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Challenges from North to South
Des défis du Nord au Sud

Characterization of Permafrost Thermal State in the Southern Yukon

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ABSTRACT
Boreholes in the northwestern portion of the Alaska Highway Corridor, Yukon were instrumented for temperature measurement between 2011 and 2013. The data acquired has enabled characterization of the ground thermal regime in this section of the corridor. Permafrost is generally warm with temperatures above -1.5°C. However, colder permafrost at temperatures as low as -3°C was found in the immediate vicinity of the Alaska border. Comparison of recent ground temperatures with those measured in boreholes by the Geological Survey of Canada in the late 1970s indicates that warming of permafrost has occurred. These instrumented boreholes complement those established previously in the southern and central Yukon and facilitate an improved understanding of the regional thermal state of permafrost.

RÉSUMÉ
Des forages, situés dans la partie nord-ouest de l'autoroute de l'Alaska au Yukon, ont été instrumentés entre 2011 et 2013 afin de mesurer la température du sol. Les données acquises ont permis de caractériser le régime thermique du sol dans cette section du corridor. Le pergélisol est généralement tempéré avec des températures supérieures à 1.5 °C. Cependant, un pergélisol froid ayant des températures aussi basses que -3 °C a été identifié à proximité de la frontière de l'Alaska. Une comparaison entre les températures du sol mesurées récemment et celles mesurées par la Commission géologique du Canada dans des forages à la fin des années 1970, indique que le pergélisol s'est réchauffé. Ces forages, nouvellement instrumentés, complémentent ceux établis ailleurs dans le sud et le centre du Yukon, et aide à une meilleure compréhension de l'état thermique du pergélisol dans cette région.

1 INTRODUCTION

The Alaska Highway Corridor traverses the discontinuous permafrost zone of the southern Yukon from the Alaska border to northern British Columbia (Figure 1). Construction and operation of infrastructure associated with transportation or development projects along with a changing climate can alter the ground thermal regime of permafrost environments resulting in ground movements (heave and settlement), drainage alteration, and landscape instability. These changes may affect infrastructure integrity and have implications for terrestrial and aquatic ecosystems. Knowledge of current permafrost conditions is therefore essential for planning infrastructure development and adapting existing infrastructure to a changing climate, and for ensuring that the integrity of infrastructure and the environment is maintained. Although permafrost characteristics were investigated in the corridor more than 30 years ago (e.g. Burgess et al. 1982) to support a previous pipeline proposal, little recent information had been collected. Furthermore, changes in permafrost conditions over the last three to four decades have been documented along the Alaska Highway Corridor between Whitehorse YT and Fort St. John BC (James et al. 2013) as well as elsewhere in northern Canada (e.g. Smith et al. 2010).

Recent proposals for a natural gas pipeline and the need to develop climate change adaptation options for infrastructure in the Alaska Highway Corridor have underlined the requirement for information on current permafrost and terrain conditions. Since mean annual air temperatures in the region have increased since the 1970s (Figure 2), it is essential that updated information on permafrost conditions be available to support design of resource development infrastructure as well as climate change adaptation planning for the existing highway.

To address the paucity of information on ground thermal conditions for the section of the corridor west of Whitehorse, nineteen boreholes up to 10 m deep were instrumented with temperature cables between 2011 and 2013. These boreholes complement those instrumented during the International Polar Year (2007-09) elsewhere in the central and southern Yukon. This paper reports the ground temperature data collected from these sites and provides a characterization of the ground thermal regime along the corridor which enhances our knowledge of regional permafrost conditions of the southern Yukon.

2 STUDY AREA AND INSTRUMENTATION

The study area is located within the Western Canadian Cordillera and the highway corridor crosses (east to west) the Teslin and Kluane Plateau over the Shakwak Trench and follows the Kluane Ranges (Mathews, 1986). Elevation in the region is variable reflecting the numerous

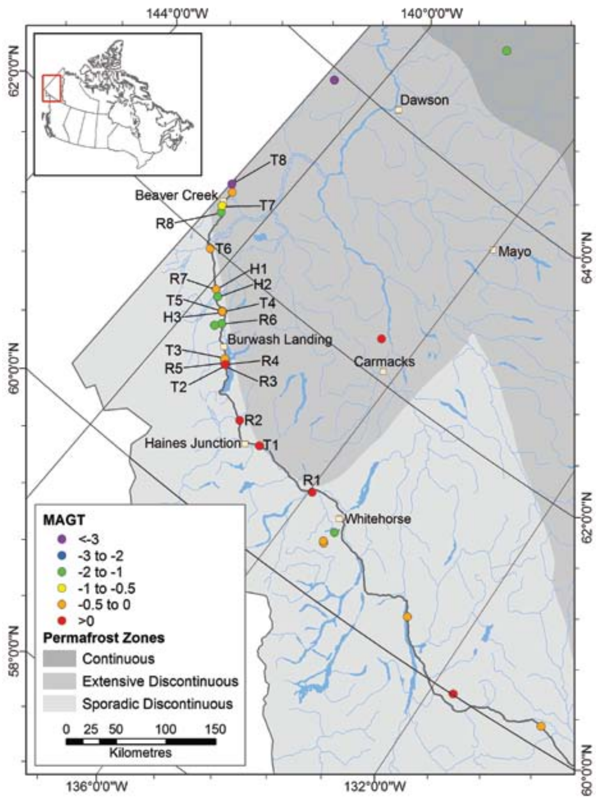

Figure 1. Mean annual ground temperature (MAGT) measured at or near zero annual amplitude depth in boreholes in the central and southern Yukon. Permafrost zones from Heginbottom et al. (1995).

mountains, valleys and plateaus. However the highway corridor itself, which follows the major valley systems, is less variable in elevation. Most of the region was glaciated during the Last Glacial Maximum although some areas around Beaver Creek remained ice-free. (Rampton 1969, 1971; Duk-Rodkin 1999). The glacial history of the region is described by Rampton (1969, 1971), Fulton (1989), Jackson et al. (1991), Duk-Rodkin (1999) and Bond (2004).

Surficial materials in the study area vary from coarse-grained sands, gravels and tills, associated largely with moraine and outwash deposits, to fine-grained silts and clays associated with alluvial and lacustrine deposits (Clague 1989; Fuller and Jackson 2009). The distribution of terrain types for segments of the corridor between the Alaska border and Whitehorse, based on terrain analysis by Foothills Pipe Lines (1979) is shown in Figure 3. Peat is generally less than 5 m thick and is common in poorly drained areas (Foothills Pipe Lines 1979; Clague 1989). Sediment thickness generally exceeds 10 m in the section of the corridor where the boreholes are located (Foothills Pipe Lines 1979).

The climate in the southern Yukon is subarctic continental, with cold winters and short mild summers (Jackson et al. 1991). Climate data from Environment Canada weather stations between Whitehorse and the Alaska border (Whitehorse, Haines Junction, Burwash

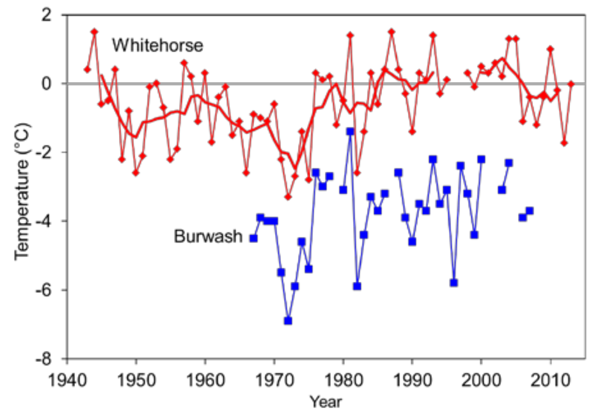

Figure 2. Air temperature records for Whitehorse and Burwash Landing. The 5-year running mean for Whitehorse is shown by the thick line.

and Beaver Creek) can be used to characterize the climate in the Alaska Highway Corridor. Mean annual air temperature (based on 1981-2010 Normals, Environment Canada 2015) ranges from 0.1°C at Whitehorse to -4.9°C at Beaver Creek. Mean January air temperature ranges from -15.5°C at Whitehorse to -25.2°C at Beaver Creek. Mean July temperatures are about 1°C lower at Haines Junction and Burwash compared to Whitehorse and Beaver Creek where they are about 14°C. Mean total annual precipitation is greater in the western portion of the corridor, where it exceeds 400 mm, compared to Whitehorse which receives 260 mm (Environment Canada 2015). The proportion of total precipitation that falls as snow is 30-40%. Examination of the air temperature records for Whitehorse and Burwash Landing (Figure 2) indicates that air temperatures have increased since about 1970. This warming averages about 0.5°C per decade for Whitehorse and 0.4°C per decade for Burwash but the record reveals a step-like increase in the mid 1970s followed by relative slow warming through to the

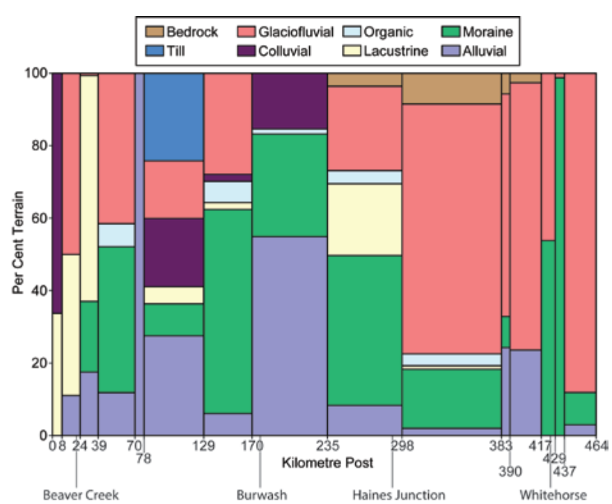

Figure 3. Surficial materials northwestern section of the highway corridor based on information from Foothills Pipe Lines (1979).

early 2000s and slightly lower temperatures over the past 10 years (Figure 2).

The highway corridor is located largely within the sporadic discontinuous permafrost zone (Figure 1, Heginbottom et al., 1995), except for the portion that is within about 50 km of the Alaska border which falls within the extensive discontinuous zone. However, studies done in the 1970s for the proposed pipeline indicate that permafrost is nearly continuous north of Kluane Lake (Foothills Pipelines 1979) and modelling studies by Bonnaventure et al. (2012) also predict continuous permafrost in this area. Permafrost is less abundant south of Kluane Lake, becoming patchy near Whitehorse where it is largely limited to organic terrain (Lewkowicz et al. 2011; James et al. 2013). Observations from geotechnical investigations and ground temperature measurements in the 1970s, indicate that permafrost is generally less than 20 m thick in the corridor and in many places it is less than 10 m thick (Burgess et al. 1982; Smith and Burgess 2002). However, Foothills Pipelines (1979) reported that permafrost thickness exceeds 45 m near the Alaska border and recent surveys utilizing Electrical Resistivity Tomography indicate that permafrost is thicker than 20 m in sections of the corridor between Burwash Landing and the Alaska border (Duguay 2013). Shallow temperature measurements made within the corridor between 1978 and 1981 indicate that mean annual ground temperatures (MAGTs) are generally above -3°C (Burgess et al. 1982).

In summer 2011 several boreholes, along the corridor northwest of Whitehorse, in which GSC had measured ground temperatures between 1978 and 1981 (Burgess et al. 1982) were relocated and instrumented with temperature cables as described by Duguay (2013). Eight boreholes between 5 and 8.8 m deep (R1-R8 in Figure 1) were instrumented with multi-thermistor cables connected to an eight channel RBR datalogger (accuracy and resolution better than ±0.1°C and ±0.01°C respectively). Three shallower boreholes (<3.5 m deep) were instrumented with temperature sensors connected to 4 channel HOBO dataloggers (H1-H3, Figure 1). The accuracy and resolution of this system is better than ±0.2°C and ±0.03°C respectively. In 2013, eight boreholes (acquired from TransCanada Pipelines Ltd.), up to 10 m deep, along the highway easement within about 300 km of the Alaska border were instrumented for temperature measurements (T1-T8 in Figure 1). Six of these were instrumented with multi-sensor cables connected to RBR loggers and two were instrumented with HOBO loggers as described by Smith and Ednie (2013). Full site descriptions for all borehole sites are found in Duguay (2013) and Smith and Ednie (2013). The boreholes complement those at higher elevations in the region.

3 GROUND THERMAL REGIME

Ground temperature envelopes showing the annual range in temperatures at each measurement depth are provided for selected sites in permafrost terrain in Figure 4. The depth of zero annual amplitude (maximum depth of annual temperature variation) ranges from less than 2 m, where permafrost is at temperatures close to 0°C, to greater than 10 m at colder sites or where vegetation cover is less dense. The maximum annual temperature profile indicates that summer thaw depth ranges between 0.8 m to greater than 2 m.

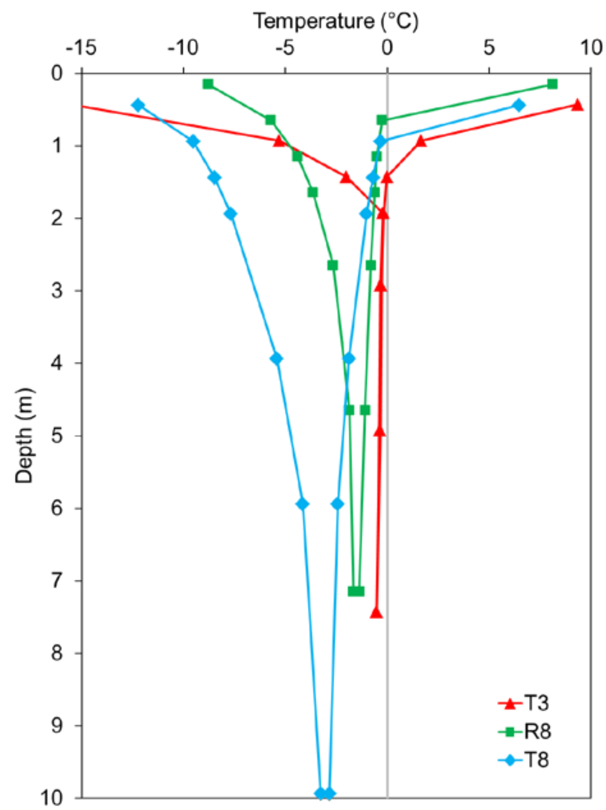

Figure 4. Ground temperature envelopes for three sites in the highway corridor. Envelopes for T3 and T8 are for 2013-14, and that for R8 is for 2012-13.

Mean annual ground temperature profiles for selected sites (Figure 5) show the range in temperatures occurring in the northwestern section of the corridor. Unfrozen conditions exist within the corridor and were found at sites between Whitehorse and Burwash Landing. MAGTs at permafrost sites were generally greater than -1°C but colder conditions were found in the Beaver Creek area near the Alaska border where permafrost temperatures can be as low as -3°C (Smith and Ednie 2015). For most sites, frozen conditions extend below the bottom of the borehole.

Data collected from all field sites along the corridor, including those to the southeast of Whitehorse instrumented as part of other studies (e.g. James et al. 2013), were used to develop a ground temperature transect for the corridor (Figure 6). Permafrost in the section of the corridor to the southeast of Whitehorse was generally at temperatures close to 0°C. James et al. (2013) found that frozen conditions in this area were generally restricted to organic terrain. Colder ground conditions were found to the northwest of Whitehorse, but unfrozen conditions can still exist as was found around Haines Junction. Although ground temperatures generally decrease with decreasing distance from the Alaska

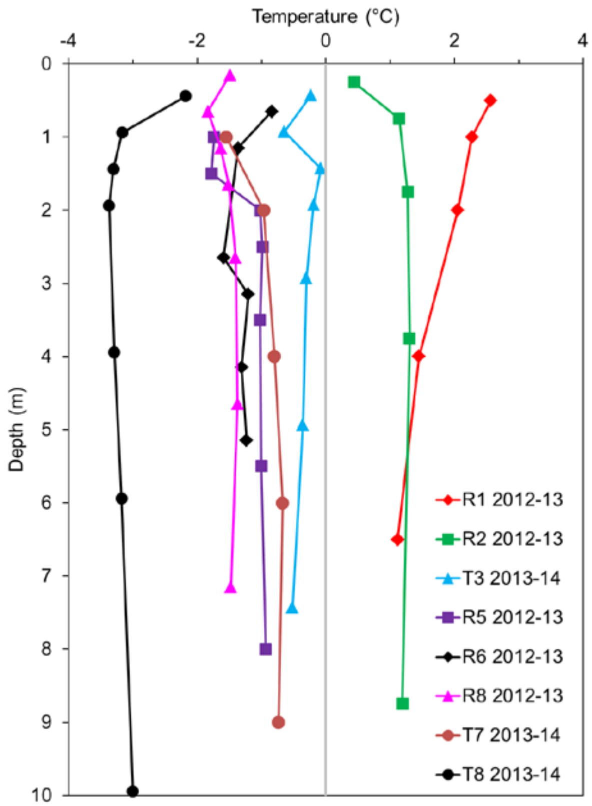

Figure 5. Mean annual ground temperature profiles for selected sites in the highway corridor.

border, a great deal of spatial variability exists that is controlled by local conditions such as vegetation and snow cover. Some of the sites located along the highway easement ("T" sites) have also been disturbed and generally do not have a dense vegetation cover resulting in warmer conditions than might be expected in nearby forested areas which are represented by most of the re-activated sites ("R" sites). The coldest conditions were found in the Beaver Creek area near the Alaska border.

Active layer thickness is variable along the corridor and ranges from less than 1 m to greater than 2 m (Figure 7). Thin active layers (<1 m) were found southeast of Whitehorse. Since frozen ground is largely limited to organic terrain in this portion of the corridor (James et al. 2013), there is adequate insulation to reduce the amount of summer thawing. Thin active layers were also found in the northeast section of the corridor particularly where there is a surface organic layer and peat layer. Active layers thicker than 1 m however were found in this section of the corridor where there was minimal organic layer and limited vegetation, which was the case for some of the easement sites.

4 CHANGE IN PERMAFROST THERMAL STATE

The short ground temperature records available for the boreholes in the corridor are not sufficient to identify long-term trends in permafrost conditions. However comparison of recent measurements in the re-activated boreholes to those made by Burgess et al. (1982) can provide some insights into the changes that have occurred since the 1970s. At sites where permafrost was found to exist in the late 1970s, frozen conditions were still found to exist in 2011 (Duguay et al. 2012).

At the site near Burwash Landing (R3), ground temperatures measured in 1978 and 1979 were lower than the minimum temperatures recorded during 2011-12 below a depth of 4 m (Figure 8A). MAGT in 2011-12 near the zero annual amplitude depth (6.6 m) was -0.7°C compared to a mean temperature measured at a similar depth of -0.9 in 1978-79. These results suggest ground warming of about 0.2°C has occurred in the last three decades. At the colder permafrost site near Beaver Creek (R8), MAGT at 7 m depth (near the zero annual amplitude depth) was -1.5°C in 2012-13 compared to -2.1°C in 1978-79 (Figure 8B) suggesting an increase since the late 1970s of about -0.6°C.

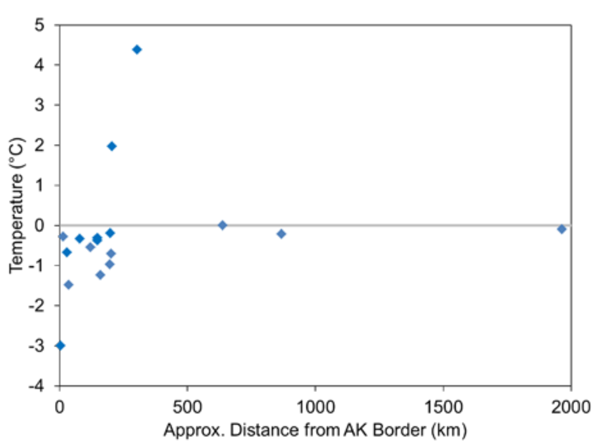

Figure 6. Mean annual ground temperature at or near the zero annual amplitude depth along the corridor.

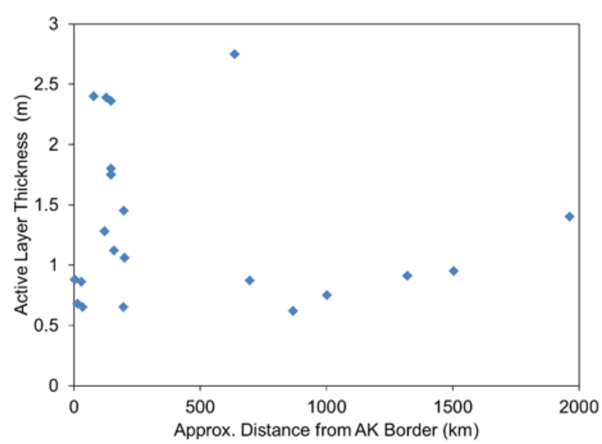

Figure 7. Active layer thickness along the corridor.

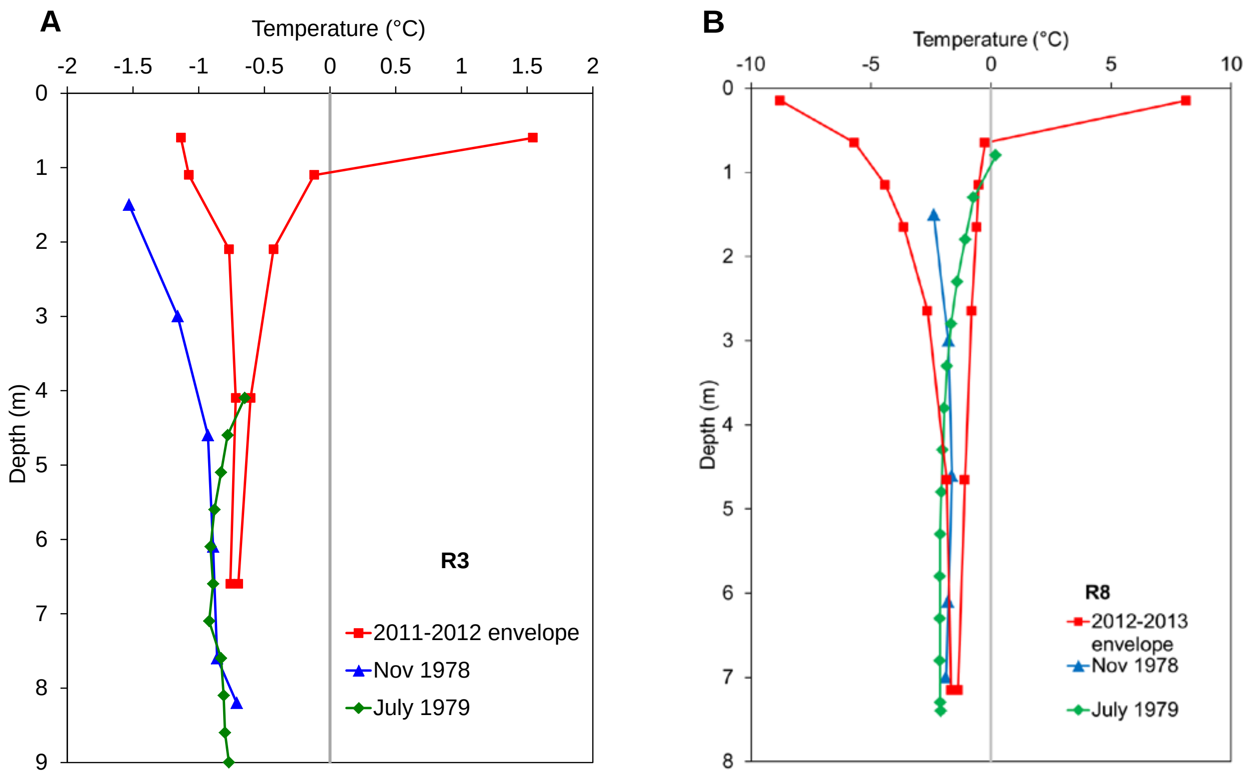

Figure 8. Recent and late 1970s ground temperatures for (A) R3 and (B) R8. Note the difference in the temperature scales between the two graphs.

As mentioned above, air temperature records (Figure 2) indicate a general warming in the region and this may be responsible for the change in ground temperatures over the last three decades. The change in ground temperature for the corridor sites is of a similar magnitude as that observed elsewhere in northwestern Canada such as the Mackenzie Valley, where smaller changes in ground temperature were also observed for warmer permafrost (e.g. Smith et al. 2010). James et al. (2013) report degradation of warm permafrost since the 1960s along the highway corridor between Whitehorse and Fort St. John BC. Complete degradation of permafrost has not occurred over the last 3 decades at any of the borehole sites in the northwestern portion of the corridor.

5 REGIONAL PERMAFROST CONDITIONS

The recent ground thermal data acquired along the highway corridor can be combined with measurements made in other boreholes (including alpine sites) in the central and southern Yukon to provide an improved picture of the thermal state of permafrost for the region (Figure 1). All sites are located in the discontinuous permafrost zone except for one located in the continuous zone. Generally permafrost is warm and at most sites it is at temperatures above -1.5°C, with colder conditions at only a few sites. The spatial variability in permafrost thermal state in this region is complex due to topography as discussed by Smith et al. (2010) and Lewkowicz et al. (2012).

Although there are still spatial gaps in the network of boreholes, our knowledge of permafrost thermal state has improved since the International Polar Year period, prior to which there was limited recent information available. Ground temperature data collected from this borehole network has been compiled and will be summarized in a publicly available database.

6 SUMMARY

Between 2011 and 2013 ground temperature measurements were initiated in numerous boreholes along the northwestern portion of the Alaska Highway Corridor. New information was provided on ground thermal conditions which has facilitated an updated characterization of permafrost thermal state along the corridor. These new data indicate that although permafrost is generally warm, colder permafrost at temperatures of -3°C exists close to the Alaska border. A comparison of recent ground temperatures with those measured in the late 1970s indicated that warming of permafrost has occurred over the last three decades.

The new data acquired from the northwestern portion of the corridor in combination with measurements made at other sites in the central and southern Yukon, are leading to improved knowledge of current regional permafrost conditions. Continued temperature measurements will ensure that updated information is available to support infrastructure planning and also improved predictions of future permafrost conditions required to inform climate change adaptation planning.

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