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doi:10.4095/298769

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Recommended citation
Smith, S.L., Ednie, M. and Chartrand, J., 2016. Ground thermal data collection along the Alaska Highway corridor (KP1559-1895), Yukon, summer 2015; Geological Survey of Canada, Open File 8000, 31 p. doi:10.4095/298769

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ABSTRACT

Ground temperature data were acquired in July 2015 from 13 boreholes along the northwestern section of the Alaska Highway corridor between kilometre post (KP) 1559 and KP 1895 near the Alaska border. Mean annual ground temperatures, determined at or near the zero annual amplitude depth, indicate that permafrost temperature in this section of the corridor is generally above -1°C with colder conditions near the Alaska border where permafrost can be as cold as -3°C. Temperatures measured in the upper 1-2 m indicate that permafrost exists at some sites where surface temperatures are above 0°C and where a sufficient thermal offset exists. Although mean annual air temperature in 2014-15 was higher than in 2013-14, there was no significant difference in the ground temperatures between the two years. The information obtained helps characterize regional permafrost conditions in the southern Yukon and informs climate change impact assessments and adaptation planning.

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INTRODUCTION

The Alaska Highway corridor traverses the discontinuous permafrost zone of the southern Yukon from the Alaska border to northern British Columbia. It is important to have information on current permafrost conditions in order to design new development projects or adapt existing infrastructure to a changing climate. Although a great deal of information on permafrost conditions including its thermal state was collected in the late 1970s to support a pipeline proposal (e.g. Burgess et al. 1982), there is limited information on current ground temperature conditions in the corridor. Changes in permafrost conditions have however, been documented in the corridor and elsewhere in northern Canada (James et al. 2013; Smith et al. 2010). Information on ground thermal conditions is essential to characterize terrain response to construction and operation of infrastructure and to ensure that the integrity of both the infrastructure and the environment is maintained under current and future climates.

To address this lack of current information on permafrost conditions, the Geological Survey of Canada (GSC) has collaborated with university and territorial partners over the last few years to instrument boreholes and collect ground temperature information in the corridor. The GSC acquired, from TransCanada Pipeline Ltd. (TCPL), a suite of cased boreholes located on the Alaska Highway easement between the Alaska border and kilometre poste (KP) 1559 near Haines Junction (Figure 1). In July 2013, these boreholes were instrumented for ground temperature measurements by the GSC in collaboration with the Yukon Department of Highways and Public Works, Yukon Research Centre and Yukon Geological Survey (Smith and Ednie, 2013). This report describes the fieldwork conducted in summer 2015, to collect data from the loggers and provides a summary of the ground thermal data for the 2014-15 period. This report also summarizes data collected in July 2015 from some of the boreholes instrumented in 2011-12 in collaboration with the University of Ottawa (see Duguay, 2013, Smith et al. 2015), including boreholes in which the GSC previously made measurements in the late 1970s and early 1980s.

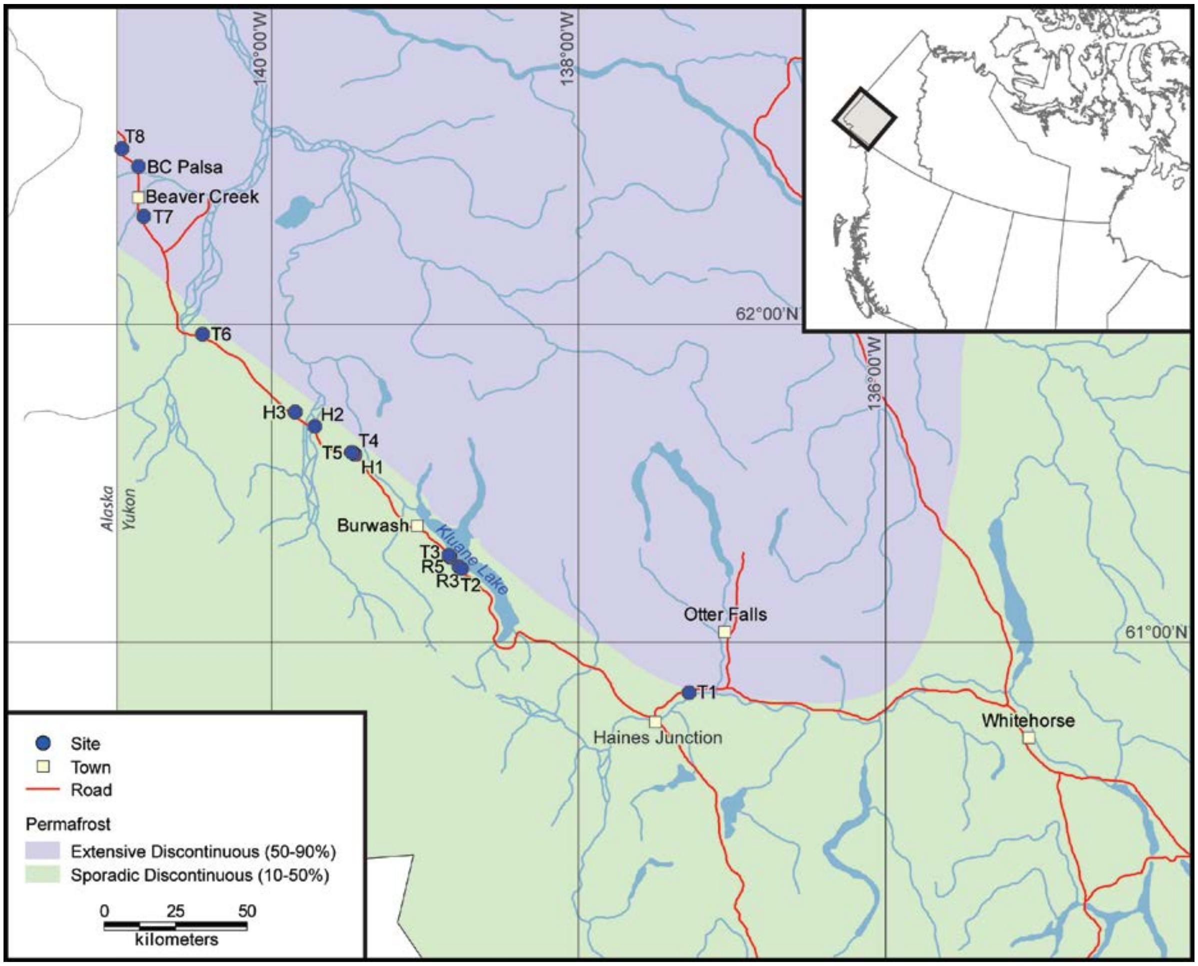


Figure 1. Location of boreholes along the Alaska Highway visited in July 2015, including ones on the easement instrumented in summer 2013 ("T" sites) and other boreholes instrumented in 2011-2012. Permafrost zones (from Heginbottom et al. 1995) are also shown.

STUDY SITES AND INSTRUMENTATION

The field sites are located along the Alaska Highway corridor (Figure 1) between KP1559 and KP1895. The study area is located within the Western 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 mountains, valleys and plateaus. However the highway corridor itself is less variable in elevation than the surrounding area with elevation of the study sites ranging from approximately 600 to 850 m a.s.l. Most of the area has been glaciated although some areas around Beaver Creek remained ice free (Duk-Rodkin 1999; Rampton 1969, 1971). The glacial history of the region is described by Bond (2004), Duk-Rodkin (1999), Fulton (1989), Jackson et al., (1991), Rampton (1969, 1971) and summarized in Smith and Ednie (2013).

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 (Fuller and Jackson, 2009; Clague, 1989). Peat, generally less than 5 m thick is found in poorly drained areas (Clague, 1989; Foothills Pipe Lines, 1979). Sediment thickness generally exceeds 10 m in the section of the corridor where the boreholes are located (Foothills Pipe Lines, 1979). According to terrain analysis presented in the Environmental Impact Statement for the original pipeline application (Foothills Pipe Lines, 1979), peat was observed in about 35% of the terrain in the section of the corridor within 370 km of the Alaska border where the study sites are located.

The climate in the southern Yukon is subarctic continental, with cold winters and short mild summers (Jackson et al., 1991). Climate data are available from Environment Canada weather stations along the corridor between Whitehorse and the Alaska border (Whitehorse, Haines Junction, Burwash and Beaver Creek). Mean annual air temperature (based on 1981-2010 Normals) ranges from -0.07°C at Whitehorse to -4.87°C at Beaver Creek. Mean January air temperature ranges from -15.2°C at Whitehorse to -25.21°C at Beaver Creek. Mean July temperatures are lower at Haines Junction and Burwash (7.24°C and 13.06°C respectively) 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 262 mm. The proportion of total precipitation that falls as snow is 30-40%.

Monthly air temperature for July 2014 to June 2015 is shown for three Environment Canada weather stations in Figure 2. Overall, the mean air temperature for 2014-15 was warmer than normal. Warmer than normal conditions occurred during winter 2014-15. At Burwash Landing for example, the January 2015 air temperature was 2.3°C higher than the normal January temperature of -20.5°C. At Whitehorse, January 2015 temperatures were 3.3°C warmer than the normal January temperature of -15.2°C. Summer air temperatures for 2014-15 were similar to normal, with July 2014 air temperatures being less than 0.2°C higher than normal at Whitehorse and Burwash.

The highway corridor is located largely within the sporadic discontinuous permafrost zone (Figure 1, Heginbottom et al., 1995), except for a portion within about 50 km of the Alaska border that is in the extensive discontinuous zone. Studies done in the 1970s for the Environmental Impact Statement for the proposed pipeline (Foothills Pipelines, 1979) as well as modelling studies by Bonnaventure et al. (2012) also indicate that permafrost is nearly continuous in the area north of Kluane Lake. South of Kluane Lake permafrost is less abundant, becoming patchy near Whitehorse where it is largely limited to organic terrain (James et al, 2013; Lewkowicz et al., 2011). 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, although permafrost thickness exceeds 45 m near the Alaska border. (Burgess et al., 1982; Foothills Pipelines, 1979, Smith and Burgess, 2002). Recent surveys utilizing electrical resistivity tomography also indicate that permafrost is thicker than 20 m in sections of the corridor between Burwash Landing and the Alaska border (Duguay, 2013). Both the earlier ground temperature measurements in the northwest section of the corridor (Burgess et al. 1982) and the more recent measurements (e.g. Smith et al. 2015; Smith and Ednie 2015) indicate that permafrost is generally warm and at temperatures above -3°C.

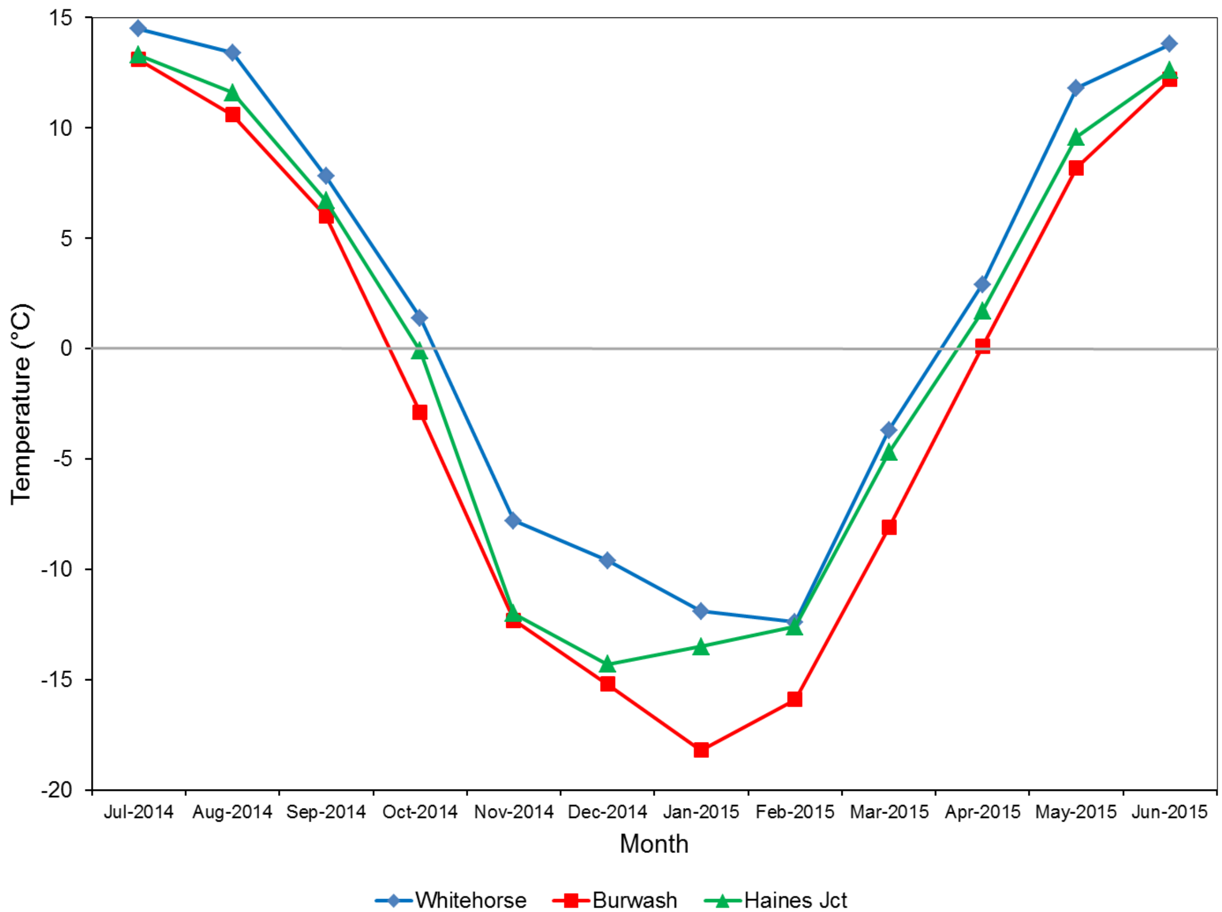


Figure 2. Air temperature for June 2014 to June 2015 for Environment Canada Weather Stations in the corridor.

The locations of the eight boreholes that were acquired from TCPL are shown in Figure 1 and brief site descriptions are provided in Table 1. Boreholes are located on the highway easement, 10 to more than 30 m from the existing highway, with many located in or near previously disturbed areas. See Smith and Ednie (2013) for additional information including site photos.

The cased boreholes were up to 10 m deep and were instrumented with temperature cables in summer 2013 (see Smith and Ednie, 2013 for more details). Multi-thermistor cables (accuracy better than ±0.1°C) attached to eight channel data loggers manufactured by RBR Ltd. (resolution better than ±0.01°C) were installed in six of the boreholes (Table 1). Data loggers recorded temperature measurements at eight hour intervals. Two of the shallower boreholes (AH2013-T1, AH2013-T5) were instrumented with 4-channel HOBO Microstation loggers (manufactured by Onset Corp.) connected to HOBO 12-bit temperature sensors to measure temperatures at four hour intervals. The accuracy and resolution of this system are better than ±0.2°C and ±0.03°C respectively.

Snow depth was measured at two sites (AH2013-T4 and AH2013-T7) using a series of nine Thermochron iButton temperature loggers (accuracy ±1°C) mounted on a wooden stake as described by Smith and Ednie (2013). Snow depths are inferred through analysis of temperature patterns at each height as described by Lewkowicz (2008). Resolution of the system depends on the sensor spacing which is 10 cm.

In 2011-12, GSC collaborated with the University of Ottawa to re-instrument eleven boreholes in the corridor in which the GSC had made ground temperature measurements in the late 1970s and early 1980s (see Duguay, 2013, Smith et al. 2015). These were instrumented with either multi-sensor cables connected to RBR loggers or HOBO microstation loggers. Selected sites adjacent to the easement were visited in July 2015 (Figure 1, Table 2). An additional borehole was instrumented in summer 2011 in a palsa near Beaver Creek (Figure 1, Table 2).

Table 1. Location and description of sites on the highway easement that were instrumented in 2013 and visited in July 2015. Borehole location also shown in Figure 1.

Site	Latitude (°N)	Longitude (°W)	Approx. KP	Site Description	Soil description	Instrumentation
AH2013-T1	60.840	137.278	1559.6	Disturbed area between highway and old road	Silt (<1m) underlain by sand	HOBO logger with sensors installed to 4.95 m
AH2013-T2	61.232	138.762	1681.4	Open area with shrubs on edge of conifer forest	Organic silt (~1 m) over sandy till	RBR logger and multi-thermistor cable installed to 9.67 m
AH2013-T3	61.273	138.847	1687.7	10-15 m from embankment, open area with shrubs, ground cover, hummocky, edge of conifer (black spruce) forest	Organic silt (~1 m) underlain by silt	RBR logger and multi-thermistor cable installed to 7.43 m
AH2013-T4	61.595	139.468	1741.9	Shrub and grass covered area adjacent to open forest	Sand (some gravel) underlain by ice rich silt at 8.5 m depth	RBR logger and multi-thermistor cable installed to 8.36 m iButton (Snow depth measurement).
AH2013-T5	61.598	139.477	1742.6	Shrub and grass covered area on edge of forested area	Organic silt (~1 m) underlain by sand	HOBO logger with sensors installed to 4.85 m
AH2013-T6	61.970	140.452	1812.5	Open area with small conifers, shrubs (re-growth)	Surface organic layer (0.1m), ice-rich silt underlain by sand at 4 m depth	RBR logger and multi-thermistor cable installed to 8.82 m
AH2013-T7	62.340	140.833	1865.3	Open mixed forest	Surface organic layer (5 cm), organic silt to ~1 m depth, Ice-rich silt underlain by till at 6 m depth	RBR logger and multi-thermistor cable installed to 9 m iButton (Snow depth measurement)
AH2013-T8	62.554	140.974	1894.5	Hummocky with small spruce, shrub, willow	Organic layer (0.1 m), peat and ice-rich silt extends to borehole bottom	RBR logger and multi-thermistor cable installed to 9.94 m

Table 2. Location and description of boreholes adjacent to the highway easement that were instrumented in 2011-12 and visited in July 2015. Location also shown in Figure 1.

Site	Latitude (°N)	Longitude (°W)	Approx. KP	Site Description	Soil description	Instrumentation
R3	61.238	138.783	1682.4	Small clearing in forested area, regrowth small spruce and shrubs	Thin peat layer underlain by clay and sand	RBR logger and multi-thermistor cable installed to 6.6 m
R5	61.268	138.842	1686.9	Hummocky, scattered spruce and shrubs	Organic silt (0.5 m) over ice-rich clay and silt	RBR logger and multi-thermistor cable installed to 8 m
H1	61.594	139.463	1768.1	Open bog area (regrown cutline), scattered spruce and shrubs; grass and sedges	Thin peat over organic silt and volcanic ash underlain by sand and gravel	HOBO logger with sensors installed to 2.87 m
H2	61.674	139.730	1760.4	Hummocky, low shrubs, spruce with aspen, birch, sphagnum mosses, grasses (regrown cleared area)	Thin peat underlain by sand and gravel	HOBO logger with sensors installed to 2 m
H3	61.715	139.843	1741.6	Wet area, low shrubs, sphagnum mosses, grasses, sedges	Peat (~1 m) with volcanic ash layer, underlain by clay (ice-rich)	HOBO logger with sensors installed to 2.39 m
Beaver Creek Palsa	62.498	140.861	1884.1	Forested palsa	Ice rich peat	RBR logger and multi-thermistor cable installed to 7.5 m

FIELD WORK CONDUCTED IN SUMMER 2015

Field sites were visited on July 6 and 7 2015. At the boreholes instrumented with RBR loggers (Table 1 and 2), manual measurements of resistance at multi-sensor cables were made using a Fluke Multimeter and later converted to temperatures (system resolution 0.01 – 0.02 K). Live readings of ground temperatures were also made at the HOBO Microstations. Manual readings were utilized to check operation of sensors and loggers and supplement the logger readings (and ensure that at least one record is available if the logger fails). RBR loggers were removed in order to download data and replaced with programmed loggers at some sites while at others, loggers were downloaded in the field. HOBO Microstations were downloaded in the field. The iButton loggers were removed to extract data but were not replaced.

DATA PROCESSING AND PRESENTATION

Data were acquired from seven of the eight loggers installed in the easement boreholes. The RBR logger at T2 failed and only the manual measurement made during the site visit is available. Data acquired from the seven loggers provided an approximately one year record of ground temperature data. Data acquired from the loggers at the six other boreholes adjacent to the highway easement provided an approximately 2-year record of ground temperatures, except for R3 where the logger stopped collecting data in December 2014.

Data records were visually inspected and erroneous data (e.g. data spikes) were removed. Daily mean temperatures were calculated and utilized to determine the annual maximum, minimum and mean temperature for each depth for the July 1 2014 – June 30 2015 period. The annual maximum and minimum temperature profiles define the ground temperature envelope. At permafrost sites the maximum temperature profile may be utilized to determine the maximum thaw depth (i.e. the active layer), while at non-permafrost sites, the minimum annual temperature profile can be used to determine the depth of winter frost penetration. Since monitoring sites were visited in July 2015, active layer and frost depths presented in this publication are for the 2014-2015 period. Thaw and frost depths were determined through extrapolation of the maximum (thaw) or minimum (frost) annual temperatures as described by Riseborough (2008). Monthly mean ground temperatures at each measurement depth were also calculated for each borehole.

The temperature records obtained from the iButton loggers were analysed to determine the daily snow depth at AH2013-T4 and AH2013-T7. The method is based on comparison of temperatures measured in the atmosphere and beneath the snow surface as described by Lewkowicz (2008).

The primary objective of the field work was to visit the easement sites. Detailed data summaries therefore are provided for the eight easement sites ("T" sites) in the Appendix. This includes graphical and tabular summaries of annual maximum and minimum temperature profiles and graphical presentation of monthly mean temperatures for 2014-15.

RESULTS

Ground temperatures measured at the time of the site visit are provided for the highway easement sites in Figure 3A. Permafrost is present at all borehole sites except for T1 and T2. At T2, seasonal frost was still present at a depth of about 1.7 m (note the data record for 2013-14 in Smith and Ednie 2015, confirms that this is seasonal frost). Mean annual ground temperature (MAGT) profiles (Figure 4A) indicate that where permafrost exists it extends below the bottom of the borehole at all sites. In the previous open file (Smith and Ednie, 2015), a permafrost base of about 8 m was reported for T4. However, an error was identified in the measurement depth which has been corrected in this report and frozen conditions extend below the bottom of borehole (8.38 m) at T4. Frozen conditions were also found at the sites adjacent to the easement with permafrost extending to depths greater than 8 m (Figures 3B and 4B).

MAGT profiles show a thermal offset in the upper metre at some of the easement sites, where the MAGT decreases with depth (Figure 4A). The thermal offset (Burn and Smith, 1988) is defined as the difference between the ground surface temperature and temperature at the top of permafrost (TTOP). Although the ground surface temperature is not available for these boreholes, the thermal offsets, based on the difference between the shallowest temperature measurement (~0.5 m or shallower) and the temperature at about 1 m depth (representative of TTOP), are at least 0.5°C at T5, 1.1°C at T3 and 1.3°C at T8. Ground temperature profiles for other sites in the northwest section of the corridor presented by Calmels et al. (2015) also show thermal offsets of a similar magnitude. Assuming equilibrium conditions exists, the thermal offset is due to differences between the thermal conductivity of frozen and unfrozen soils (Romanovksy and Osterkamp, 1995; Riseborough and Smith, 1998).

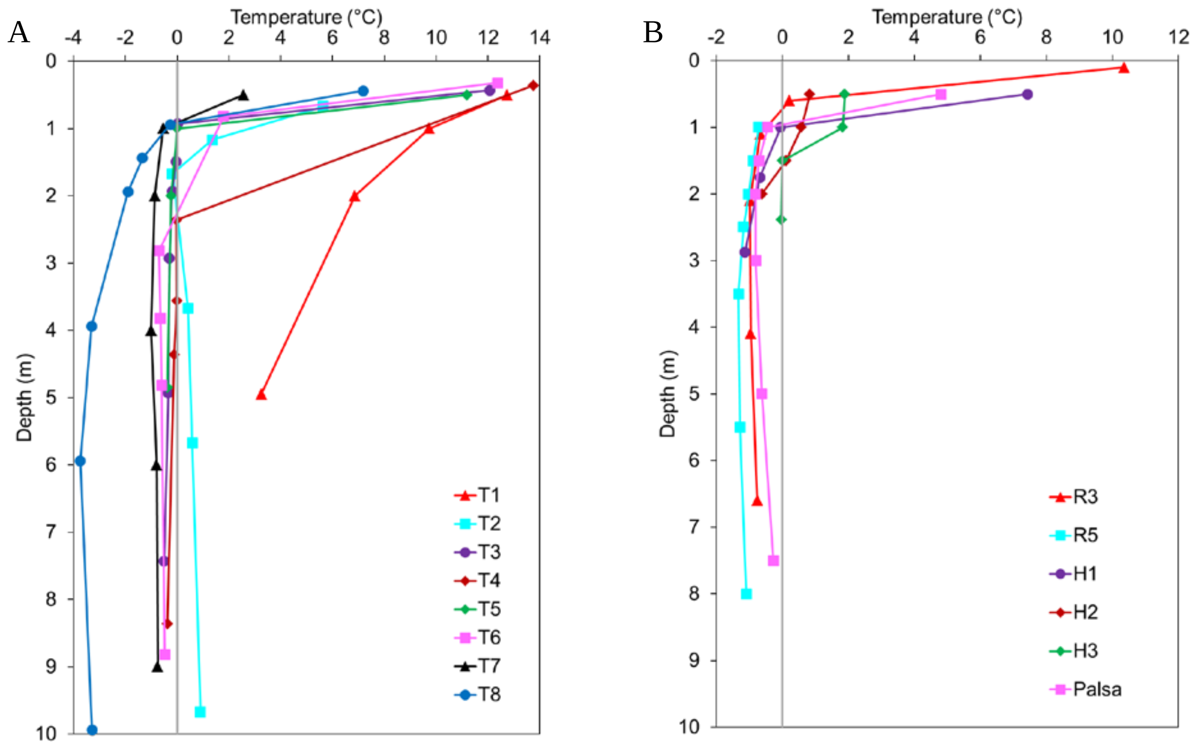


Figure 3. Ground temperatures measured July 6-7 2015 at (A) the highway easement sites and (B) adjacent sites.

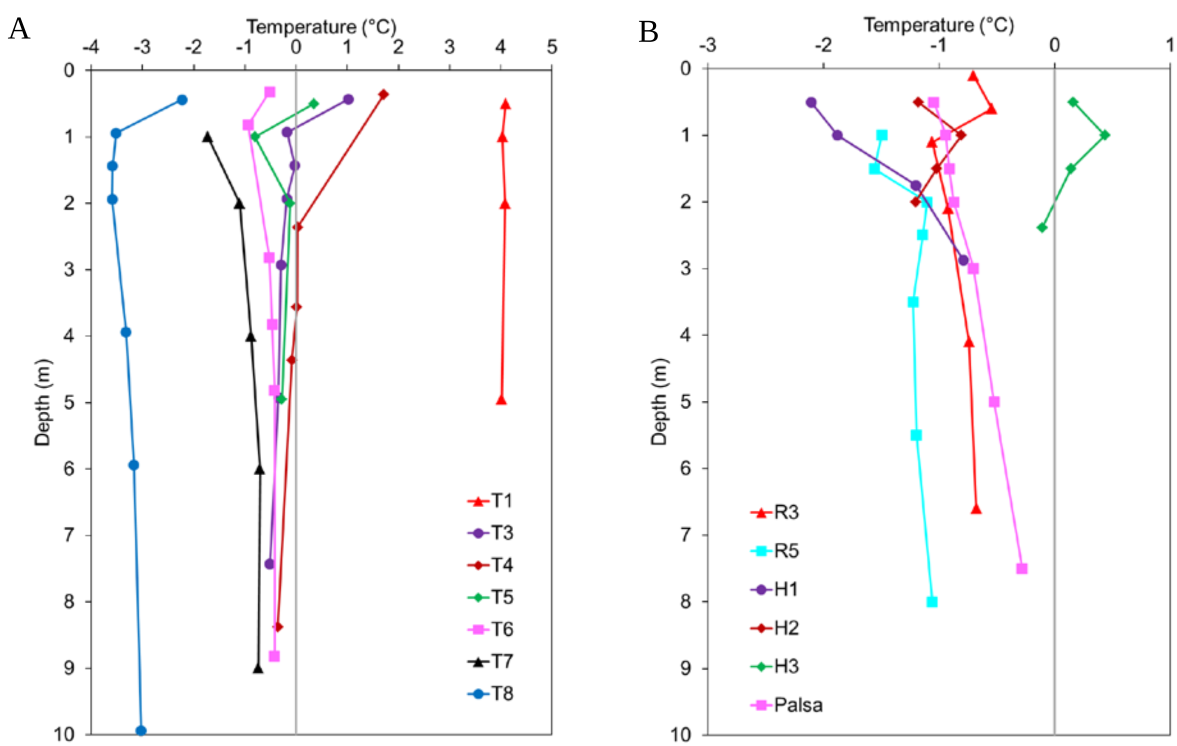


Figure 4. MAGT profiles for 2014-15 for (A) easement and (B) adjacent sites. Note MAGT could not be determined for T2 due to logger malfunction. Profile for R3 is from 2013-14.

Soils in the upper part of the ground (within the active layer) at T3, T5 and T8 are fine-grained or organic and have high moisture contents which means that there is likely a significant difference between frozen and unfrozen thermal conductivity. Since mean annual surface temperatures (based on the shallow MAGT) are above 0°C at T3 and T5 (Figure 4A), the difference between frozen and unfrozen thermal conductivity would appear to be sufficient to maintain permafrost (Riseborough and Smith, 1998). Permafrost conditions at these sites appear to be dependent on the thermal offset and could be classified as ecosystem driven or ecosystem protected (Shur and Jorgenson, 2007). At T4 where surface temperatures also appear to be above 0°C (Figure 4A), the coarse soils within the active layer have a low moisture content, and so a significant difference between frozen and unfrozen thermal conductivity is unlikely. Permafrost may be warming at this site, perhaps due to surface disturbance, and the observed thermal offset may be due to the lag between warming at the surface and at depth. The thermal offset in this case is a result of the presence of permafrost rather than the reason for permafrost existence (James et al. 2013).

The ground temperature envelopes (provided for easement sites in Appendix) can be utilized to determine the depth of zero annual amplitude (ZAA), which for practical purposes, is the depth at which the annual temperature range is less than 0.1°C (Williams and Smith, 1989). At the easement sites, ZAA depth could only be determined for T3, T4, T6 and T7, where it ranged from less than 1.5 m at T3 to 6 m at T7 (Table 3). The ZAA depth at the other easement boreholes was greater than the measurement depth and for T8 where the lowest ground temperatures were observed, ZAA depth exceeds 9.9 m. For the sites adjacent to the easement, borehole depth was not sufficient to determine ZAA depth except at R3 and the palsa site (Table 4).

The MAGT at the ZAA depth has been determined where measurements were made to sufficient depth. For other sites, the MAGT at the deepest measurement depth has been determined. These values are summarized in Tables 3 and 4 for the easement and adjacent sites, respectively. MAGT at ZAA depth (or measurement depth closest to it) for permafrost sites ranges from about -3°C to -0.02°C (Figure 5). MAGT at one of the non-permafrost sites is just above 4°C. Generally the coldest permafrost is found closer to the Alaska border but very warm permafrost (>-0.5°C) can still be found within 50 km of the border (Figure 5). Calmels et al. (2015) also report MAGT of -3°C near the border in the vicinity of T8 with MAGT of -1 to -2°C for other nearby sites.

Table 3. Summary of ground thermal conditions at easement sites. Mean annual ground temperature is near the depth of zero annual amplitude or at deepest measurement depth (indicated by “*” for measurement depth) if depth of ZAA is not reached. Maximum summer thaw depth for permafrost sites or depth of winter frost penetration for non-permafrost sites is also provided. MAGT could not be determined for T2 due to logger malfunction.

Borehole	Mean Annual Temperature (°C)	Measurement Depth (m)	Permafrost Y(es) or N(o)	Thaw (T) Depth or Frost (F) Depth (m)
AH2013-T1	4.02	4.95 *	N	1.09 (F)
AH2013-T2	NA		N	~1.70** (F)
AH2013-T3	-0.02	1.43	Y	0.97 (T)
AH2013-T4	-0.08	4.36	Y	3.64 (T)
AH2013-T5	-0.27	4.95*	Y	2.01 (T)
AH2013-T6	-0.42	4.82	Y	0.95 (T)
AH2013-T7	-0.71	6.0	Y	0.97 (T)
AH2013-T8	-3.02	9.94*	Y	0.93 (T)

**estimated frost depth based on July profile

Table 4. Summary of ground thermal conditions at sites adjacent to the easement (including re-activated sites). Mean annual ground temperature is near the depth of zero annual amplitude or at deepest measurement depth (indicated by “*” for measurement depth) if depth of ZAA is not reached. Maximum summer thaw depth is also provided.

Borehole	Mean Annual Temperature (°C)	Measurement Depth (m)	Thaw Depth (m)
R3	-0.68	6.6	0.69
R5	-1.06	8*	<1.0
H1	-0.79	2.87*	1.05
H2	-1.20	2*	~2.0
H3	-0.11	2.39*	1.58
Beaver Ck Palsa	-0.28	7.5	0.98

Thaw depths at the time of the site visits ranged from about 0.6 m to >2 m (Figure 3). However, the site visits occurred early in the thaw season and these values are not representative of the maximum summer thaw penetration. Estimates of maximum summer thaw depth (or active layer thickness) for 2014 determined using maximum annual ground temperature profiles are summarized in Table 3 and 4 for permafrost sites. Maximum winter frost penetration estimated from minimum annual temperature profiles is also provided for non-permafrost sites. Thicker active layers are generally found along the easement compared to those observed at the adjacent sites which are located in undisturbed conditions with denser vegetation cover. Thaw depths along the northwestern section of the corridor range from 0.6 m to >3 m (Figure 6). There is no apparent spatial pattern but within 100 km of the border, thaw depths are less than 1 m. Organic layers or peat likely limit thaw penetration at these sites.

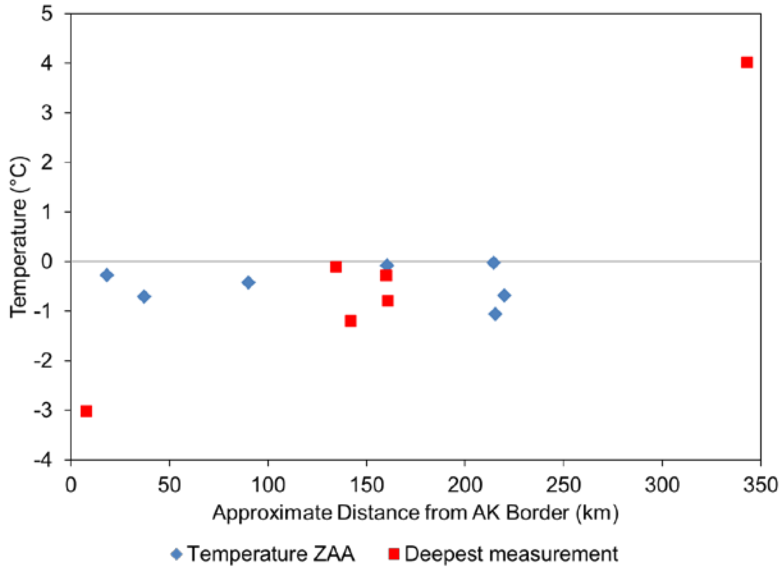


Figure 5. MAGT (2014-15) in the northwest section of the corridor at or near the ZAA depth.

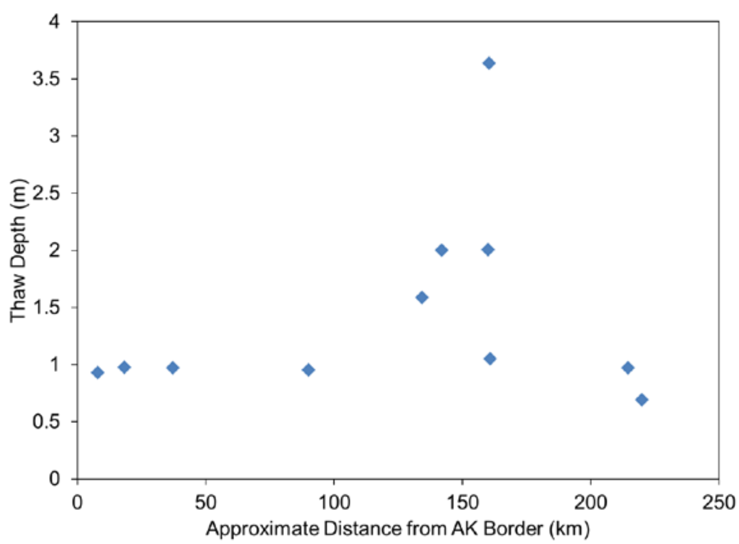


Figure 6. Maximum summer thaw depth (or active layer thickness) in the northwest section of the corridor.

Maximum snow depth for winter 2014-15, based on data acquired from iButtons was 30 cm for both T4 and T7 (Figure 7). However for most of the winter, snow depth at T7 was greater than at T4. Maximum monthly snow depth for T4 was 10 cm from November to March except in January where the maximum monthly depth was 30 cm. Since the resolution of the measurement system is 10 cm the overall difference between snow depths for January and other

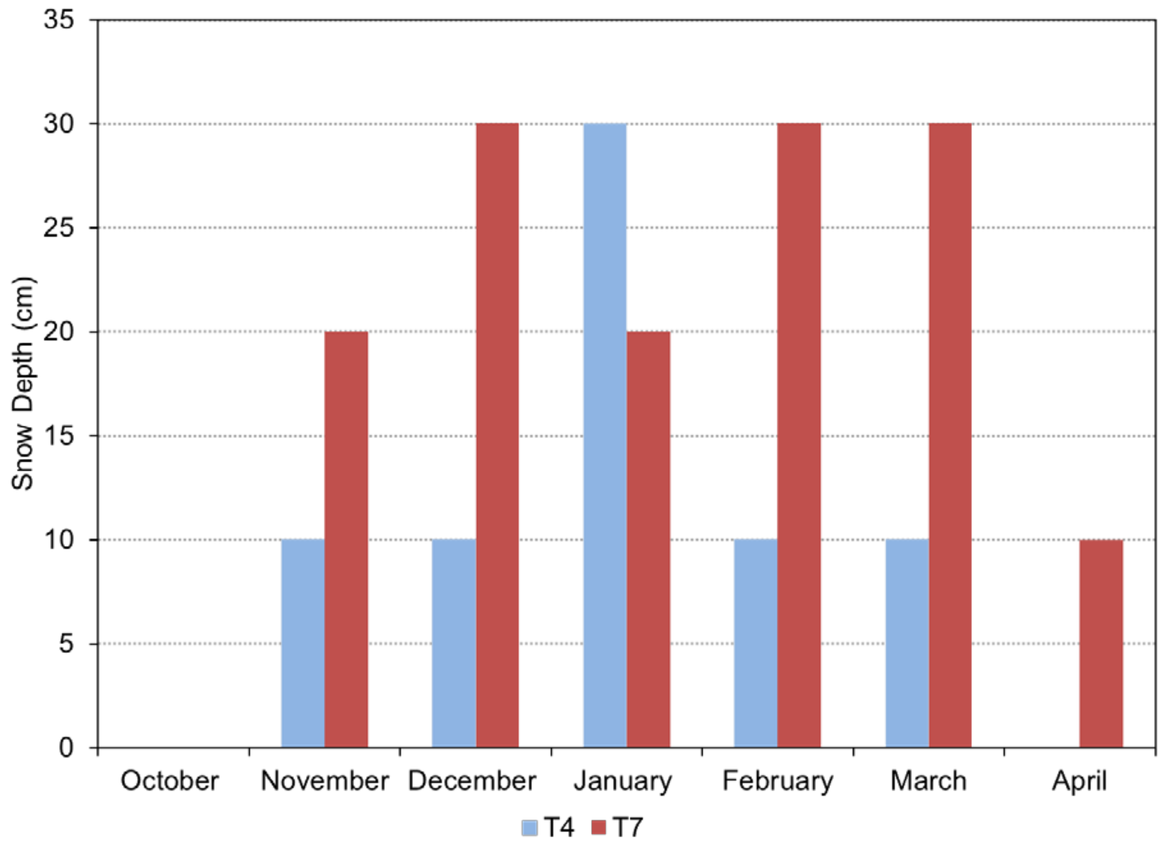


Figure 7. Maximum monthly snow depth at T4 and T7 determined from i-Buttons for the period October 2014 to April 2015.

months may be only a little more than 10 cm. At T7, maximum monthly snow depths were 20-30 cm throughout most of the winter. Maximum snow depths determined for T7 appear to agree with those at the Environment Canada weather station at Beaver Creek (the closest station), where the maximum depth was 36 cm. At Burwash (closest station to T4), snow depths are less than 11 cm throughout the winter which is, similar to T4 except for January. Snow cover appears to have melted completely (i.e. snow cover less than 5 cm) earlier at T4 compared to T7 (Figure 7).

COMPARISON OF 2014-15 AND 2013-14 GROUND TEMPERATURES

Air temperature records for winter 2013-14 indicated that there was a warm period in January 2014 where temperatures rose above 0°C for 3 days at Beaver Creek and 12 days at Burwash and Haines Junction (Smith and Ednie, 2015). Maximum daily air temperatures during January 2014 were as high as 11°C at Beaver Creek. These warm conditions resulted in an increase in shallow ground temperatures in January 2014 at some sites, while at other sites cooling of the ground was delayed (Smith and Ednie, 2015). In winter 2014-15, there was no similar warm period (Figure 2) and shallow ground temperatures at the easement sites gradually decreased during the fall and winter (see Appendix).

Although air temperatures were several degrees higher in January 2014 compared to January 2015 (more than 8°C higher at Burwash for example) overall the winter of 2014-15 was 1 to 3°C warmer than winter 2013-14. However, a comparison of minimum ground temperatures in the upper part of the ground (upper 1-2 m) for 2013-14 and 2014-15 indicates that at some sites ground conditions were warmer in 2014-15 but colder at others (Figure 8). Snow cover will play a role in determining the impact of warmer winter conditions on the shallow ground thermal regime. Snow depth at T4 and T7 was thinner in 2014-15 compared to 2013-14 (Smith and Ednie, 2015) and reduced insulation may be the reason that minimum shallow ground temperatures at both these sites were lower in 2014-15 compared to 2013-14.

Overall mean air temperatures were higher for the 2014-15 period compared to 2013-14. A comparison of MAGT measured at or close to ZAA for the two periods (Figure 9) indicates

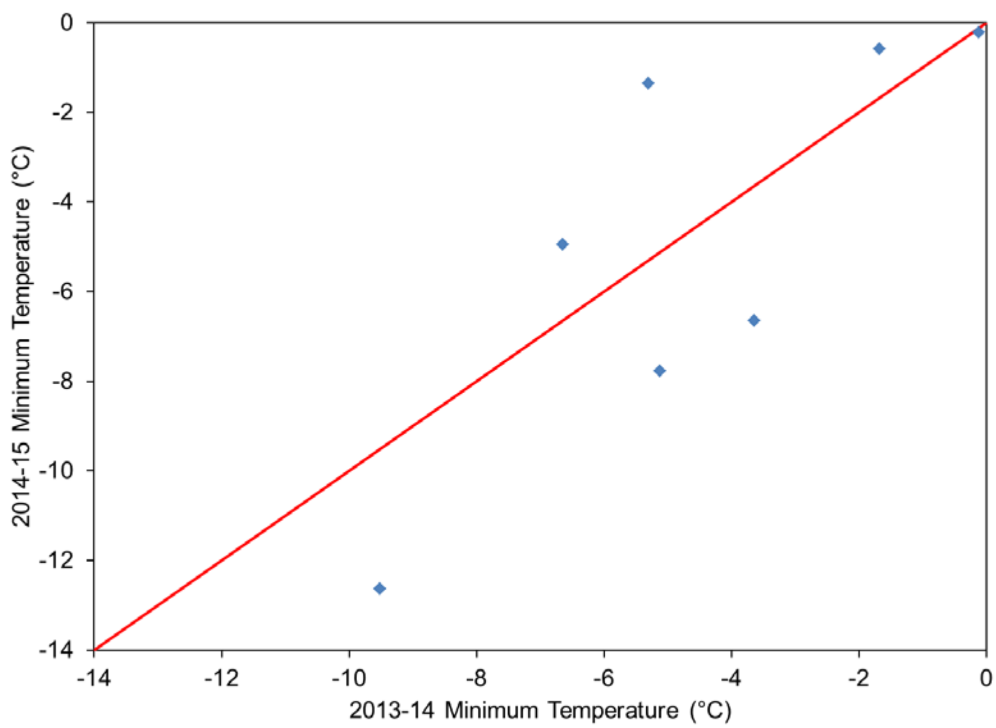


Figure 8. Comparison between 2014-15 and 2013-14 annual minimum ground temperature at 1 to 2 m depth for the easement sites. The 1:1 line is also shown on the graph. Data for 2013-14 from Smith and Ednie (2015).

that the difference in MAGT is less than 0.1°C and for many sites less than 0.05°C. The largest difference is observed at the non-permafrost site T4, where MAGT at 4.95 m depth was 0.36°C higher in 2014-15 compared to 2013-14. However, the measurement depth is above the ZAA depth and annual variations in temperature are almost 2°C. Temperatures at this depth will therefore be more responsive to shorter term fluctuations in air temperature than at greater depth.

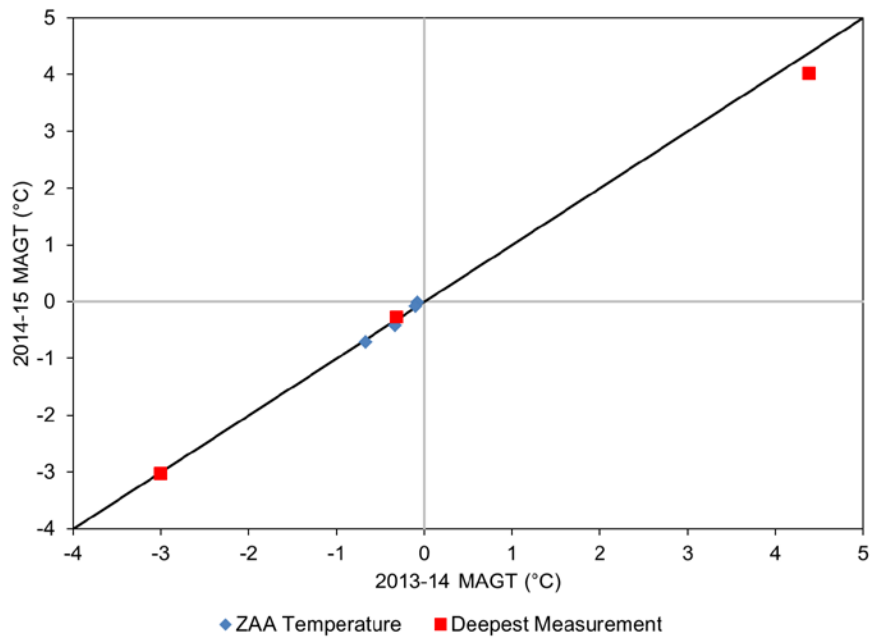


Figure 9. Comparison between 2014-15 and 2013-14 MAGT at or near the ZAA depth. The 1:1 line is also shown on the graph. Data for 2013-14 from Smith and Ednie (2015).

SUMMARY

Ground temperature data were acquired from eight highway easement boreholes and five adjacent boreholes in July 2015. A continuous record of temperatures for the previous year was obtained for almost all of the sites. Permafrost is generally warm between highway kilometre post 1559 and the Alaska border with mean annual ground temperatures at most sites above -1°C. However, colder ground conditions exist at the site closest to the border with MAGT of -3°C. Although mean annual air temperatures were higher in 2014-15 compared to 2013-14, ground temperatures measured at or close to the ZAA depth at permafrost sites in 2014-15 were not significantly different than those recorded in 2013-14.

Shallow (upper 1-2 m) mean ground temperature profiles indicate that at some warm permafrost sites, ground surface temperatures are likely above 0°C. The thermal offset however is sufficient to maintain permafrost at these sites, but permafrost can be considered ecosystem protected or ecosystem driven and may be vulnerable to thawing, especially if the surface is disturbed.

A ground temperature record at least two years long is now available for the easement boreholes and adjacent sites and allows an improved characterization of ground thermal conditions in the northwest section of the Alaska Highway corridor. Continued data collection is planned and this will facilitate documentation of fluctuations in ground temperatures and build up the time series which will support detection of trends in permafrost conditions in the southern Yukon. The public availability of these data can support climate change impact assessments and adaptation planning in the region.

ACKNOWLEDGEMENTS

Field investigations have been supported by Natural Resources Canada and the Program for Energy Research and Development (2011-14). Field sites along the easement are collaboratively maintained with the Yukon Research Centre, Yukon College, who also provide logistical support. Other sites in the corridor were established and maintained in collaboration with the University of Ottawa. Boreholes on the highway easement were drilled by TransCanada Pipeline Limited and we thank them for making the boreholes available to us and the Yukon Department of Transportation and Public Works for allowing us to maintain them. Comments on an earlier version of the manuscript by N. Couture are much appreciated.

REFERENCES

Bond, J. 2004. Late Wisconsinan McConnell glaciation of the Whitehorse map area (105D), Yukon. In Yukon Exploration and Geology 2003. Yukon Geological Survey. pp. 73-88.

Bonnaventure, P.P., Lewkowicz, A.G., Kremer, M., and Sawada, M.C. 2012. A permafrost probability model for the southern Yukon and northern British Columbia, Canada. Permafrost and Periglacial Processes, 23: 52-68.

Burgess, M.M., Judge, A.S. and Taylor, A.E., 1982. Yukon ground temperature data collection - 1966 to August 1981, Earth Physics Branch Open File 82-1, E.M.R., Ottawa.

Burn, C.R., and Smith, C.A.S. 1988. Observations of the “thermal offset” in near-surface mean annual ground temperatures at several sites near Mayo, Yukon Territory, Canada. Arctic, 41(2): 99-104.

Calmels, F., Roy, L.-P., Laurent, C., Pelletier, M., Kinnear, L., Benkert, B., Horton, B., and Pumple, J. 2015. Vulnerability of the North Alaska Highway to Permafrost Thaw: A Field Guide and Data Synthesis, Northern Climate ExChange, Yukon Research Centre, Whitehorse, Yukon.

Clague, J.J. (compiler), 1989. Quaternary geology of the Canadian Cordillera. In Chapter 1, Quaternary Geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, no. 1. pp. 17-95.

Duguay, M.A. 2013. Permafrost changes along the Alaska Highway Corridor, southern Yukon, from ground temperature measurements and DC electrical resistivity tomography. M.Sc. Thesis, University of Ottawa, Ottawa. 335 pp.

Duk-Rodkin, A. 1999. Glacial limits map of Yukon Territory. Geological Survey of Canada Open file 3694, Indian and Northern Affairs Canada Geoscience Map 1999-2.

Environment Canada 2015. National climate data archive http://climate.weather.gc.ca/ (Accessed 29-01-2015).

Foothills Pipe Lines (South Yukon) Ltd. 1979. Environmental Impact Statement for the Alaska Highway Gas Pipeline.

Fuller, T. and Jackson, L. 2009. Quaternary Geology of the Yukon Territory, Yukon Geological Survey.

Fulton, R.J. 1989. Quaternary Geology of Canada and Greenland. In Geology of Canada. Geological Survey of Canada, p. 839.

Heginbottom, J.A., Dubreuil, M.-A., and Harker, P.A. 1995. Canada – Permafrost. National Atlas of Canada, 5th Edition Ottawa: Geomatics Canada, National Atlas Information Service, and Geological Survey of Canada, Plate 2.1 (MCR 4177).

Jackson, L.L., Ward, B., Duk-Rodkin, A., and Hughes, O.L. 1991. The last Cordilleran ice sheet in southern Yukon Territory. Géographie physique et Quaternaire, 45: 341-354.

James, M., Lewkowicz, A.G., Smith, S.L., and Miceli, C.M. 2013. Multi-decadal degradation and persistence of permafrost in the Alaska Highway corridor, northwest Canada. Environmental Research Letters, 8 045013. Doi: 10.1088/1748-9326/8/4/045013

Lewkowicz, A.G. 2008. Evaluation of miniature temperature-loggers to monitor snowpack evolution at mountain permafrost sites, northwestern Canada. Permafrost and Periglacial Processes, 19: 323-331.

Lewkowicz, A.G., Etzelmuller, B. and Smith, S.L., 2011. Characteristics of discontinuous permafrost from ground temperature measurements and electrical resistivity tomography, southern Yukon, Canada. Permafrost and Periglacial Processes, 22: 320-342.

Mathews, W.H. 1986. Physiographic map of the Canadian Cordillera. Geological Survey of Canada Map 1701A.

Rampton, V.N. 1969. Pleistocence geology of the Snag-Klutlan area, southwestern Yukon Territory, Canada, Ph.D. Thesis, University of Minnesota. 237 pp.

Rampton, V.N. 1971. Late Pleistocene glaciations of the Snag-Klutlan area, Yukon Territory. Geological Society of America Bulletin, 82: 959-978.

Romanovsky, V.E., and Osterkamp, T.E. 1995. Interannual variations of the thermal regime of the active layer and near-surface permafrost in northern Alaska. Permafrost and Periglacial Processes, 6: 313-315.

Riseborough, D.W., and Smith, M.W. 1998. Exploring the limits of permafrost. In Proceedings of Seventh International Conference on Permafrost. Yellowknife, Canada. June 1998. Collection Nordicana Vol. 57, pp. 935-941.

Riseborough, D.W. 2008. Estimating active layer and talik thickness from temperature data: implications from modeling results. In Ninth International Conference on Permafrost. Edited by D.L. Kane and K.M. Hinkel. Fairbanks, Alaska. Institute of Northern Engineering, University of Alaska Fairbanks, Vol. 2, pp. 1487-1492.

Shur, Y.L., and Jorgenson, M.T. 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes, 18: 7-19.

Smith, S.L. and Burgess, M.M., 2002. A digital database of permafrost thickness in Canada, Geological Survey of Canada Open File 4173.

Smith, S.L., and Ednie, M. 2013. Preliminary Ground Thermal Data from Field Sites Established Summer 2013 along the Alaska Highway Easement, Yukon Territory, Geological Survey of Canada Open File 7507. DOI: 10.4095/293314

Smith, S.L., and Ednie, M. 2015. Ground thermal data collection along the Alaska Highway easement (KP 1559-1895) Yukon, summer 2014, Geological Survey of Canada Open File 7762. DOI: 10.4095/295974

Smith, S.L., Lewkowicz, A.G., Ednie, M., Duguay, M.A., and Bevington, A. 2015. Characterization of permafrost thermal state in the southern Yukon. Paper 331. In

GEOQuébec 2015 (68th Canadian Geotechnical Conference and 7th Canadian Conference on Permafrost). Québec. GEOQuébec 2015 Organizing Committee.
Smith, S.L., Romanovsky, V.E., Lewkowicz, A.G., Burn, C.R., Allard, M., Clow, G.D., Yoshikawa, K., and Throop, J. 2010. Thermal state of permafrost in North America - A contribution to the International Polar Year. Permafrost and Periglacial Processes, 21: 117-135.
Williams, P.J., and Smith, M.W. 1989. The Frozen Earth: fundamentals of geocryology. Cambridge University Press, Cambridge, U.K. 306 pp.

APPENDIX
Detailed data summaries for boreholes on the highway easement

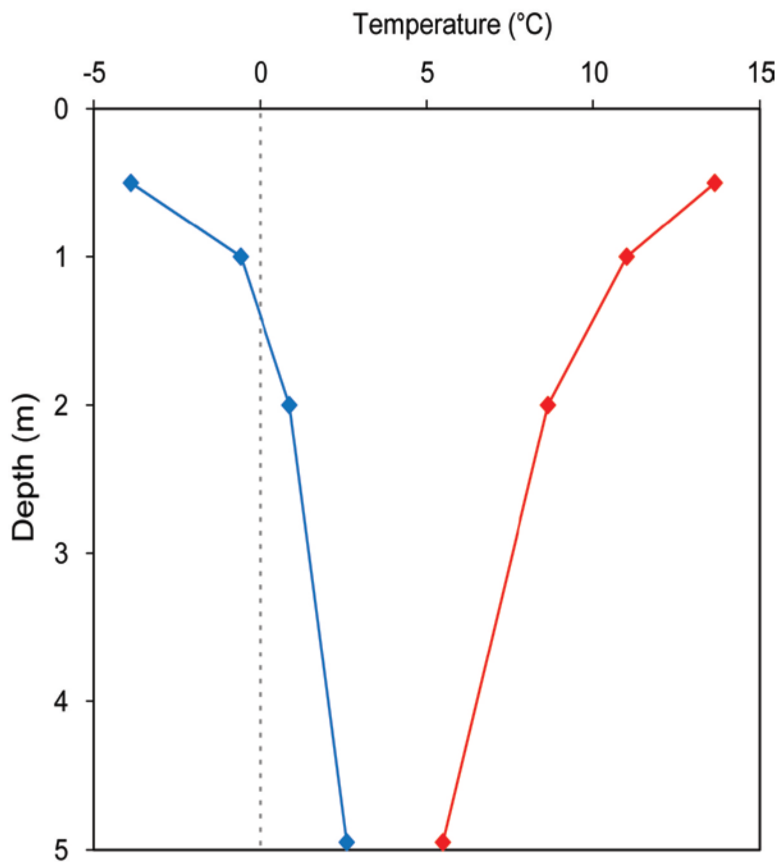
For each site the following are provided:

- Graphical and tabular presentation of ground temperature envelopes for the July 1 2014 – June 30 2015 period (annual maximum and minimum ground temperatures).
- Graphical presentation of monthly mean ground temperatures for 2014-15.

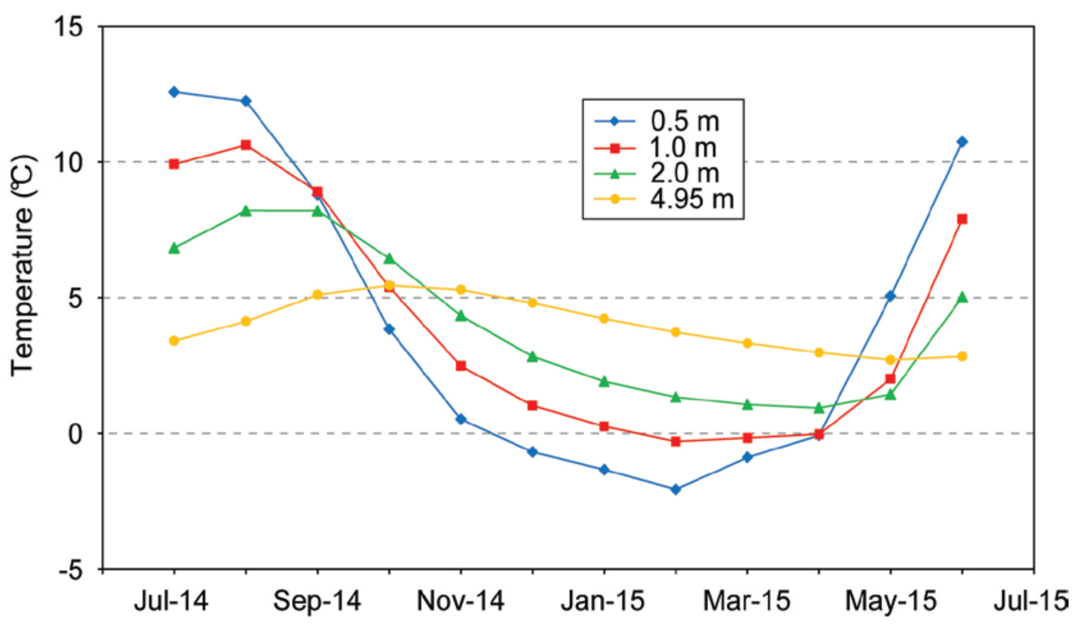
Thaw depths provided for permafrost sites are determined from shallow maximum annual ground temperatures. Seasonal frost depths at non-permafrost sites are determined from shallow annual minimum ground temperatures.

Information on terrain type was determined from:
Lipovsky, P.S. and Bond, J.B. 2014. Yukon digital surficial geology compilation, digital release 1, 08-Apr-2014. Yukon Geological Survey.
http://www.geology.gov.yk.ca/digital_surficial_data.html

AH2013-T1
Moraine, undulating
Latitude: 60.840 N Longitude: 137.278 W
Elevation: 686 m a.s.l.
Max Frost Depth: 1.09 m

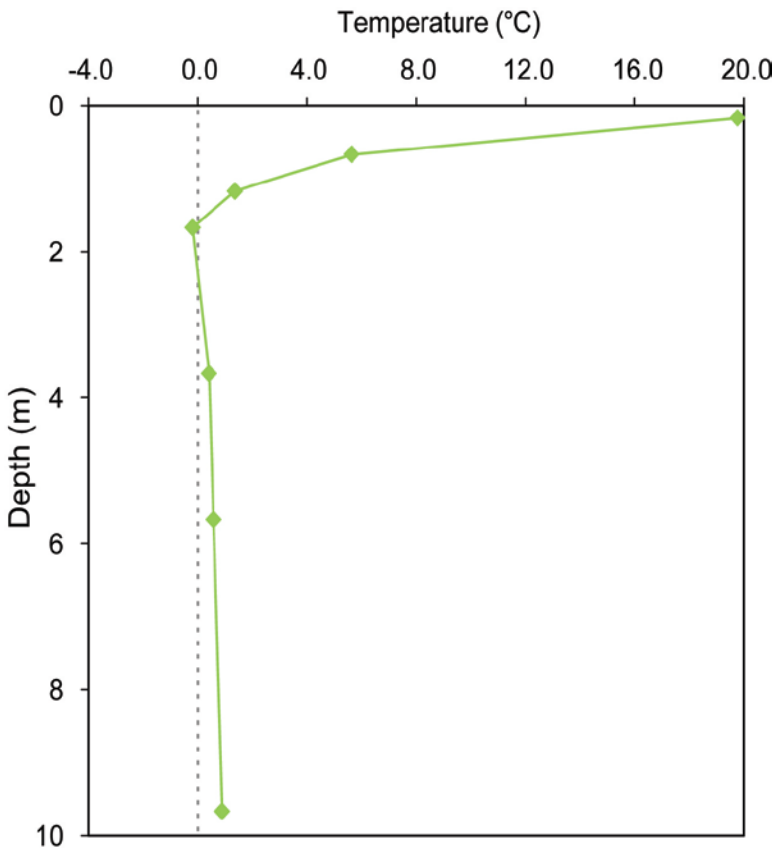


Depth (m)	Temperature (°C) Max	Min
0.5	13.65	-3.88
1.0	11.01	-0.58
2.0	8.65	0.88
4.95	5.48	2.61



AH2013-T2

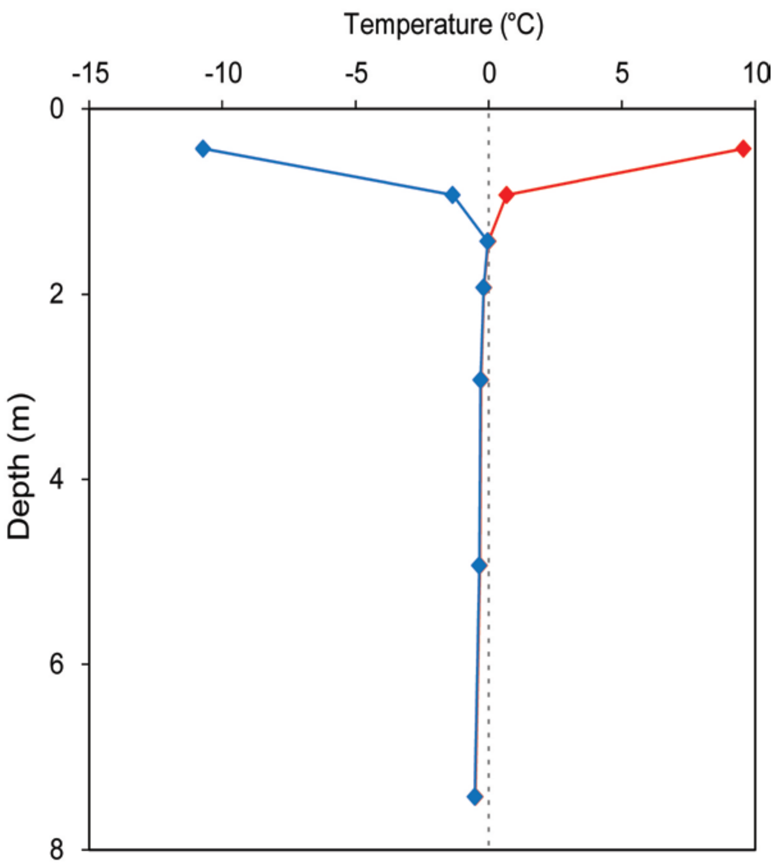
Moraine plain
Latitude: 61.232 N   Longitude: 138.762 W
Elevation: 841 m a.s.l.
Seasonal frost depth: ~1.7 m (based on July 6 2015 ground temperature profile).
Note: Logger malfunctioned and only manual temperature measurements on July 6 2015 were available.



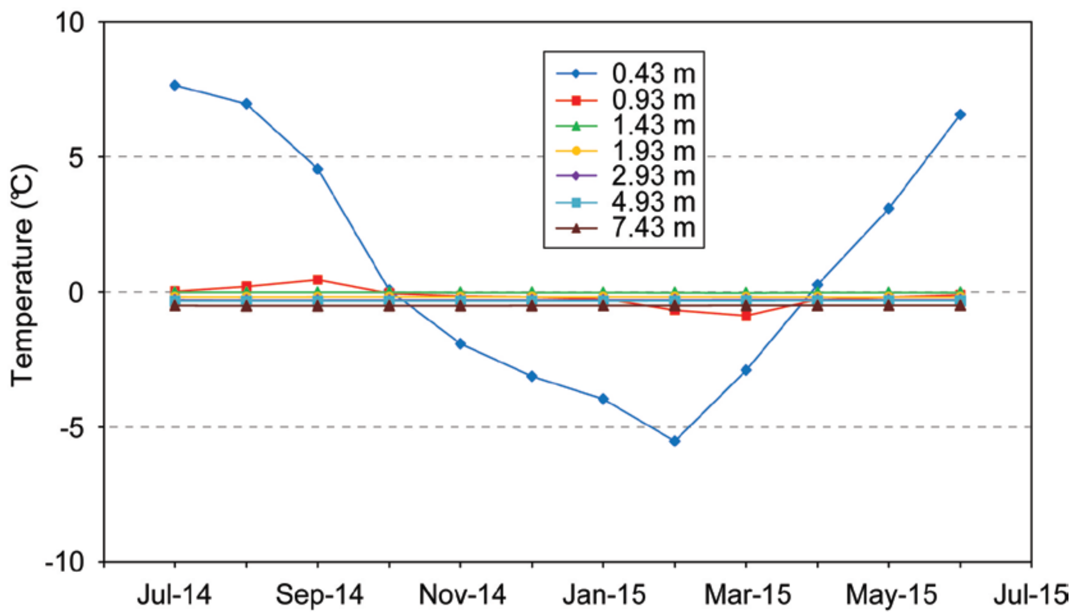
Depth (m)	Temperature (°C)
0.17	19.77
0.67	5.64
1.17	1.36
1.67	-0.18
3.67	0.42
5.67	0.58
9.67	0.9

AH2013-T3

Alluvial fan
Latitude: 61.273 N　　Longitude: 138.847 W
Elevation: 833 m a.s.l.
Max Thaw Depth: 0.97 m

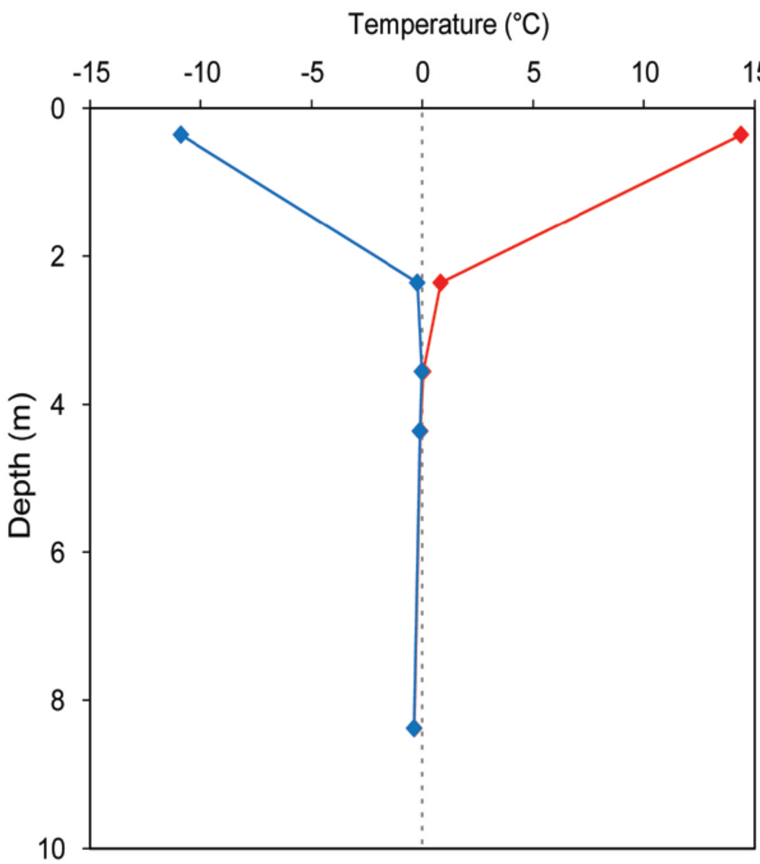


Depth (m)	Temperature (°C) Max	Min
0.43	9.56	-10.71
0.93	0.67	-1.35
1.43	-0.01	-0.04
1.93	-0.17	-0.19
2.93	-0.28	-0.30
4.93	-0.33	-0.35
7.43	-0.50	-0.52

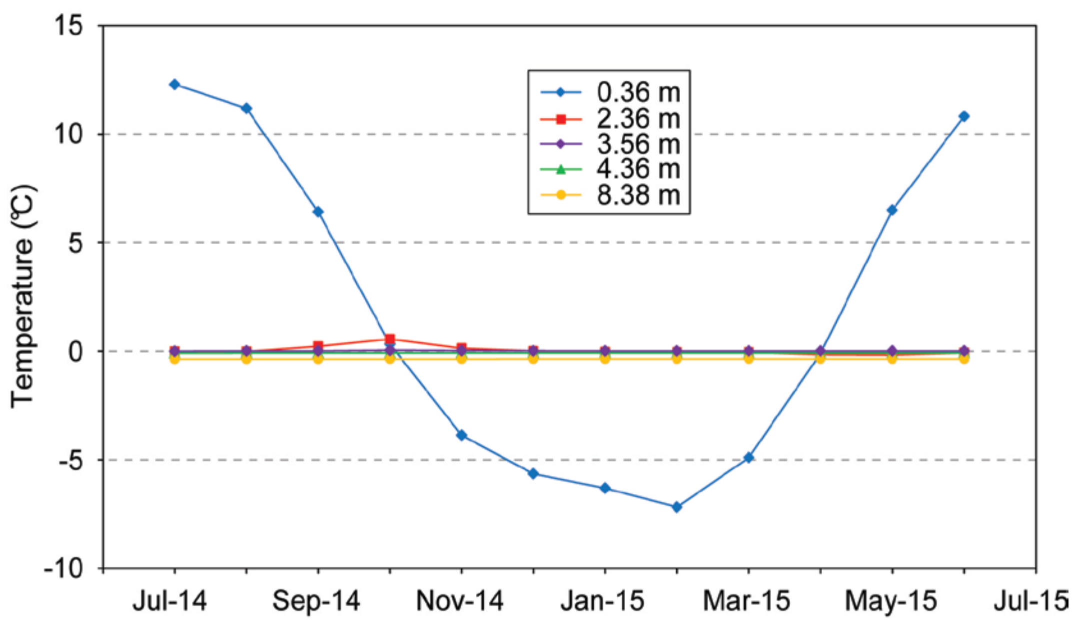


AH2013-T4

Moraine
Latitude: 61.595 N   Longitude: 139.468 W
Elevation: 783 m a.s.l.
Max Thaw Depth: 3.64 m

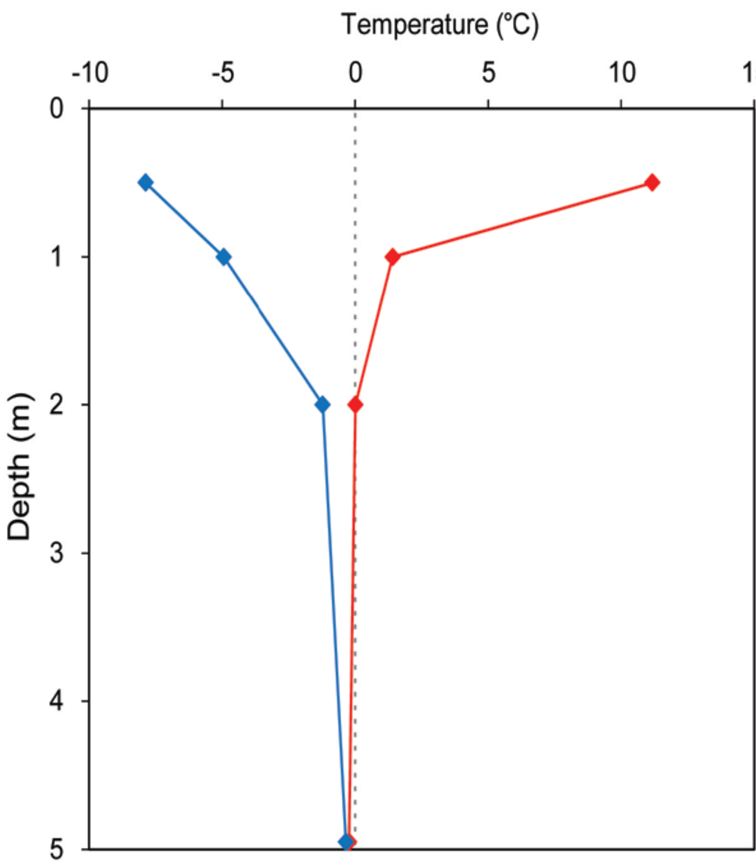


Depth (m)	Temperature (°C)	
	Max	Min
0.36	14.38	-10.90
2.36	0.84	-0.21
3.56	0.05	-0.01
4.36	-0.08	-0.09
8.38	-0.35	-0.36

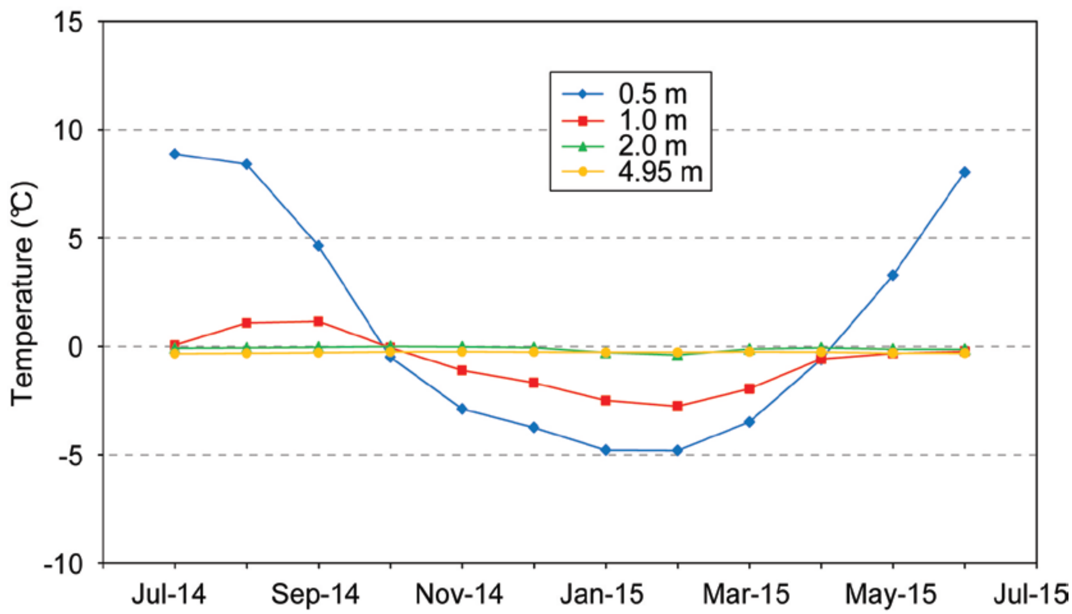


AH2013-T5

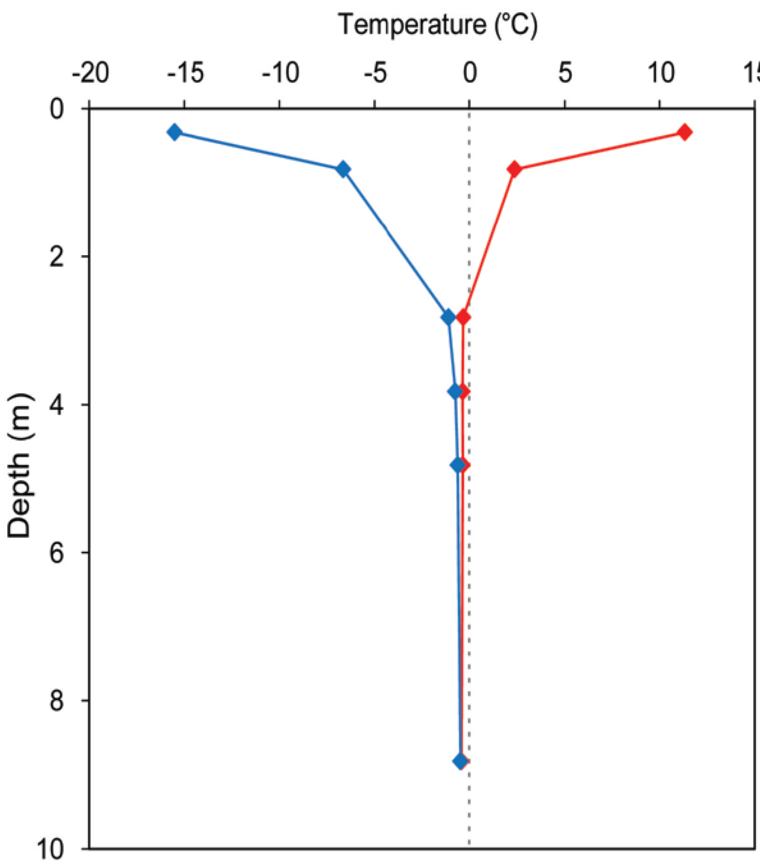
Moraine
Latitude: 61.598 N Longitude: 139.477 W
Elevation: 747 m a.s.l.
Max Thaw Depth: 2.01 m



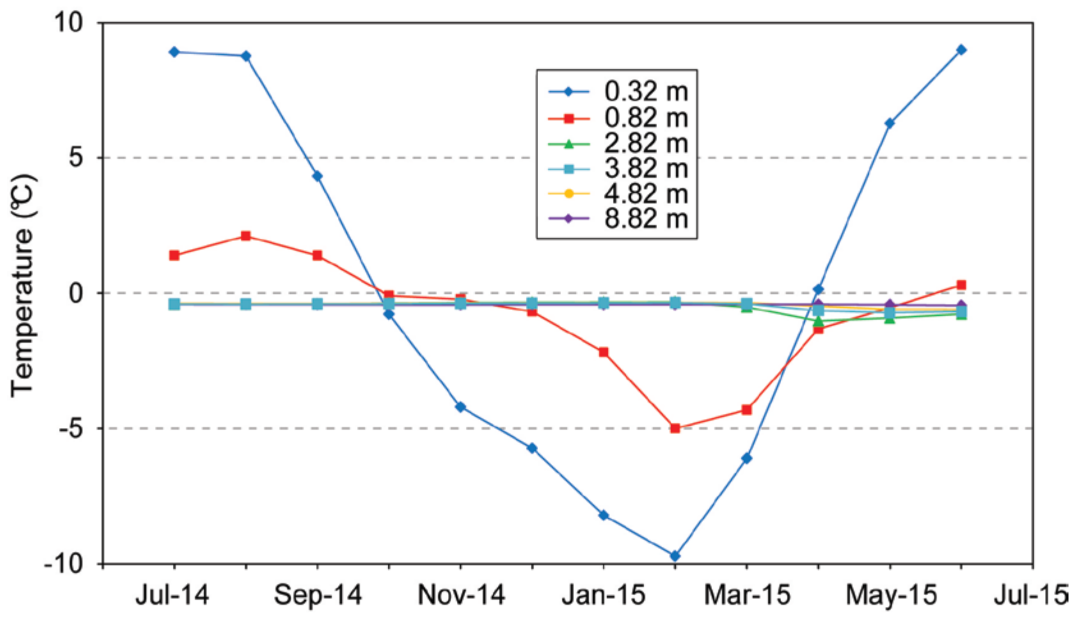
Depth (m)	Temperature (°C)	
	Max	Min
0.5	11.18	-7.87
1.0	1.41	-4.94
2.0	0.01	-1.21
4.95	-0.22	-0.34



AH2013-T6
Alluvial terrace
Latitude: 61.970 N Longitude: 140.452 W
Elevation: 672 m a.s.l.
Max Thaw Depth: 0.95 m



Depth (m)	Temperature (°C)	
	Max	Min
0.32	11.34	-15.52
0.82	2.38	-6.65
2.82	-0.32	-1.09
3.82	-0.35	-0.73
4.82	-0.34	-0.61
8.82	-0.41	-0.46



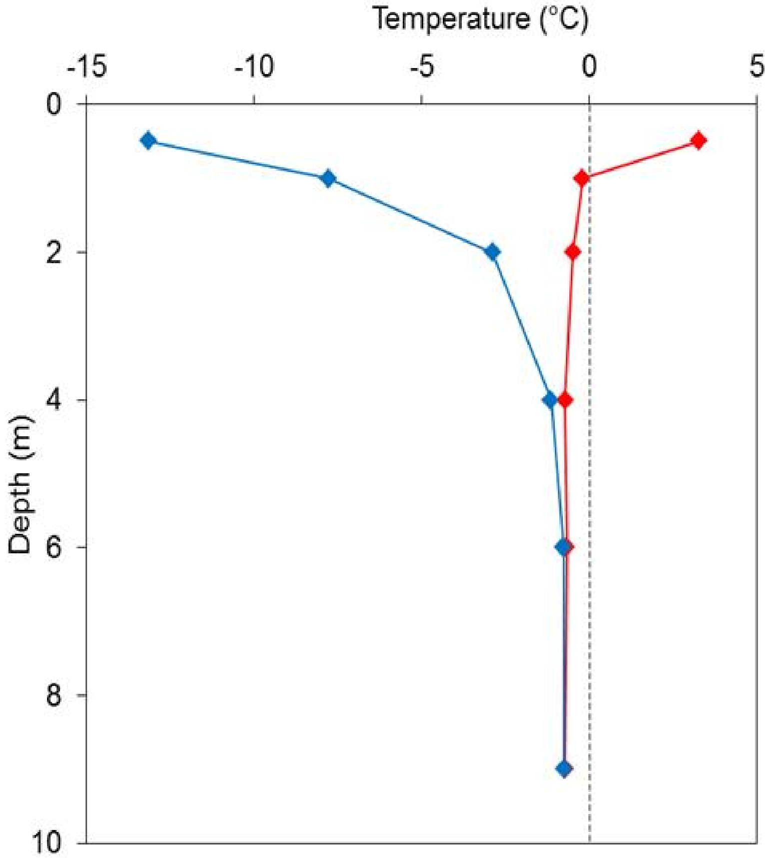
AH2013-T7

Moraine

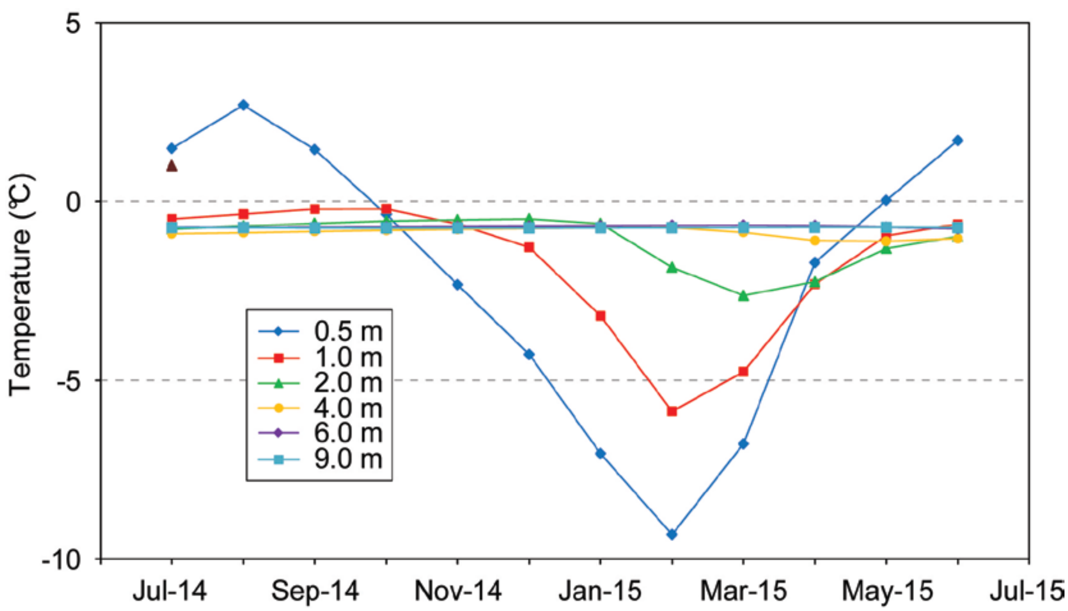
Latitude: 62.340 N   Longitude: 140.833 W

Elevation: 701 m a.s.l.

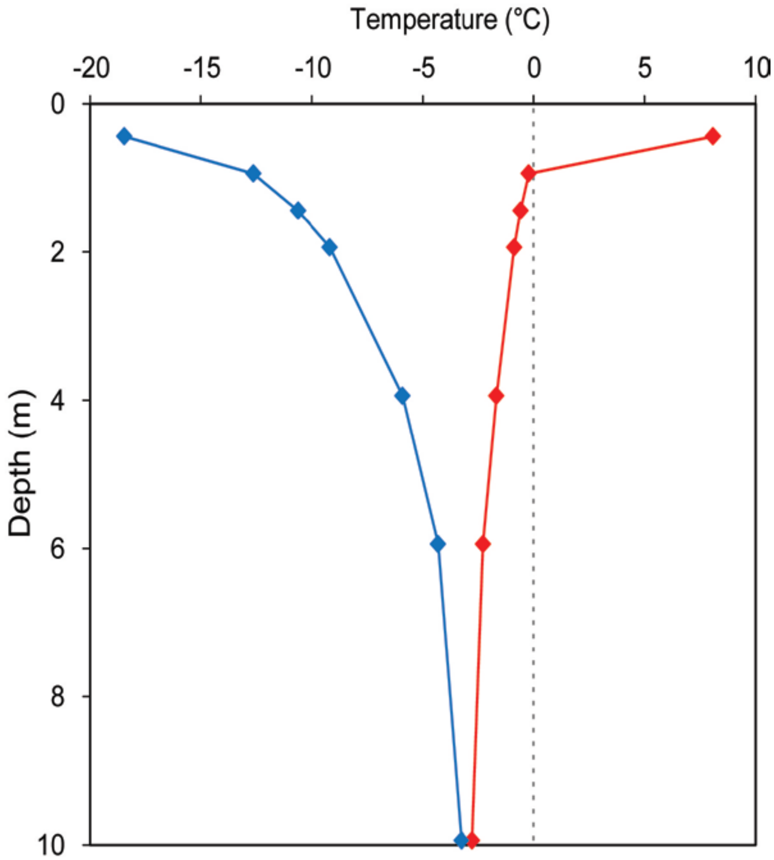
Max Thaw Depth: 0.97 m



Depth (m)	Temperature (°C) Max	Min
0.5	3.26	-13.13
1.0	-0.19	-7.77
2.0	-0.48	-2.88
4.0	-0.72	-1.15
6.0	-0.66	-0.77
9.0	-0.72	-0.75



AH2013-T8
Alluvial plain
Latitude: 62.554 N   Longitude: 140.974 W
Elevation: 610 m a.s.l.
Max Thaw Depth: 0.93 m



Depth (m)	Temperature (°C) Max	Min
0.44	8.08	-18.45
0.94	-0.22	-12.64
1.44	-0.59	-10.63
1.94	-0.87	-9.18
3.94	-1.67	-5.91
5.94	-2.27	-4.32
9.94	-2.77	-3.26