Disequilibrium permafrost conditions on NWT Highway 3

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ABSTRACT
The thermal and physical states of permafrost in natural and developed settings along NWT Highway 3 are examined and implications of recent realignment between Behchoko and Yellowknife are discussed. Permafrost occurs in natural terrain beneath peatlands and forested fine-grained (glacio) lacustrine sediments. Natural and developed sites indicate surface warming especially beneath the highway embankment, which was straightened and reconstructed between 1999 and 2006. Fine-grained sediments are thaw-sensitive and ice-rich. The terrain could experience up to 1.3 m of settlement with thawing of the top 5 m of permafrost. Permafrost had aggraded into the old highway embankment comprised of fine-grained materials, but is unlikely to be sustained beneath the new highway embankment comprised primarily of blast rock.

RÉSUMÉ
Cet article étudie l'état thermique et physique du pergélisol dans des milieux naturels et aménagés le long de l'autoroute 3 dans les Territoires du Nord-Ouest. Les implications du réalignement récent de l'autoroute entre Behchoko et Yellowknife sont aussi discutées. Le pergélisol, qui se situe dans les milieux naturels, se retrouve sous les tourbières et dans les zones boisées de sédiments fins (glacio-) lacustres. Un réchauffement de surface de la température du sol est observé pour les sites naturels et aménagés, en particulier sous les nouveaux remblais de l'autoroute, réalignée et reconstruite entre 1999-2006. Les sédiments fins, qui sont riches en glace et susceptibles au dégel, présentent un maximum de 1.3 m de tassement potentiel dans les premiers 5 m du pergélisol. Le pergélisol s'était développé dans l'ancien remblai de l'autoroute qui était composé de matériaux à grains fins. Par contre, il est peu probable que le pergélisol se développe dans le nouveau remblai de l'autoroute, puisque celui-ci est principalement composé de roches produites par dynamitage.

1 INTRODUCTION

Permafrost in the North Slave region around Yellowknife, Northwest Territories (Fig. 1) is present beneath peatlands and most forest-cover types underlain by fine-grained unconsolidated sediments (Brown 1973; Karunaratne, et al. 2008; Morse et al. this volume). The presence of warm, discontinuous permafrost hosted in thaw-sensitive sediments has significant implications for transportation infrastructure. However, soil stratigraphy, ground ice content, and thermal characteristics are not well documented, and developed sites have not been compared to natural settings. This paper examines the thermal and physical states of permafrost in natural and developed settings, and discusses the implications of permafrost warming on highway infrastructure.

2 BACKGROUND

The study area is along the northeastern shoreline of the North Arm of Great Slave Lake, between Yellowknife and Behchoko, NT (Fig. 1). Yellowknife has a continental climate, with a mean annual air temperature of -4.3°C and mean daily temperatures ranging from 17°C in July to -26°C in January within the 1981-2010 normal period (Environment Canada http://www.climate.weather.gc.ca/).

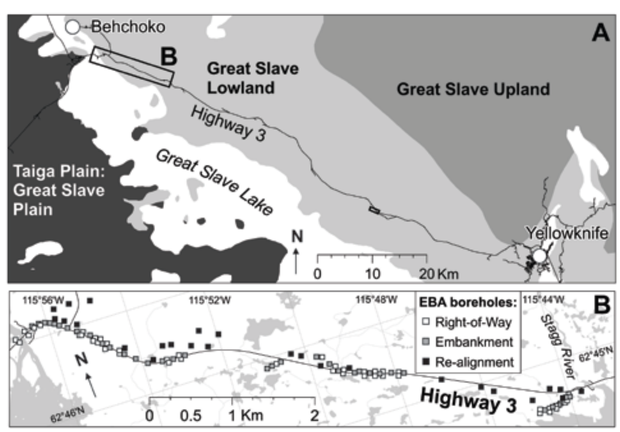

Figure 1. North Slave region and borehole locations.

Mean total precipitation is 289 mm, with about 59% as rain, and average maximum snow depth is 0.38 m. An air temperature warming trend of about 0.3°C per decade since the 1940s (Hoeve et al. 2004; Riseborough et al. 2012), has accelerated to about 0.6°C per decade since 1980 (Morse et al. this volume).

Discontinuous permafrost is assumed to be extensive (50-90% by area), and ground ice content in the upper 10 to 20 m is medium to low (<10 - 20% ice by volume) (Heginbottom et al. 1995). Permafrost occurs beneath scattered peatlands (Brown 1973, Karunaratne et al. 2008), but is most common beneath forest-cover types underlain by fine-grained unconsolidated sediments (Riseborough et al. 2013; Zhang et al. 2014; Morse et al. this volume). Extensive within the Lowland (Stevens et al. 2012a), these sediments are commonly ice-rich (Wolfe et al. 2011a, 2014). Permafrost near Yellowknife is generally less than 50 m thick (Brown 1973) and warm (>-2°C) (Brown 1973; Hoeve et al. 2004; Karunaratne et al. 2008; Morse et al. this volume).

The GNWT Highway 3 (Fig. 1a) is an example of road infrastructure traversing discontinuous permafrost through a highly heterogeneous landscape. It was constructed across Great Slave Lowland High Boreal ecoregion during the mid-1960s utilizing locally-available silt and clay excavated from shallow pits along the right-of-way (Wolfe et al. 2011b). The alignment largely avoided water bodies and bedrock, and preferentially crossed natural terrain including peatland and clay-rich terrain.

Major highway realignments between 1999 and 2006 maximized bedrock traverses to minimize the extent of thaw-sensitive permafrost and thus embankment settlement (Hoeve et al. 2004). The new highway consists primarily of an open-graded, blast-rock-filled embankment (max. size: ~60 cm diameter) with a chip-sealed surface treatment. It extends across natural terrain, including peatland, fine-grained sediments, ponds and bedrock, and across developed terrain, including the former highway and borrow pits (Wolfe et al. 2011b). Geothermal modelling predicted permafrost persistence beneath the new embankment under present-day climate, but thaw beneath embankment slopes considering climate warming and snow accumulation at the embankment toe (Hoeve et al. 2004).

Surface water occurs along embankment sections, where natural or subsidence-induced topographic depressions inhibit drainage (Stevens and Wolfe 2013) and where natural flow was interrupted. Warming air temperature trends (e.g., Hoeve et al. 2004; Riseborough et al. 2012), together with surface disturbance and changes in drainage resulting from highway construction also create potentially significant challenges regarding the future stability of road infrastructure in this region. Differential settlement of the blast-rock embankment, for example, has already been observed since construction (Hoeve et al. 2004; BGC 2011; Seto et al. 2012).

3 METHODS

3.1 Thermal Analysis

Ground temperatures from natural settings were measured in boreholes to depths of up to 11.5 m and recorded hourly by data loggers (XR-420-T8, RBR Ltd.) (Morse et al. this volume). True temperatures are known to ±0.1°C, but actual temperature change with time may be resolved at 0.001°C increments. The high resolution of the instrumentation allows trends in monthly mean permafrost temperatures at depths below the zero degree annual amplitude to be examined. Temperatures were determined manually at four other sites at approximately 4-month intervals with a multimeter (model 77-IV, Fluke Corporation). To compare developed areas to natural settings, we also examined ground temperatures measured manually to 15-m depth reported in geotechnical engineering reports (EBA 1996, 1997, 2003). Site details are in Table1.

3.2 Physical Analysis

Stratigraphic and geotechnical data include borehole logs and sample analysis from over 100 boreholes (EBA 1995) drilled along a 14-km section of the old NWT Highway 3 embankment and right-of-way, and within natural terrain for the highway re-alignment. Boreholes, drilled in March when the active layer was typically frozen, went to 5-m depth or to refusal on probable bedrock. Samples of rotary air-track auger cuttings were collected every metre of drill depth. All depths were adjusted relative to the top of the mineral soil surface; including embankment boreholes over-topped with fill material and organic material overlying natural ground.

Data include depth to probable bedrock, frozen-unfrozen interfaces, material type, grain size, estimates of visible ice, and moisture content. Converted to volumetric values, moisture content results imply that, for the most part, visible ice observed during drilling was properly represented. Samples containing a high percentage of fines (<80 µm) were tested for sand, silt and clay content, and Atterberg limits (EBA 1995).

Unit thaw strains were calculated for soil samples using the method of Crory (1973):

$$\delta = (\rho_{dt} - \rho_{df}) / \rho_{dt} \qquad [1]$$

where ρ_{dt} and ρ_{df} are the thawed and frozen dry soil densities, respectively. Gravimetric water contents were used to estimate ρ_{dt} and ρ_{df}. Given the high silt and clay content, a specific gravity of 2.7 was assumed for all samples (Andersland and Ladanyi 2004; Table 2-1, p. 23). A general value for ρ_{dt} was determined using average moisture content of thawed samples (assumed full saturation), but ρ_{df} was calculated for each frozen moisture content sample, taking into account unfrozen water and calculating relative ice content (Crory 1973). Unfrozen water contents were estimated based on the Atterberg limits (U.S.S.R. Building Code 1969). Unit thaw strains were calculated as average values over 0.5 m depth intervals.

Table 1. Ground temperature site location, description, bedrock depth, disturbance regime, recording interval, and time period.

Site	Lat. (°N)	Long. (°W)	Site Description	Depth to Bedrock (m)	Disturbance Regime	Recording Interval*	Time Period
BS-1	62.60300	-114.11577	spruce forest	-	natural	IM	2009-2013
BS-2 (BGC05)	62.51064	-114.81647	spruce forest	-	natural	4 h	2010-2011
BS-3	62.60331	-114.11525	spruce forest	-	natural; lake shore	2 h	2010-2013
WB-1	62.52787	-114.95937	birch forest	-	natural	4 h	2011-2013
WB-2	62.52848	-114.95657	birch forest	-	natural; degrading	4 h	2011-2013
WB-3	62.50630	-114.27708	birch forest	-	natural; degrading	2 h	2010-2013
WB-4 (BGC12)	62.54333	-114.98446	birch forest	-	natural	IM	2010-2013
WB-5	62.52797	-114.95921	birch forest	-	natural; degrading; lakeshore	4 h	2011-2013
PL-1 (BGC07)	62.51114	-114.81799	peatland	-	natural	4 h	2011-2013
PL-2	62.55370	-114.01361	peatland	-	burned & cut; degrading	4 h	2010-2012
PL-3	62.55373	-114.01222	peatland	-	burned & cut; degrading, lakeshore	4 h	2010-2013
CL-1 (EBA1643)	62.72004	-115.62489	centre line	4.1	new HWY 3 embankment	IM	2003-2008
CL-2 (EBA1644)	62.74396	-115.73807	centre line	13.7	new HWY 3 embankment; culvert	IM	2003-2009
CL-3 (EBA1645)	62.74394	-115.73787	centre line	-	new HWY 3 embankment	IM	2003-2009
CL-4 (EBA1646)	62.75428	-115.78842	centre line	3.5	old HWY 3 embankment	IM	2003-2004
SH-1 (EBA1647)	62.72009	-115.62482	shoulder	4.6	new HWY 3 embankment	IM	2003-2008
SH-2 (EBA1648)	62.75422	-115.78848	shoulder	2.5	old HWY 3 embankment	IM	2003-2008
T-1 (EBA1649)	62.75418	-115.78922	toe	2.7	old HWY 3 embankment	IM	2003-2008
T-2 (EBA1650)	62.72012	-115.62476	toe	6.6	new HWY 3 embankment	IM	2003-2008
BS-4 (EBA1651)	62.75468	-115.78853	spruce forest	-	natural, off-ROW old HWY 3	IM	2003-2009
BS-5 (EBA1652)	62.72025	-115.62455	spruce forest	4.0	natural, off-ROW old HWY 3	IM	2003-2009

*IM = intermittent manual

4 RESULTS

4.1 Ground Thermal Characteristics

The variation in ground thermal profiles demonstrates the influence of a diverse range of surface and subsurface conditions encountered in this study. Ground temperature profiles at road embankment sites are typically warmer than natural sites (Fig. 2). Annual mean ground temperature profiles (2012-2013) at natural sites indicate that permafrost temperatures in silts and clays at 8-m depth range from about -1.4 to 0°C. Beneath Highway 3 centreline, shoulder and toe, long-term average temperatures (2003-2009) 8-m below the present surface range from -0.9 to 0.7°C. The highest ground temperatures are beneath the old Highway 3 shoulder and toe, resulting from about 45 years of disturbance (1965-2009). Thermal inversions of mean annual temperature profiles, indicative of persistent surface warming, are present at all Highway 3 sites as well as some natural sites (Fig. 2). At other natural sites, temperature profiles are nearly isothermal (Fig. 2), being indicative of substantial latent heat effects observed in this region that are associated with the phase-change of pore water in fine-grained materials of the active layer and permafrost (Morse et al. this volume).

Ground temperature time series indicate general warming at depth (Fig. 3). The most rapid warming rates are at disturbed sites where bedrock is relatively shallow (Fig. 3, Table 1). Although the warming trend in shallow bedrock is clear, the depths to zero annual amplitude (DZAA) are below the deepest thermistors. Therefore, the magnitude of warming may not be directly comparable to natural and fine-grained sites where temperature trends shown are from below the DZAA. The exceptions to the warming trend are two natural sites (WB-2 and BS-4; Fig. 3a and b). The large amplitude at PL-1 reflects the position of the thermistor, which is closer to the depth of zero degree annual amplitude than the other sites.

4.2 Physical characteristics

4.2.1 Stratigraphy and Sedimentology

Sediment stratigraphy is shown in Figure 4. All of the 102 boreholes encountered silt or clay at depth. Sand or gravel units occurred in 32% of the boreholes, typically below silt or clay sediments, and in 85% of these boreholes, bedrock was within about 1 m below the coarse-grained materials.

Sediment textures of samples with high fines content are shown in Figure 5a. These represent the dominant underlying sediments throughout the region and typically contain 50-75% clay 25-50% silt, and less than 5% sand.

Atterberg tests illustrate the relation between the liquid limit and plastic index (Fig. 5b). Most samples plot above the “A-line” and are classified as clays of intermediate (CI) to high (CH) plasticity (BSI, 1990). These plot on a line, parallel to the A-line, indicating the clays are similar in type and origin (Skempton, 1953).

Atterberg limits shown in Figure 5b indicate that these soils behave mechanically as clays when thawed, despite their comparatively high silt content. This is likely due to relatively high proportion (up to 34%) of clay-size sediment (<2 µm) and the overall fine grain size of the sediment. The high fraction of <4 µm fines (20-45%), in particular, includes clay minerals (muscovite, kaolinite and chlorite) most likely affecting the properties of the overall sediment sufficiently to create clay-like behaviour under

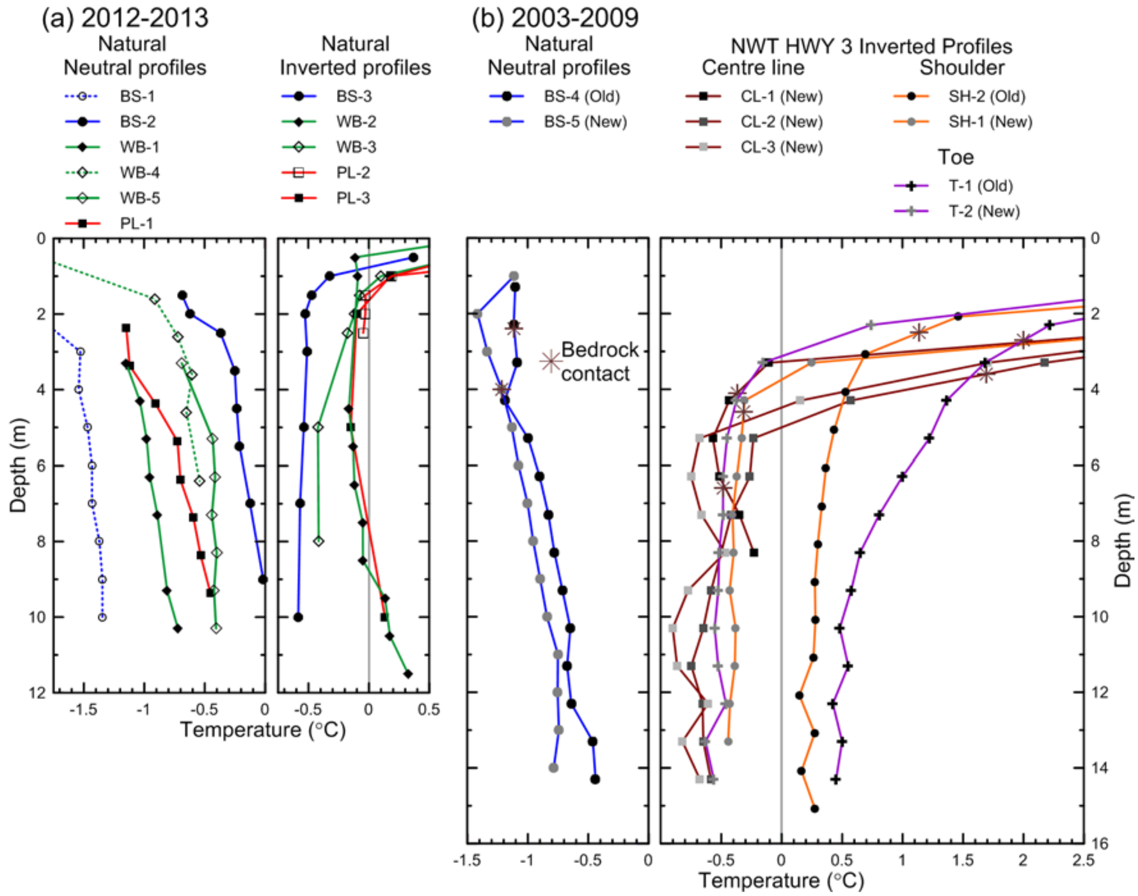

Figure 2. Detailed ground temperature profiles at natural and developed sites. (a) Annual mean ground temperatures (2012-2013) are shown for natural site types: black spruce forest (BS), white birch forest (WB), and peatland (PL). For sites with intermittent manual readings the midpoints between minimum and maximum measured temperatures are shown (dashed lines and hollow symbols). (b) 2003-2009 average ground temperatures are shown for natural black spruce (BS) and old and new Highway 3 site types: embankment centreline (CL), embankment shoulder (SH), embankment toe (T). Bedrock contacts below fine-grained materials are indicated. Depths are below the present surface.

under thawed conditions (Aden, 2014).

4.2.2 Permafrost, Ground Ice, and Thaw Strains

Thirty of the 32 boreholes (94%) drilled in natural terrain prior to highway re-alignment contained frozen sediments at depth (Fig. 4). Most sites (62%) had a thin organic cover (less than 0.2 m) and the rest had organic cover in the range of 0.2 to 1.0 m. This confirms the widespread nature of permafrost in unconsolidated sediments.

Of the 58 boreholes drilled in developed terrain of the old Highway 3 corridor, 31 were through the old highway embankment (Fig. 4). In 94% of these boreholes, the fill materials were completely frozen, and in 72% of the boreholes the underlying sediments were also frozen throughout. This suggests that permafrost remained preserved below much of the former highway surface, and aggraded into the embankment since initial construction in the mid-1960s. In contrast, 70% of the 39 right-of-way boreholes contained thawed sediments at depth, indicating the presence of either a near-surface talik or complete absence of permafrost.

A number of the boreholes contained ice-rich layers typically within the clay units, particularly in the vicinity of Stagg River (Fig. 4). Ice-rich layers near the surface along the re-alignment may represent ice at the active-layer base or aggradational ice (Mackay, 1983). Figure 5c, showing the overall variation in moisture content and (thus ice) with depth for all frozen silty and clayey samples, indicates that moisture content tends to increase with depth. Derived unit thaw strains also increase with depth (Fig. 5d), averaging 0.10 within the upper 2 m and 0.21 below 2-m depth. On average, thawing of the top 5 m of fine-grained permafrost can potentially result in 1.3 m of settlement.

5 DISCUSSION

5.1 Permafrost Thermal Conditions

Overall, the ground temperature profiles and time series from beneath natural and Highway 3 sites are indicative of thermal disequilibrium and regional ground temperature warming that follows surface warming (Figs 2 and 3). At

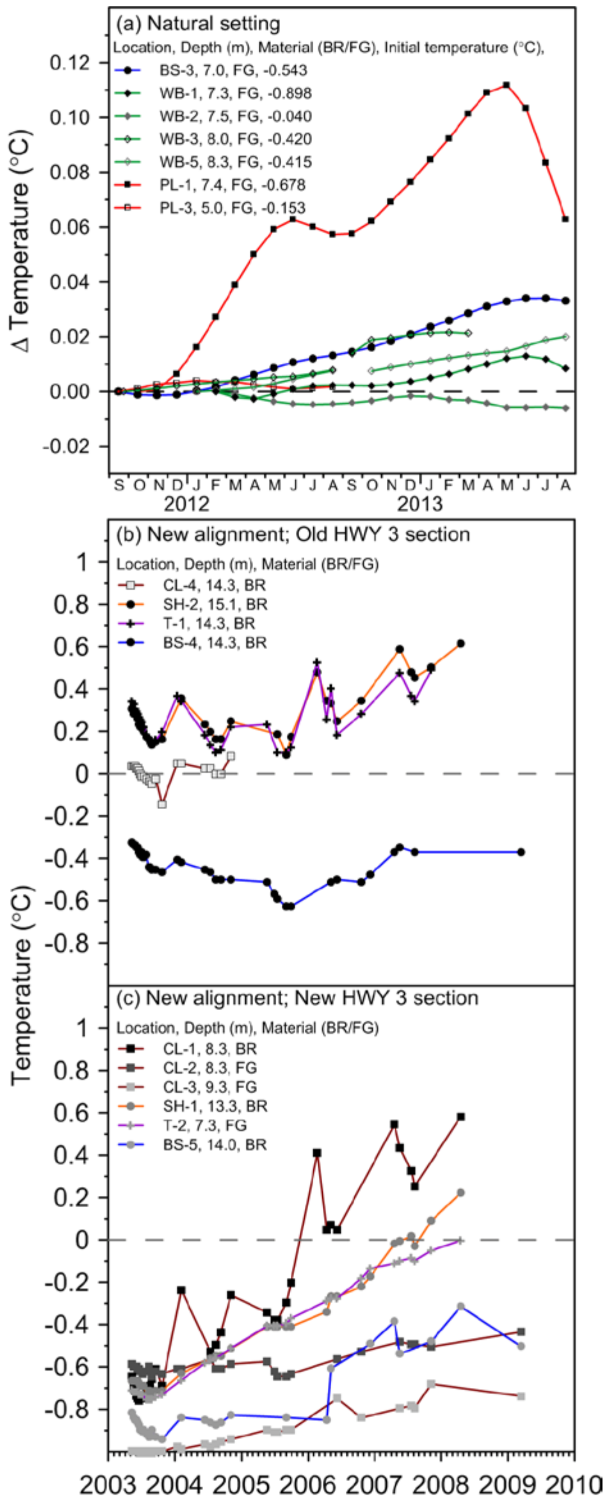

Figure 3. Ground temperature trends in bedrock (BR) and fine-grained material (FG): (a) short-term change from initial monthly mean temperatures at natural settings; (b) long-term trends along the new alignment at old settings; and (c) long-term trends along the new alignment at new settings. Temperatures in FG are from below the depth to zero annual amplitude (DZAA), and those in BR are all above DZAA, but are the deepest available.

natural sites, the relatively thin (<50 m depth), warm (-1.4°C to 0°C) permafrost exhibits neutral (near-isothermal) and inverted ground temperature profiles, whereas all Highway 3 sites demonstrate strongly inverted profiles with very warm ground temperatures (-0.9 to 0.7°C) and permafrost absence at some sites (Fig. 2). Ground temperatures measured beneath the old (up-graded) highway embankment and at natural sites have increased consistently over time (Fig. 3).

Thermal disequilibrium of permafrost at natural sites is likely in response to regional air temperature warming trends (Hoeve et al. 2004; Riseborough et al. 2012). Recent highway construction has accelerated disequilibrium and permafrost thaw beneath the embankment slope (shoulder and toe) and centre line, beyond that of natural sites. In contrast to sites with shallow bedrock, the rate of ground temperature change in fine-grained sediments is mitigated due to latent heat effects, but this permafrost is also thaw sensitive.

5.2 Stratigraphy and Permafrost Physical Conditions

Sediment stratigraphy over bedrock is regionally consistent, being dominated by silty-clay occasionally overlain or underlain by clayey-silt, and commonly underlain by a sand or gravel unit (Fig. 4). This stratigraphic sequence is a result of the post-glacial depositional history, where basal sands and gravels typically represent outwash sediments derived from tills (Kerr and Wilson 2000), silty-clay represents Glacial Lake McConnell sediments deposited prior to 8,500 years BP (Aden 2014), and overlying clayey-silts typically represent nearshore lacustrine or alluvial deposits (Gaanderse 2015).

Borehole stratigraphy indicates that excess ice is distributed in the near surface and at lower depths within the ubiquitous fine-grained sediments (Fig. 4). Given the post-glacial depositional history of the region and the general absence of evidence polygonal terrain or wedge ice, ground ice within permafrost may be almost exclusively epigenetic segregated ice, with some additional near-surface aggradational ice at the base of the active layer. Areas of high ground ice content, such as at Stagg River (Fig. 3b) and Boundary Creek (Gaanderse 2015) may be attributed to late Holocene growth and development of lithalsas (permafrost mounds formed by ice segregation in fine-grained sediment) (Wolfe et al. this volume).

Unit thaw strains as depicted in Figure 5d are likely indicative of the minimum expected thaw settlement for several reasons. First, if permafrost thaw exceeds the rate of excess pore water dissipation, which is likely within these fine-grained clay-like soils, shear strengths may be significantly reduced as the sediments exceed their liquid limit. Second, total settlements are likely larger than calculated herein, due to additional post-thaw soil consolidation. Third, ground ice contents may be expected to increase additionally with depth below 5 m, as evidenced at Stagg River, Boundary Creek and elsewhere (Fig 3b; Gaanderse 2015; Wolfe 1998).

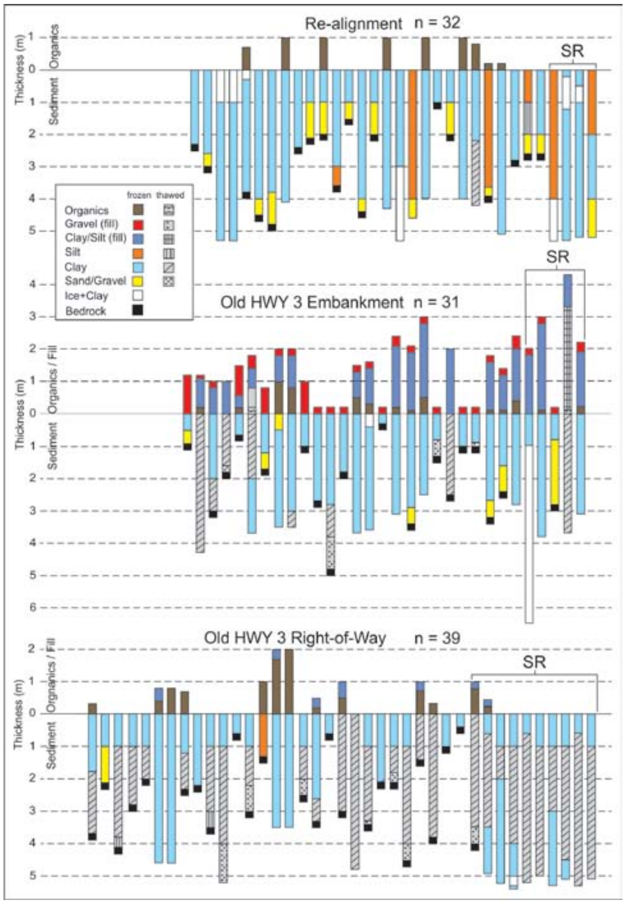

Figure 4. Simplified stratigraphy of EBA boreholes drilled in re-alignment, former embankment and right-of-way settings along the Highway 3 corridor between Behchoko and Stagg River (SR) (date from EBA 1995).

5.3 Highway Infrastructure Implications

The direct implication of permafrost degradation includes potentially large, long-term thaw settlement and reduced soil strength caused by the thawing of ice-rich permafrost at depth (Fig. 4 and 5). For example, 95 cm of settlement in the last 4 to 5 years since construction has been observed west of Yellowknife, where the highway embankment crosses ice-rich terrain (Stevens et al. 2012b). Sub-grade excavation of ground ice is not a practical option in such areas due to the deep occurrence of segregated ice (Wolfe et al. 2014; Gaanderse 2015). For that reason, alternative geotechnical considerations should be given to locations where thicker sediment sequence and higher occurrence of ground ice is common (Stirling et al., this volume).

Borehole data indicate a prevalence of permafrost within the natural and old highway embankment boreholes, thus most of the thawed sediments noted below the right-of-way are likely due to thawing of permafrost subsequent to highway construction in the mid-1960s. Typical highway right-of-way disturbances include initial vegetation and surface soil removal and subsequent increases in snow cover, soil moisture and ponding that create surface conditions conducive to thermal degradation. If soil conditions become saturated, as has been observed in some areas (Stevens and Wolfe 2012), right-of-way thermal conditions may be similar to saturated organic conditions, which are generally near 0°C or warmer (Morse et al. this volume). Significantly, borehole data indicate that permafrost had actually aggraded into the former highway embankment since its construction (Fig. 4). As the original highway embankment was constructed from fine-grained material, with an average water content of only about 23%, well below the average liquid limit (~48%) and on par with the plastic limit, the embankment retained a frozen core that was relatively rigid and restrictive to surface and groundwater flow. With abandonment, these sections thawed and subsided, suggesting that snow clearing and highway maintenance may have sustained permafrost into the 1990s on the old highway.

In addition to right-of-way thaw settlement, a number of factors have likely induced thawing of permafrost and settlement beneath the open-graded blast-rock highway embankment. First, the open-graded blast rock fill may be susceptible to accumulation of water beneath the embankment as it is more porous than the old highway constructed from fine-grained borrow fill sediments. Thus, obstructed water may flow within the embankment, increasing the potential for advective heat transfer (de Grandpre et al. 2012). Second, though air convection through the granular embankment may reduce thaw settlement of the highway embankment (e.g. Goering 2003), the common placement of a silt-clay cap over much of the blast-rock embankment, meant primarily to improve safety and also to reduce water infiltration, may reduce or eliminate any potential winter pore air convection, as does snow cover.

6 CONCLUSIONS

The main findings from this study are:

1. Ground temperatures below the depth of zero annual amplitude (~8 m) are sub-freezing, but typically warmer than about -1.4°C in natural terrain and range from -0.9°C to 0.7°C beneath the new Highway 3 embankment. Temperature inversions and warming at depth are indicative of thermal disequilibrium that relates to surface warming and widespread thermal degradation of permafrost.
2. Permafrost within unconsolidated fine-grained sediment is commonly ice-rich. This intra-sedimental ground ice is primarily segregation ice and, in some instances near the top of permafrost table, aggradational ground ice.
3. Underlying sediments have an intermediate to high plasticity and typically contain moisture contents approaching the liquid limit when thawed, and are thus highly susceptible to thaw settlement. Potential thaw settlement in the upper 5 m of permafrost may be a minimum of 1.3 m and likely higher at greater depths in relation to increasing ground ice contents.
4. Permafrost was historically sustained beneath the original NWT Highway 3 embankments constructed from local fine-grained sediment but degraded from

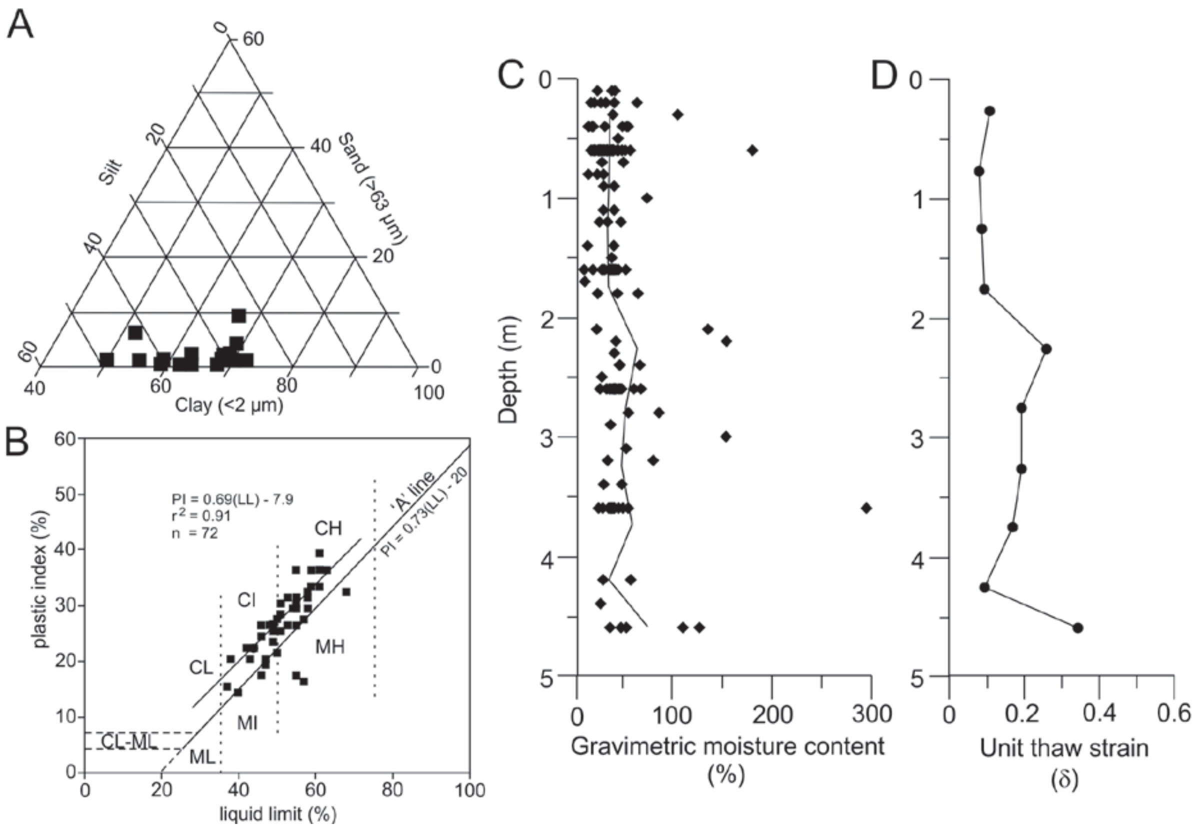

Figure 5. Permafrost physical characteristics determined from EBA boreholes: (a) grain-size distribution; (b) Atterberg test results; (c) dry-basis gravimetric moisture contents; and (d) estimated thaw strain.

adjacent highway right-of-ways, and has subsequently degraded below abandoned highway sections.

5. Based upon thermal trends, permafrost thaw and settlement beneath the open-graded blast-rock highway embankment are inevitable. However, rate of degradation could be reduced by snow management, and improving drainage and air convection through the embankment at problem sections.

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