Monitoring permafrost conditions along the Dempster Highway

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
The Dempster Highway, which connects the western Arctic to the national highway network, is built almost entirely on permafrost. Four long-term permafrost monitoring sites were established on the highway in 2013-14 to determine baseline thermal conditions and to follow changes in ground temperatures driven by climate change. The sites are at km 124 and 421 in Yukon and km 8.5 and 51.5 in NWT. Boreholes, up to 10 m in depth, were drilled at each site in the highway centerline, at the embankment toe, and in undisturbed ground. Data have been retrieved from thermistor cables at these sites since February 2014. The embankment toe is the warmest location at each site. In undisturbed ground, annual mean temperatures range from -3.6 to -1.1 °C. The centerline is relatively cold, with annual mean temperatures ranging from -3.9 to -2.4 °C. The permafrost at km 124 is unexpectedly thin due to groundwater movement.

RÉSUMÉ
L'autoroute Dempster connecte l'Arctique de l'ouest au réseau autoroutier national. Elle est presque entièrement construite sur le pergélisol. Quatre sites ont été instrumentés le long de la route en 2013-2014 afin de fournir un suivi thermique des conditions du pergélisol dans le contexte des changements climatiques. Les sites sont localisés aux km 124 et 521 au Yukon et aux km 8.5 et 51.5 au TNO. Des trous ont été forés à chaque site au milieu de la route, au pied du talus et dans le terrain non-perturbé jusqu'à une profondeur maximale de 10 m. Les données sont enregistrées par des câbles à thermistances depuis février 2014. Le pied du talus est l'endroit le plus chaud. Les températures moyennes annuelles du terrain non-perturbé s'échelonnent de –3.6 à –1.1 °C. Le centre de la route est relativement froid avec des températures s'échelonnant de -3.9 à -2.4°C. Le pergélisol au km 124 est étonnamment mince à cause des mouvements d'eau souterraine.

1 INTRODUCTION

The Dempster Highway is a critical component of Canada's transportation infrastructure, because it is the only all-weather road connecting the western Arctic to the national highway network (Figure 1). For about 90% of its 736 km length, the highway is on continuous permafrost. Transport Canada (TC) has established a Network of Expertise in Northern Transportation Infrastructure Research to assist governments to adapt roads, airports, and marine facilities to challenges posed by climate change. One of the Network's projects concerns establishment of baseline data collection and assessment of permafrost response to climate warming alongside transportation infrastructure in Yukon and NWT.

This paper describes four long-term monitoring sites on the Dempster Highway that were established in 2013-14 to characterize permafrost conditions and follow changes in ground temperatures due to climate change and the thermal influence of the embankment. The sites were selected at locations anticipated to be sensitive to long-term disturbance due to evidence of near-surface ice-rich permafrost. Ground conditions at the sites are described and one year's ground temperatures are presented in order to characterize mean annual permafrost temperatures (T_p) along the route. The thermal differences between undisturbed terrain and ground affected by the embankment are examined.

2 BACKGROUND

The Dempster Highway connects the Klondike Highway (Yukon Highway 2), 40 km east of Dawson City, Yukon, to Inuvik, NWT. The first 80 km of the route lies in the extensive discontinuous permafrost of North Klondike River valley (Heginbottom et al. 1995). In this section, the road climbs from about 400 m a.s.l. to over 1200 m a.s.l. at the continental divide. The route traverses continuous permafrost north of the divide. Latitude and elevation vary so that the highway route passes through forest and tundra.

The route covers a series of physiographic units with varying surficial materials (Burn et al. 2015). Glacial history is a key influence on ground materials, including ground ice content. The terrain was glaciated from km 0 to the vicinity of Chapman Lake (km 116) in Yukon, and northeast of km 30 on Peel Plateau and in the plains of NWT. In these sections, surficial materials are dominated by till (Beierle 2002; Lacelle et al. 2013). The remainder of the route was unglaciated, and the surficial materials are glacial outwash, alluvial, and colluvial deposits in valleys and a weathered colluvial veneer in the uplands of Eagle Plain. Massive ground ice has been observed in glacial deposits near Chapman Lake and in the Peel Plateau (Lacelle et al. 2007, 2013). Ice-wedge polygons are prevalent in the terrain of the Blackstone River valley, from km 85 to 130, and in other tundra areas. Icings are common in the discontinuous permafrost section. Extensive sheets of river icing develop in the Blackstone and North Klondike river channels (Figure 2) (Hu and Pollard 1997).

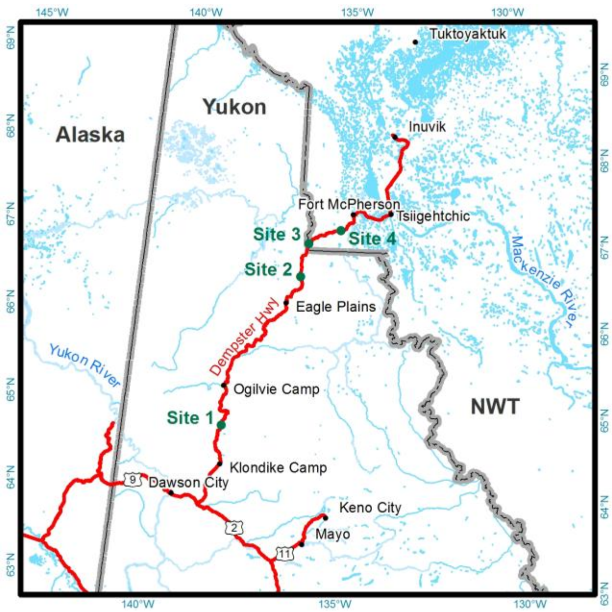

Figure 1. Location map for permafrost monitoring sites on the Dempster Highway, Yukon and NWT.

Figure 2. Blackstone River near Chapman Lake, showing extensive river icing, May 2014.

The 1981-2010 climate normal mean annual air temperature (T_a) varies from -4.1 °C at Dawson to -8.2 °C at Inuvik (Environment Canada 2015). The coldest location on the route is the steep and incised terrain near the Ogilvie River, where shading and cold-air drainage promote severe cooling in winter. T_a at Ogilvie Camp (km 200) is comparable to Inuvik, although there are insufficient data for calculation of a 30-year average. Recently, O'Neill et al. (2015a) have shown that air temperature inversions create significantly warmer winter conditions on Peel Plateau than on low-lying Peel Plain at Fort McPherson.

Since 2009, ground temperatures have been collected near NorthwesTel's microwave towers along the highway route. These data are discussed in a companion paper, but the key observations are of relatively low T_p (~ -4 °C) in the tundra of the Blackstone Uplands and in the Richardson Mountains at the Yukon-NWT border (Burn et al. 2015). The ground is warmer on Peel Plateau (T_p ~ -2 °C) (O'Neill et al. 2015a), and the warmest observed permafrost is in taiga near Inuvik, with T_p ~ -1.6 °C (Burn et al. 2009). Smith et al. (1998) recorded little difference in T_p between forest sites spread as far apart as Takhini River valley near Whitehorse, YK, and Inuvik. The observed T_p indicate that atmospheric inversions and snow accumulation are important modifiers of ground temperature. The effects of snow are important for permafrost adjacent to road embankments in tundra regions, where there is commonly a significant supply of blowing snow. Accumulation of snow on the embankment slopes may lead to permafrost degradation at the toe, where increased wetness commonly promotes the growth of shrubs, fertilized by road dust (Gill et al. 2014). Trapping of snow by shrubs further amplifies snow depth (e.g., Roy-Léveillée et al. 2014).

Climate warming, particularly in autumn and winter, has been observed in Canada's western Arctic since 1970 (Burn and Kokelj 2009), and near-surface permafrost is warming at a rate that has been reconciled with observed atmospheric warming (Burn and Zhang 2009, 2010). Coincidental rehabilitation since 2005 of the Dempster Highway in the NWT through Richardson Mountains and Peel Plateau has cost approximately $65M. Much of this construction has been designed to reduce the effects of permafrost degradation on the driving surface. The project described in this paper is explicitly intended to gather information on permafrost temperatures beneath and adjacent to the highway embankment in tundra sections of the route and to install equipment that will be used to monitor long-term changes in permafrost conditions.

3 SITE SELECTION

Four sites were selected for monitoring of permafrost conditions along the highway (Figure 1). The sites were chosen to span much of the route, and were located in tundra areas in order to examine conditions where the effects of snow on embankment stability are likely greatest. In addition, installation disturbance is less in such terrain than in the forest, where trees must be removed for access by drilling equipment. Sites were identified with evidence of near-surface ground ice, either observed in the field or known from historical investigations. Two sites were selected in Yukon and two in NWT. The specific locations were determined during a field investigation and reconnaissance survey along the highway in late August 2013. The four locations are in the Blackstone Uplands at the Chapman Lake airstrip (Yukon km 124); near Glacier Creek, on the slopes of Richardson Mountains north of the Arctic Circle (Yukon km 421); in Richardson Mountains near the Yukon-NWT border (NWT

Table 1. Monitoring site characteristics

Site	Informal Name	Km post	N	W	Surface conditions
1	Chapman Lake airstrip, YT	124	64.903	138.278	Mosses and lichens; ice-wedge polygons; flat
2	Glacier Creek, YT	421	66.701	136.358	Mosses and lichens; ice-wedge polygons; gentle cross slope
3	Territorial border, NWT	8.5	67.109	136.088	Mosses, lichens and dwarf birch; inclined with road
4	Midway airstrip, NWT	51.5	67.241	135.263	Alder bushes, mosses and sedges; inclined with road

km 8.5); and on Peel Plateau, 1.8 km west of the emergency airstrip near at Midway Lake (NWT km 51.5). Coordinates of the sites and brief site descriptions are given in Table 1, and photographs of the sites are presented in Figure 3.

Site 1 is in the northernmost portion of the Blackstone Uplands, where the road follows the broad Blackstone River valley (Figure 3a). The site is north of the glacial limit (Beierle 2002). A gravel pit 1 km south of the airstrip indicates the surficial materials are mostly glaciofluvial outwash, covered by a veneer of silt. The site has well developed networks of ice-wedge polygons. These are outlined at the ground surface by slight depressions in the moss and lichen surface vegetation. Numerous willow bushes have grown adjacent to the road at the toe of the embankment. In 2005-2010, ground temperatures were measured with HOBO H-008 miniature data loggers and TMC6-HA sensors at three locations in this flat valley floor, about 500 m from the site. T_p at 1-m depth at the three sites were -4.7, -4.5, and -5.0 °C (Burn et al. 2015). The glaciofluvial terrace surface at the site is about 30 m above the Blackstone River, which flows north, subparallel to the road, about 200 m to the east.

Site 2 is 15 km north of the Arctic Circle crossing, at the foot of the western escarpment of Richardson Mountains (Figure 3b). The road runs across the slope at the site. The vegetation cover is dominated by mosses and lichens, with few bushes. The ground was not glaciated, so the gentle gradient of the lower slopes is the result of colluvial deposition continuing over millennia. Ice-wedge polygons are apparent, but their form is muted, with little development of bounding ridges and troughs.

Site 3 is on the NWT side of the territorial border (Yukon km 465) in the high Richardson Mountains (Figure 3c). It is near the location of a serious accident caused by collapse of the roadbed following thermal erosion of an ice wedge beneath the embankment. The site is on a slope descending westwards. The area is covered by dwarf birch bushes growing in mosses and lichens. The area was not glaciated, so the surficial materials are dominantly the result of colluvial processes. Bedrock exposures are visible from the road, but not at the precise location of the monitoring site. In June 2014 a large frost blister was examined on the south side of the road near the site, indicating the efficacy of water movement through the active layer at this site.

Site 4 is in Peel Plateau (Figure 3d), within the area glaciated by the Laurentide Ice Sheet. The region is underlain by extensive deposits of buried glacier ice. The rolling terrain is covered by shrub tundra, and dense alder thickets have grown alongside the highway since it was built in the 1970s (Gill et al. 2014). Tills cover much of the region (Lacelle et al. 2013). Permafrost in the Peel Plateau is remarkably warm for a tundra environment in the western Arctic (O'Neill et al. 2015a).

The embankment height is variable between the sites, being least at site 1 and greatest at site 4 (Table 2). Snow accumulation along the embankment slope is evident in Figure 4, which presents views of the embankment at site 2 in summer and winter.

4 METHODS

The four monitoring sites were established in late November and December 2013. At the highway centerline, holes were drilled to reach 10 m below grade. At the toe and at the undisturbed ("field") sites, the nominal intentional depth was 8.5 m. The holes were drilled by Marl M4CT and Sandvik Marlin M5 rigs. Surficial materials and any unfrozen ground were penetrated by auger, but in frozen ground a 4-inch CRREL barrel was used. Cores were retrieved with the CRREL barrel, but only grab samples were recovered when drilling with the auger. The ground materials retrieved from the holes were logged, with some samples returned to Whitehorse for laboratory examination. Grain-size and moisture content analyses were by Tetra Tech EBA. A one-inch, capped PVC tube was installed in the holes as casing for thermistor cables. The holes were backfilled with dry sand. Figure 5 is a schematic diagram of the installation at the sites.

Unanticipated conditions were encountered at sites 1 and 3. At Site 1 the materials were largely unfrozen and water logged, and impenetrable boulders required redrilling of the holes at the toe and beneath the centerline. This was completed in January 2014. At Site 3 the holes were drilled to bedrock, which was closer to the surface than the intended depths of drilling. Table 2 presents the depth of boreholes and embankment materials, and the height of the embankment at each site. Thermistor cables were installed in the borehole casings in late February 2014. The sensors (YSI 44007) have a tolerance of ±0.2 °C below 0 °C. The nominal depths of sensors are 0.3, 1.0, 1.5, 2.0, 3.0, 4.5, 6.0, 8.0, (and 10.0) m below the surface. The number of sensors varies between cables, being 9 at the centerline and 8 elsewhere, except at Site 3. There the cables terminate at 3.0, 6.0, and 8.0 m with 5, 7, and 8 sensors at the field, toe, and centerline positions respectively (Table 2).

Table 2. Depth of boreholes and embankment fill, and height of road surface above toe at each site (m).

Site	Field	Toe	Centerline	Fill	Height
1	8.53	8.53	10.00	1.80	1.15
2	8.53	8.84	10.00	2.40	1.85
3	3.20	6.10	8.40	4.00	2.30
4	8.40	8.23	10.06	2.00	1.70

Figure 3. Permafrost monitoring sites along the Dempster Highway, late July 2014. (a) Chapman Lake airstrip; (b) Glacier Creek; (c) Territorial border; (d) Midway airstrip.

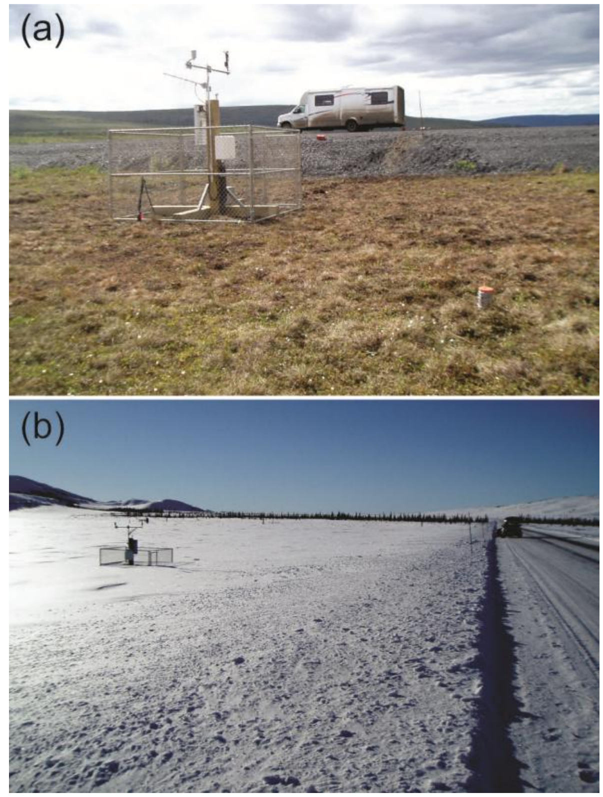

Figure 4. Site 2 shown (a) in summer and (b) in winter to illustrate the accumulation of snow beside the road embankment.

A weather station was erected at the field installations, 15 m from the toe of the embankment (Figure 3). This station includes Campbell Scientific HC2-S3-L air temperature and relative humidity sensors, and an anemometer and wind direction sensor (RM Young 05103AP-10-L). Data from these atmospheric sensors and the thermistors are collected by a Campbell Scientific CR1000-55 data logger via a multiplexer board (AM 16/32B XT). Weather data are stored on an hourly basis; ground temperatures are collected every four hours. As from early June 2014, data from sites 1 and 2 have been relayed by GOES satellite to a server in Whitehorse. Data are stored at sites 3 and 4 until collected.

Surface disturbance during drilling was minimal at sites 2 and 3, and moderate at site 1, where two attempts were required for completion of the installation (Figure 3). Disturbance was greatest at site 4, due to the need to clear alders and other bushes (Figure 3d).

Ground and air temperatures were recovered from all sites in June 2014. Further recovery was made in March 2015. Data are available at the time of writing from sites 1, 2 and 3 for a full year, but at site 4 data were not downloaded successfully.

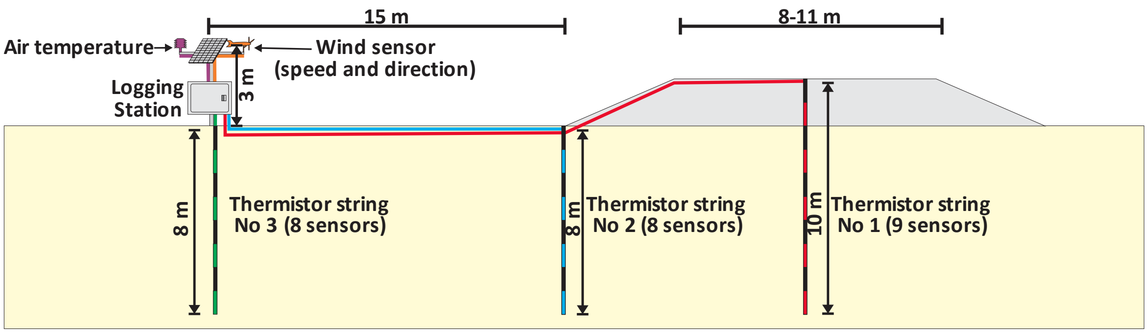

Figure 5. Schematic diagram of drill holes and meteorological equipment at each site.

Table 3. Summary of undisturbed ground conditions at the monitoring sites

Site	Ground	Surficial materials	Excess Ice content
1	Unfrozen below ~7 m	Veneer of silt above outwash gravel	Wedge ice and intrusive ice in upper 3 m
2	Frozen	Organic-rich silt above colluvial diamicton	Wedge and aggradational ice in upper 3.5 m
3	Frozen	Colluvial silt and weathered bedrock	Wedge and aggradational ice in upper 4.0 m
4	Frozen	Stoney silt and clay till	Ice-rich throughout

5 RESULTS

The drilling program and installation of sensors provide some of the few well documented data on permafrost conditions beneath and adjacent to the Dempster Highway.

5.1 Ground materials

Table 3 presents a summary of ground materials at each site. Excess ice was encountered in the uppermost 3.5 m of the field borehole at each site. The stratigraphy of these boreholes is presented in Figure 6. Full stratigraphic data, including photographs of retrieved core, are in Northern Climate ExChange (2014).

5.1.1 Site 1, km 124, Chapman Lake airstrip

Permafrost was anticipated in the surficial materials at site 1 because of the low near-surface annual mean ground temperatures (< -4.0 °C) measured nearby. Surprizingly, unfrozen ground and free water were encountered at depth in all drill holes at this site. A thin layer of permafrost was penetrated at the field installation and in the embankment. At the field site, foliated massive ice, interpreted as wedge ice, was recovered in silts (Mod. USC - ML) above gravel, and a 0.35-m layer of pool ice was found within the permafrost (Figure 6a). The silts were ice rich, with two tested samples giving excess ice contents of 49 and 69 %. The outwash gravels included a range of clast sizes, including boulders that terminated initial drilling. Groundwater discharge through the gravel into Blackstone River channel leads to surface icing in winter (Figure 2). The exceptionally thin permafrost for a site with T_p of < -4 °C is likely due to convective heat transfer in the ground water.

5.1.2 Site 2, km 421, Glacier Creek

Ice-poor gravelly diamicton is overlain at the site by a layer of ice-rich organic silt and clay (Mod. USC – CL), 1 – 2 m thick (Figure 6b). The diamicton is interpreted as a colluvial deposit that originated from the nearby slopes of Richardson Mountains (Figure 3b). The restriction of ice enrichment to the uppermost 3.5 m suggests that the excess ice is associated with permafrost aggradation during deposition of the fine-grained materials. Excess ice content in this material ranged from 20 – 50 %. Wedge ice was recovered in the toe borehole. The organic content of the upper 2 m indicates burial by surface deposition or cryoturbation.

5.1.3 Site 3, km 8.5, Territorial border

Schist bedrock is close to the surface at this site. The lower surficial material is dominantly weathered rock. Ice-rich sediment and massive ice were found in the near surface (Figure 6c). The materials are sand and silt sized at the surface (Mod. USC – ML), becoming coarser with depth (MH), reaching gravel size. The ice is a combination of wedge ice, intrusive ice, and aggradational ice. Excess ice contents of 25 – 52% were measured in the ice-rich material, but relatively few samples were collected due to the shallow holes.

5.1.4 Site 4, km 51.1, Midway airstrip

The terrain is covered by diamicton (till), dominated by silt and clay with numerous stones (Figure 6d). Some beds of clay and silty clay were encountered in the drill holes (Mod. USC – Cl), but samples of diamicton tested also contained up to 10% gravel. It is ice-rich throughout, with excess ice contents of up to 57%, but generally in the range of 40 – 50 %. No massive icy bodies were encountered in the drill holes.

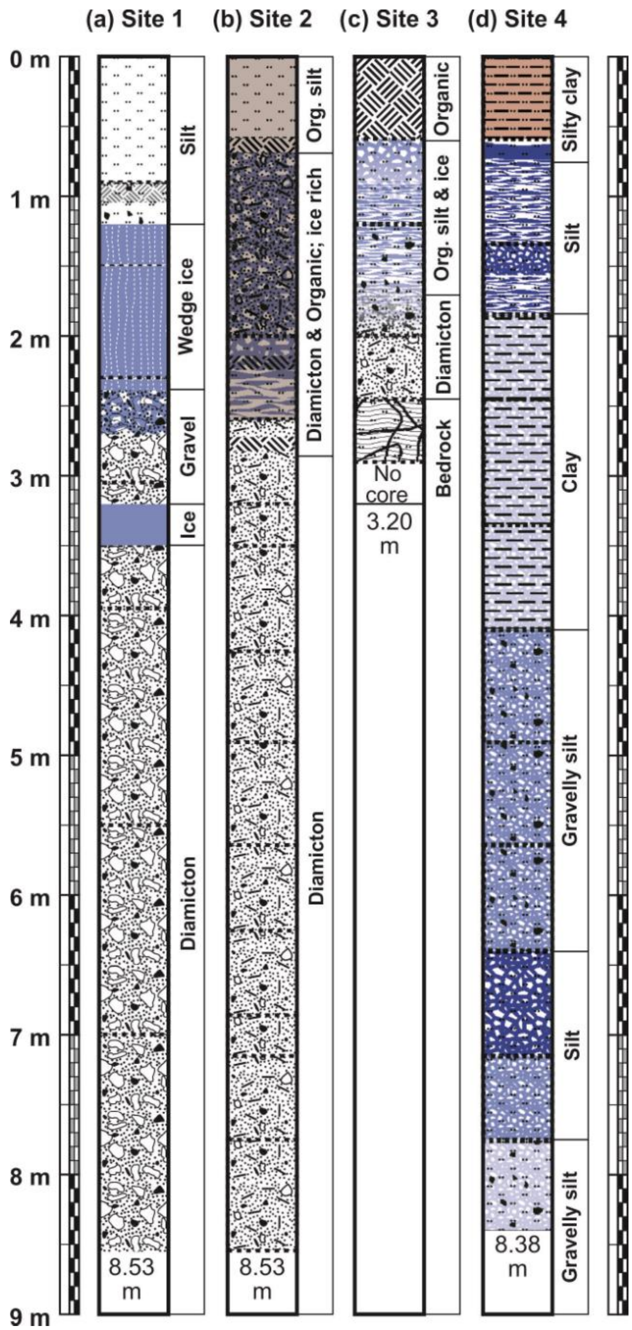

Figure 6. Representative stratigraphy of boreholes drilled in undisturbed ground (field) at the monitoring sites. The base of permafrost at site 1 is at approximately 7 m depth.

5.2 Ground thermal regime

Table 4 presents summary data on ground thermal conditions at each site. Data for sites 1 to 3 are derived from a full year of observations, but the information for site 4 is interpreted from only 3 months' data. There is considerable other thermal information from Peel Plateau that is consistent with these values (e.g., O'Neill et al. 2015a, b). Figures 7a-c present mean annual ground temperature profiles from the field, toe and embankment cables at sites 1-3, and Table 5 presents snow depths measured at sites 1-4 in mid-March 2015. We note several general characteristics: (1) ground temperatures are highest at the toe in association with a snow bank that accumulates there each winter; (2) the temperatures at the centerline are cooler at the surface than in the field sites; (3) the temperature profile of the embankment appears to converge at depth with the profile from the toe.

5.2.1 Site 1, km 124, Chapman Lake airstrip

T_a at site 1 was the lowest recorded in this study (Table 4), and is consistent with the relatively low T_p recorded previously in Blackstone River valley (Burn et al. 2015). Near-surface T_p at the field site was low, as anticipated. However, we did not anticipate that permafrost would be < 8 m thick at this site, or that it would have degraded completely beneath the toe of the embankment (Figure 7a). Maximum temperatures measured over the year indicate the base of permafrost is at about 7 m depth at both field and centerline sites. We attribute the thin layer of permafrost to heat transfer in groundwater flowing through the glacial outwash at the site. The extensive icing in Blackstone River is derived from groundwater discharge throughout winter (Figure 2). Permafrost at the toe cannot be sustained, due to snow accumulation at the edge of the road from ploughing and trapping of blown snow in willows and alder bushes (Figure 3a) (Table 5). Within the embankment, at the centerline, permafrost is sustained, and T_p, just below the active layer is comparable with the field site (-2.4 °C) (Table 4).

5.2.2 Site 2, km 421, Glacier Creek

Permafrost is sustained at site 2, but has been warmed at depth beneath the road and toe, due to the deep snow banks that accumulate on the side slopes (Figure 4) (Table 5). The field site appears to be located away from thermal disturbance associated with the embankment. The site is exemplary because it demonstrates (1) overall warming of permafrost by the road; (2) relatively cold conditions in the embankment; (3) relatively warm conditions at the toe.

5.2.3 Site 3, km 8.5, Territorial border

Bedrock was encountered near the surface at site 3, reducing the depths at which ground temperatures have been measured. The embankment at centerline is relatively cold at the site (Figure 7c), but the similarity between conditions at the toe and field sites suggests that the influence of the snow bank created by the road extends away from the embankment (Table 5). Permafrost appears to be degrading at the toe, as indicated by annual mean temperature above 0 °C

Table 4. Annual mean air temperature (Ta, °C), annual mean temperature at the top of permafrost (T_p, °C), thaw depths (m), and permafrost state at sites 1-3, 1 Mar 2014 - 28 Feb 2015. Data for site 4 interpreted from deepest thermistor and only for 24 Feb – 3 June 2014.)

Site	T_a	T_p Centerline	T_p Toe	T_p Field	Thaw depth Centerline	Thaw depth Toe	Thaw depth Field	Permafrost state Centerline	Permafrost state Toe	Permafrost state Field
1	-6.8	-2.4	-	-2.7	2.9	-	0.8	Aggrading	Degraded	Equilibrium
2	-4.9	-2.3	-1.4	-3.6	2.8	0.9	0.4	Aggrading	Degrading	Equilibrium
3	-5.4	-3.9	-1.0	-1.1	2.9	1.4	0.9	Aggrading	Degrading	Equilibrium
4	-5.2	-4.3	-1.1	-0.7	1.9	1.4	0.9	Aggrading	Degrading	Degrading

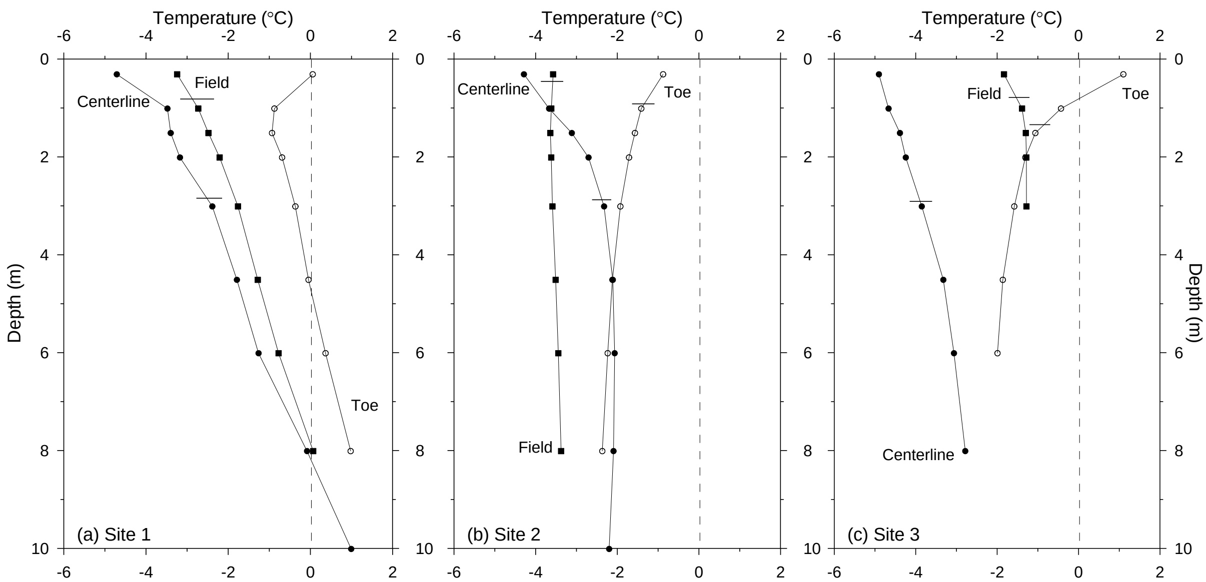

Figure 7. Annual mean temperature profiles from sites 1 – 3 for 1 Mar. 2014 – 28 Feb. 2015. Thaw depths are indicated by a horizontal line at each site. Maximum temperatures were > 0 °C throughout the profile at the toe location of site 1.

within the active layer, which is 0.5 m thicker than at the field location.

5.2.4 Site 4, km 51.1, Midway airstrip

Thermal data at site 4 are presented in Table 4 from only 3 months of observations. The values for T_p, measured at the 8 and 10-m boreholes, are consistent with the relatively warm permafrost conditions interpreted for Peel Plateau by O'Neill et al. (2015a). We do not compare these values with data for site 3 here because of the limited time for data collection, but we note that the time of observation corresponds with a relatively cold period of the year at depth, and therefore we expect mean annual values to be higher than those presented for information purposes in Table 4.

Table 5. Snow depth (m) at the four study sites, 16-17 March 2015.

Site	Field	Toe	Centerline
1	0.80	1.00	-
2	1.00	1.50	-
3	1.20	1.25	-
4	1.40	1.40	-

6 CONCLUSIONS

From the data presented above we note the following:

(1) Permafrost is stable and aggrading beneath the centerline of the embankment of the Dempster Highway at the three sites from which a year's ground temperatures have been collected.

(2) Permafrost has degraded or is degrading beneath the toe of the embankment at these three sites.

(3) Thin permafrost has been measured at the site with lowest air temperature in association with groundwater movement.

(4) The integrity of the embankment along the highway appears to be related to the abundance of near-surface ground ice, because conclusion (2) implies that side slope failure is inevitable where the ground is thaw sensitive.

ACKNOWLEDGEMENTS

The research reported in this paper has been supported by: Transport Canada; Transportation Engineering Branch, Government of Yukon; Department of Transportation, Government of the Northwest Territories; Yukon College; and Carleton University. The authors thank, in particular, Greg Cousineau (GNWT), Janice Festa (TC), Steve Kokelj (GNWT), John-Paul Handrigan (TC), Don Hayley (EBA), Gurdev Jagpal (GNWT), Paul Murchison (GY), Sandra Orban (YG), and Richard Trimble (EBA) for assistance with site selection and numerous helpful discussions. We thank Brendan O'Neill (Carleton University) for assistance with downloading data in March 2015 and for comments on the paper, and Steve Kokelj for a helpful review.

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