effect may be relatively confined, spatially. For example, the Imnavait Creek data (Figure 6) show that within a few hundred meters of the thermokarst disturbance, nutrient concentrations had returned to near background levels. This decrease in nutrient concentrations may be due to biological uptake or may be due to simple dilution by lateral inputs of surface or subsurface water. We think that simple dilution is less likely, in part because lateral inputs tend to be low in these permafrost-dominated streams and in part because the lateral inflow often has high concentrations of ammonium and phosphate [*Wollheim et al.*, 1999]. Furthermore, phosphate and ammonium are known the be taken up rapidly [*Peterson et al.*, 1993; *Wollheim et al.*, 2001; *Slavik et al.*, 2004]. It is likely that the declines in concentration of nutrients depicted in Figure 6 are due to a combination of physical dilution and biological uptake. Further fieldwork will be required to determine the relative importance of these two mechanisms.

[33] We conclude from this preliminary work that even sparsely disturbed thermokarsts in hilly or mountainous terrain could have important influences, potentially for many years, on the stream ecosystems and headwater areas they drain. The primary impact may be due to increased

sediment loading, but increased nutrient loading may have important impacts as well. This conclusion is consistent with findings reported by *Kokelj et al.* [2005] who found that if thermokarsts occupied as little as 2% of the watershed area draining to a lake there could be significant and long-term (decades) influences on lake chemistry. There is overwhelming evidence that the Arctic region is warming and that thermokarst activity is increasing in, for example, the flat coastal plains of the North Slope, Alaska and the Seward Peninsula. The data we present here suggests that thermokarst activity in the foothills and mountainous areas of the Brooks Range has also increased and have the potential to significantly impact the structure and function of headwater streams.

[34] There are a number of important characteristics of thermokarsts in mountainous and foothills regions that deserve greater attention. For example, we do not yet know how to relate the frequency of thermokarst occurrence to important physical landscape characteristics in these regions, to predict their distribution over larger areas. Second, we do not know how to reliably age the current distribution of thermokarsts and so, do not have a reliable way to link thermokarst ages with relevant ecological processes, though the recent work by [*Jorgenson et al.*, 2006] provides valuable insight. Finally, we have very little direct information to quantify how these disturbance features affect freshwater ecosystem dynamics in the short term and landscape structure and function in the long term, though recent work reported by *Jorgenson et al.* [2001], *Jorgenson and Osterkamp* [2005] and *Schuur et al.* [2007] suggests that these influences could be important. It is essential to address these questions to fully understand the impacts of warming in the Arctic.

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