Vulnerability of the North Alaska Highway to Permafrost Thaw

A Field Guide and Data Synthesis

Northern Climate ExChange
YUKON RESEARCH CENTRE • Yukon College

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Contents

1. Introduction

Yukon, Alaska and northern British Columbia depend heavily on road transportation to link communities and connect industrial activities to international markets. The Alaska Highway is the central transportation corridor in Yukon. It is crucial to maintaining and expanding economic development, the quality of life of the population and international ties.

In the context of current and anticipated climate change, permafrost temperature has warmed significantly in northern territories and is expected to continue to rise (SNAP 2014). The stability of northern transportation infrastructure may be compromised by changes in permafrost, particularly in areas where the soil contains large amounts of ice. This may lead to negative impacts on economic development, including increasing the complexity and cost of road maintenance and the price of shipping goods in the North.

This report can be used to support decisions regarding road maintenance and future measures to mitigate permafrost thaw. Northern Climate ExChange (NCE) has partnered with Yukon's Highways and Public Works (HPW) to assess the vulnerability of the Alaska Highway to permafrost thaw along a 200-km section between Burwash Landing and the Yukon/Alaska border. Since its construction, this section of highway has been affected by permafrost thaw. The communities of Burwash Landing and Beaver Creek, as well as the traditional territories of White River First Nation and Kluane First Nation, are adjacent to the highway. All the people in the area depend on reliable access to transportation infrastructure to support their livelihoods.

1.1 Context

The Alaska Highway between Burwash Landing and the Yukon/Alaska border is underlain by extensive discontinuous, warm and frequently ice-rich permafrost. The disturbance caused by construction of the road and climate warming has already led to the thawing of permafrost, which has had an impact on the road. Some sections of the highway have experienced longitudinal cracking, embankment failure, differential settlement and even complete collapse.

There is considerable variation in local topographic and environmental conditions (e.g., air temperature, geology, surficial soil deposits, soil water and ice content) along the Alaska Highway. This makes it difficult to predict precisely how sections of the highway will respond to variability and change in climate. These are the general characteristics of this section of the highway:

- The section of the road being assessed extends from 60°45'N to 62°37'N.
- The region is part of the Cordilleran Orogeny geological class. This includes various mountain belts with elevations that range from 250 metres above sea level (masl) in the Yukon River to higher than 5000 masl in the St. Elias Mountains.
- The highway crosses heterogeneous soil surface deposits, ranging from very fine sediments to very coarse sediments such as gravel, pebble and cobble. Their origins are glacial (Pliocene to Early Pleistocene), postglacial (late Pleistocene) and recent (Holocene).
- Many parts of the highway cross warm permafrost, where the ground temperature is close to 0°C. Current permafrost temperatures are the combined result of previous climate conditions, construction activities and changes in surficial conditions.
- The current climate of the region is mainly subarctic continental, varying slightly with elevation and mountainside orientation. Winters tend to be long and cold, and summers short and warm. Precipitation in both winter and summer is limited: less than 400 mm per year.

- Projected increases of mean annual air temperature (MAAT) range from 1°C to 3°C of warming by 2050, depending on the success of efforts to reduce greenhouse gas emissions (SNAP 2014).

Because of this complex environment, the report uses multiple sources of data and a combination of methods to interpret permafrost vulnerability and anticipate future conditions. Geophysical data, previous geotechnical reports, HPW maintenance records, surficial geology maps, satellite photos and other available information were combined with field investigation and laboratory soil testing to investigate the thaw sensitivity of the permafrost that underlies the highway.

The report provides descriptions of permafrost characteristics underneath the highway on a section-by-section basis. It has been created for a broad range of users, including community members, decision-makers, civil engineers and road maintenance workers.

The report is structured as follows:

- Chapter 1 provides an introduction to the report.
- Chapter 2 details the field and lab methodologies.
- Chapter 3 provides specific guidance on using this report.
- Chapter 4 provides an overview of findings.
- Chapter 5 comprises the section-by-section interpretation of thaw vulnerability along the highway, with 13 section maps. Each map is accompanied by a short interpretation that explains how the surficial geology, permafrost conditions, and current and projected climate have combined and determine the vulnerability of the permafrost to thaw.
- Annex 1 provides the supporting data (e.g., borehole logs, ERT Profiles, ground temperature logs, etc.) used to determine vulnerability for each section. Annex 2 provides a glossary of terms used in the report. Annex 3 provides a list of references cited in the report.

The authors have attempted to minimize the use of scientific terminology in order to ensure broad understanding of the results. It is hoped that the contents of this report will be used to develop strategies to adapt to climate change and mitigate the hazards associated with ground settlement.

2. Methodology

Several forms of data were used to determine the vulnerability of the highway to permafrost thaw. They included reviews of previously collected data as well as collection of new field data and assessment of climate projection data. The methods used to collect and analyze the data are described in the following sections.

2.1 Assessment of existing data

Topographical and surficial deposit maps prepared by the Yukon Geologic Survey and aerial and satellite images, as well as thermal and geophysical data in geotechnical reports that were previously commissioned by HPW were interpreted as part of the project. This may give information about highway sections that are already experiencing negative impacts from permafrost thaw.

These data were supplemented by discussions with civil engineers, community members and permafrost specialists. Data and personal communications were combined, analyzed and interpreted before implementing a targeted field survey that collected data to complement previous efforts.

2.2 Field surveys

2.2.1 Permafrost drilling and sample collection

A light and portable GÖLZ Earth-drill system was used. It was coupled with coring tools that were designed and enhanced over the years at Centre d'études nordiques (CEN) of Université Laval in Quebec City and the Department of Earth and Atmospheric Sciences (EAS) of University of Alberta in Edmonton. They were used to collect permafrost cores at key points along the highway.

Boreholes were initiated by shoveling a fore hole down to the thaw front (Calmels, Gagnon and Allard 2005). At the thaw front, the Earth-drill system drill was used. The drill was mounted on a small Stihl engine with a high-speed transmission (600 rpm). Stainless steel rods 1 metre in length and 4.5 cm in diameter connected to a core barrel that was 40 cm long and 10 cm in diameter, with diamonds set in carbide alloy teeth. This made it possible to drill in unconsolidated, fine- to medium-grain material (sand to clay). A core catcher was used to extract frozen core from the borehole, allowing for the collection of continuous, undisturbed permafrost samples. This type of drilling was limited to a maximum drilling depth of approximately 5 to 6 m under optimal conditions. In order to drill boreholes at deeper depths, a conventional water-jet diamond drill was used.

A total of 21 boreholes were drilled. The same sampling and drilling protocols were followed for each borehole. The site was first described (e.g., hydrology, vegetation type and density, topography), photos were taken, and locations were recorded using a hand-held GPS. Each sample was photographed and described in situ (e.g., soil type, soil moisture, presence or absence of organic matter, any notable features). Each sample extracted from a borehole was identified by borehole name and depth. Samples were put in polybags and sealed immediately after being extracted. Samples were kept frozen and stored in a freezer that was taken back to the laboratory for further analyses. At the laboratory, each core was cleaned with cold water to remove drilling mud and then photographed.

2.2.2 Permafrost sample analysis

Laboratory analyses were carried out to measure the properties of the permafrost samples. Both soil grain characteristics and ice characteristics were evaluated. To evaluate soil grain characteristics, a grain-size analysis was performed on selected samples. To evaluate ice characteristics in permafrost samples, the cryostructure, volumetric ice content and gravimetric ice content were quantified. These methods are described below. For more information, please refer to Andersland and Ladanyi 2004. Results of these analyses are presented in Annex 1.

Grain-size analysis

Sieve and hydrometer analyses of grain size were performed following a specifically modified American Standard and Testing Method protocol (ASTM D422-63, 2000). The sieves used were 4, 2, 1, 0.5, 0.25, 0.125 and 0.063 mm.

Cryostructure

Permafrost cryostructure (the geometry of the ice in the permafrost) depends on water availability, the soil's ice-segregation potential, and the time of freezing, all of which affect the development of ice structures in the soil matrix. Information such as soil genesis, climate conditions at the time of freezing, permafrost development history, and ground vulnerability when permafrost degrades can be interpreted from cryostructure (the shape of the ground ice), cryofacies (groups of cryostructures) analysis, and general cryostratigraphy (assemblages of cryofacies).

Because field descriptions are based only on a visual interpretation of the core, the samples were described a second time more thoroughly in the laboratory using standard terminology (Murton and French 1994). Frozen core samples were warmed to near 0°C and any refrozen mud was scraped off before the sample was described.

Gravimetric ice content

Ice content was calculated using: $u_1 = \frac{(M_1)}{(M_s)}$

where MI is the ice weight, measured as weight loss after drying (g), and MS is dry soil weight in grams. Results are expressed as percentages (dimensionless).

Volumetric ice content

The volumetric ice content was calculated by immersing the frozen sample, bagged in vacuum-sealed polybags, in a recipient to measure its volume (Vtot). The sample was then thawed and put in the oven to dry. The remaining dry material was immersed again to determinate its volume (Vsed). The volume of excess content was calculated using:

Vtot – Vsed = Vice

The volumetric ice content is expressed as percentages (fundamentally meaning cm3/cm3).

2.2.3 Borehole logs

A log for each permafrost borehole was created by assembling laboratory photos of the cores. Borehole logs include maximal depths, grain size ratio and volumetric ice content (see Annex 1 for all borehole log descriptions and data). These logs were used as supporting data for mapping.

2.2.4 Ground temperature and climate monitoring

A selection of the newly drilled boreholes was instrumented to monitor ground temperature, beginning in the summer of 2013. In three cases, the borehole made using the portable Earth-drill was deepened using a water jet drill. Four boreholes from the Alaska Pipeline program were also instrumented.

Data were logged using either a Campbell Scientific weather station, or a HOBO (U12-008) four-channel external data logger. The CR1000 station uses a programmable data logger (CR1000) attached to the sensors. In this study, the CR1000 station monitored wind speed and direction (RM YOUNG Wind Monitor); air temperature (109-L); and ground temperature (CU-BOM11012). Ground temperatures were monitored using an 11-thermistor string. This accurately records temperatures ranging from –50°C to +70°C, with interchangeability to a tolerance of +/– 0.05°C or better. The CR1000 then processed and stored the data. Measurement rates and data recording intervals are independently programmable and the program can be modified at any time to accommodate different sensor configurations or new data processing requirements. The complete set-up is powered by a ten-watt solar panel and a six-volt deep-cycle battery and is attached to a 2- to 3-metre adjustable galvanized steel tripod anchored to the permafrost. The battery and data logger were placed in a sealed fiberglass enclosure. The Campbell Scientific weather station was used at two sites (BH01 and BH12).

To monitor ground temperature at all the other sites, a HOBO (U12-008) four-channel external data logger was used. This stand-alone weatherproof logger can record data at various intervals and uses a direct USB interface for fast data offload. The logger requires one three-volt CR-2032 lithium battery. Each battery will typically last one year when logging intervals are greater than one minute. To ensure uninterrupted operation, the data loggers were placed in a sealed 15-cm x 15-cm junction box that was connected to the borehole casing. All borehole casings were made of electrical-grade PVC filled with silicone oil. The temperature sensors (TMC6-HD to TMC50-HD) are able to accurately record temperatures ranging from –20°C to +70°C, with interchangeability to a tolerance of +/–0.25°C from 0°C to 50°C. They have a resolution of 0.03°C at 20°C.

In addition, ground surface temperature temperature was monitored using the HOBO Pendant data logger (UA-002-08). This miniature waterproof two-channel data logger is able to accurately record temperatures ranging from –20°C to +70°C with interchangeability to a tolerance of +/– 0.53°C from 0°C to 50°C. The UA-002-08 loggers have a resolution of 0.14°C at 25°C.

Results from the ground and air temperature loggers are used to support the vulnerability assessment for specific sections of the highway. Records are presented in Annex 1, along with the other field data that were collected for each highway section.

2.2.5 Electrical Resitivity Tomography

Electrical resistivity tomography (ERT) is a geophysical method that uses stainless steel electrodes driven into the ground surface to measure the resistivity distribution of the subsurface. Resistivity is the mathematical inverse of conductivity and indicates the ability of an electrical current to pass through a material. Mineral materials (with the exception of specific substances such as metallic ores) are mostly non-conductive. Therefore, the resistivity of a soil or rock profile is governed primarily by the amount and resistivity of pore water present in the profile, and the arrangement of the pores. This makes ERT very well suited to permafrost and hydrology applications. Because most water content in frozen ground is in the solid phase, and typically has a higher resistivity than unfrozen water content, permafrost distribution can be inferred based on changes in resistivity between frozen and unfrozen ground.

An ERT system consists of an automated multi-electrode resistivity meter and a set of wires connected to an electrode array. The system used for the surveys presented in this report is an IRIS electrical resistivity system, consisting of a one-channel imaging unit and two electrode cables, each with 24 take-outs at five-metre intervals. To conduct a survey, 48 electrodes are driven into the ground along a survey line and connected to the electrode cables. A direct current electrical pulse is sent from the resistivity meter along the survey line. The resulting data consists of a cross-sectional (2D) plot of the ground's resistivity (Ω.m) versus depth (m) for the length of the survey.

Results of the surveys are post-treated and analyzed at the NCE using inversion software (Res2DInv 64 and Res3DInv 32).

2.3 Climate projections

Scenarios Network for Alaska + Arctic Planning (SNAP), located at University of Alaska Fairbanks, provided 2 km^2-resolution downscaled climate projections for the 2030s and 2050s. The data in the SNAP models used averages of five General Circulation Models (GCMs) that were found to perform best over Alaska and the Arctic. Model ensemble data (the combined average of several models) are presented for the a1b and b1 emission scenarios. The b1 scenario projects low to moderate increases in emissions, with eventual stabilization of emissions over the next century, while the a1b scenario anticipates medium to high emissions with eventual stabilization. These two scenarios are presented in this report because they provide a reasonable range of anticipated shifts in climate conditions over the study area. The use of an ensemble of models reproduces observed average monthly climate more reliably than any individual model, and it is expected that the average of model projections will also produce a better estimate of average future climate (SNAP 2014).

The GCMs are regionally downscaled using data available from the Parameter-elevation on Independent Slopes Model (PRISM). The downscaled data provided by SNAP is limited by the resolution of available PRISM data (SNAP 2014). Projections were provided to NCE as Ascii files and then converted to Excel spreadsheets. Projected change in climate was determined by averaging the grid cells that covered each highway section.

3. Guidance for users

3.1 Ranking process

The ranking of highway vulnerability is based on the probability of extensive damage occurring as a result of complete permafrost degradation. Vulnerability to permafrost thaw is described in three categories:

- Low-vulnerability sections may have no thaw sensitivity due to a lack of permafrost or if highway stability is independent of thermal state. Some low-vulnerability areas may degrade, even intensely, for a relatively short period of time (several years). After that, degradation will be complete and the highway will be stable despite thaw.
- Moderately vulnerable areas are expected to undergo thaw settlement over time scales of years to decades, but degradation of the highway will be easily manageable.
- Highly vulnerable sections may already be degrading and will continue to be affected by thaw for multiple decades, with heavy damage before permafrost degradation is complete. In some areas, it may take decades before any degradation takes place, until the lowering of the permafrost table reaches ice-rich ground, but once that happens, the impact of thaw will be substantial.

To develop this ranking, the relationship of ground excess ice content, ground temperature, and thickness of the permafrost to surficial geology and climate was assessed. The classification does not directly consider where permafrost has degraded or is degrading, or where the road is damaged.

Thaw-sensitive permafrost is perennially frozen ground which, when it thaws, will experience significant settlement and lose the strength required to support the highway. Ice-rich permafrost is thaw-sensitive. The more ice-rich the permafrost is, the more intense the thermokarst processes will be during its degradation. Highway sections that cross ice-rich permafrost rank as highly vulnerable.

Warm permafrost (with a ground temperature between –2 and 0°C) is more likely to degrade than colder permafrost. Permafrost with warm temperatures all along a vertical profile is symptomatic of ice-rich, fine textured permafrost. Therefore, warm permafrost is more likely to undergo heavy thermokarst processes when degrading, and will rank as highly vulnerable.

The thicker the permafrost, the longer its degradation is expected to last. Thick permafrost, even with moderate ice content, will produce major thermokarst processes over a longer period of time.

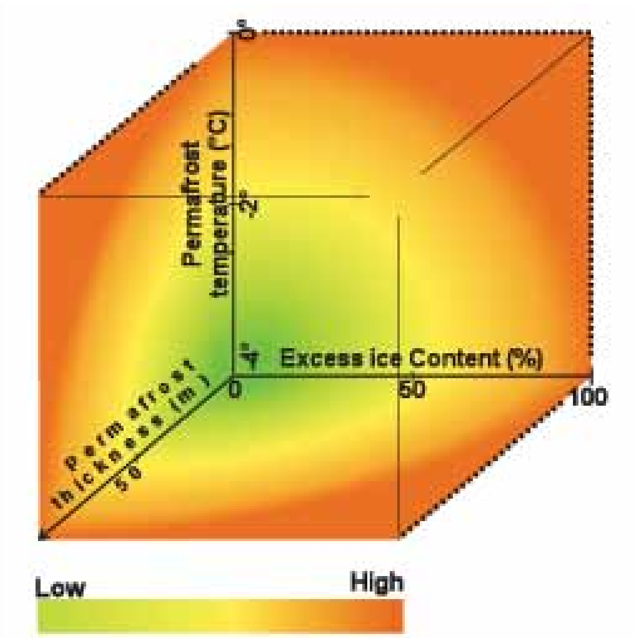
The relationship among these factors are summarized conceptually in Figure 1.

This approach allows sites with different characteristics to be ranked in the same category. For example, moderately ice-rich, thick permafrost may be ranked equally to ice-rich yet significantly thinner permafrost.

3.2 Limitations of the vulnerability assessment

All geophysical methods are limited in their ability to fully characterize subsurface and permafrost conditions. The combination of approaches used in this study helps minimize the potential for error. One of the major limitations in the study is the fact that the permafrost assessment was performed in natural, undisturbed sites along the highway corridor. Sites were selected to be far enough from the highway embankment that the highway would have little impact on permafrost conditions. Permafrost conditions observed at these sites may not be entirely representative of permafrost condition underneath the embankment. The highway may have already had severe impacts on the underlying permafrost; the years or decades of disturbance during construction and maintenance of the highway may have extensively degraded permafrost and considerably lowered the level of the permafrost table. If permafrost has completely degraded, it is no longer thaw-sensitive. In that case, the ranking of vulnerability to thaw may be inaccurate; the permafrost under the road may be less thaw-sensitive than expected.

Figure 1. Diagram of vulnerability to permafrost thaw



3.3 User guidelines

Chapter 4 provides a section-by-section analysis of the available data to describe the vulnerability of the highway to permafrost thaw. Sections range in length from approximately 15 to 20 km, depending on the complexity of the landscape for each section. All the information collected during fieldwork and laboratory analyses has been combined in order to obtain the most accurate assessment of permafrost vulnerability to thaw.

Six key pieces of information are shown in each map: satellite photos, symbols for key features, surficial geology, soil texture, ground ice nature, and a colour-coded assessment of permafrost vulnerability to thaw.

Satellite photos are provided to situate the reader in the spatial context of each site, and to show key features that are not always mapped, such as gravel pits, small lakes, rivers and landforms.

Symbol features precisely locate the reader on the road section; they include the location of the boreholes and the highway km posts.

The nature of each section's surficial geology includes colluvial, fluvial, lacustrine, organic, eolian, drift, morainal (till), glaciofluvial and glaciolacustrine sediments and bedrock. Geological terms are defined in the glossary (Annex 2).

The soil texture is represented by a small letter (key), which was provided by the Yukon Geological Survey map and legend standards (Table 1). Table 1 shows the keys and the names of ground texture classes, with their respective particle size and physical properties. The surficial geology deposits and ground texture are illustrated by different colours and key abbreviations (small letters), respectively. It uses the Yukon Terrain Classification System, which is an adaptation of the British Columbia Terrain Classification system (Howes and Kenk 1997). The Yukon Geological Survey provided the database through its Integrated Data System (YGSIDS). These data were used as map and legend standards and database structure. This classification was selected for its flexibility and its well-documented database. The symbols and colours that represent geological form features and surficial deposits are relatively simple and easy to understand.

Table 1. Yukon terrain classification system for texture

Key	Name	Size	Properties
a	blocks	> 256 mm	angular
b	boulders	> 256 mm	rounded
k	cobbles	64–256 mm	rounded
P	pebbles	2–64 mm	rounded
s	sand	0.062–2 mm	
z	silt	0.002–0.062 mm	
c	clay	< 0.002 mm	
m	mud	> 2 mm	rounded angular
d	mixed fragments		
g	gravel	> 2 mm	rounded; mix of b, k and p
X	angular fragments	2–256 mm	angular particles
r	rubble		
v	shells		
e	fibric organic		poorly decomposed
u	mesic organic		intermediate decomposition
h	humic organic		highly decomposed

The vulnerability to permafrost thaw section is shown in one of three colours: green (low), yellow (moderate) and red (high).

Information presented in the maps is supported by a written description that includes five components: Vulnerability assessment, Geology, Permafrost, Climate and Supporting data. These complement the map and for a full understanding they should be read in their entirety.

- The vulnerability assessment briefly explains the key points that determined the vulnerability for the section.
- The geology paragraphs summarize the surficial geology and ground texture.

- The permafrost paragraphs describe the physical and thermal properties of corresponding permafrost.
- The climate paragraphs summarize climate projections and possible impacts on permafrost thaw, according to the corresponding cell-grid scale of the SNAP climate projection.
- Supporting data is provided for most sections. The supporting data is presented in Annex 1. These data include borehole logs and any other analyses performed on cores, results of ERT surveys, and plots of ground temperature.

Scientific terms used in maps and description texts are described in the glossary (Annex 2). The definitions are scientifically accepted standards first published in the *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms* (van Everdingen 2005) and the *Dictionary of Geological Terms* (Bates and Jackson 1984).

4. Vulnerability summary

Table 2 presents a summary of the vulnerability to permafrost thaw. Overall, for the 200-km section between Burwash Landing and the Yukon/Alaska border, 42.7% is highly vulnerable to permafrost thaw, 38.5% has moderate vulnerability, and 18.8% has low vulnerability.

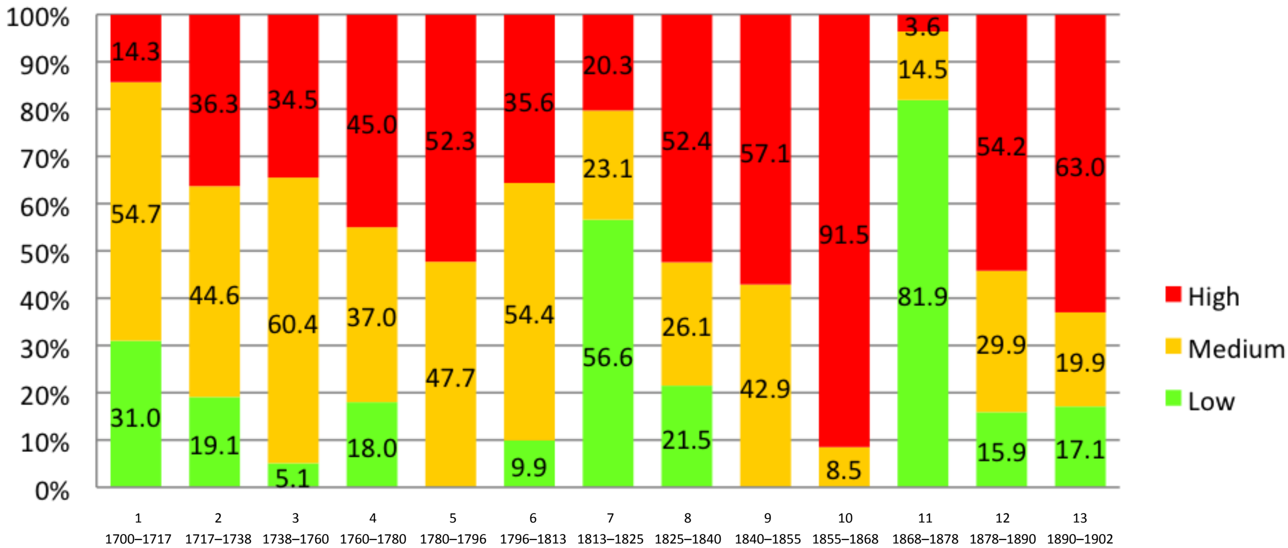
Table 2. Vulnerability to permafrost thaw of the North Alaska Highway

Section number	Section km	High vulnerability		Moderate vulnerability		Low vulnerability		total
		%	km	%	km	%	km	km
1	**1700 to 1717**	14.30	2.41	54.70	9.25	31.00	5.24	16.90
2	**1717 to 1738**	36.40	7.61	44.60	9.36	19.00	3.97	20.94
3	**1738 to 1760**	34.50	7.61	60.40	13.35	5.10	1.14	22.10
4	**1760 to 1780**	45.00	9.00	37.00	7.40	18.00	3.61	20.01
5	**1780 to 1796**	52.30	8.37	47.70	7.62	—	—	15.99
6	**1796 to 1813**	35.60	6.05	54.50	9.24	9.90	1.67	16.96
7	**1813 to 1825**	20.30	2.44	23.10	2.78	56.60	6.79	12.01
8	**1825 to 1840**	52.40	7.89	26.10	3.93	21.50	3.24	15.06
9	**1840 to 1855**	57.10	8.52	42.90	6.41	—	—	14.93
10	**1855 to 1868**	91.50	11.91	8.50	1.10	—	—	13.01
11	**1868 to 1878**	3.60	0.36	14.50	1.48	81.90	8.34	10.18
12	**1878 to 1890**	48.30	5.76	35.70	4.25	16.00	1.90	11.91
13	**1890 to 1902**	63.00	8.03	19.90	2.54	17.10	2.18	12.75
total: km 1700–1902		45.78	92.47	32.55	71.08	21.67	39.19	202.74

Note: Not all measured distances will match named kilometre markers due to minor highway realignments over the years.

Section 10 (1855–1868) and Section 13 (km 1890–1902) are ranked as the most sensitive to permafrost thaw, while Section 7 (km 1813–1825) and Section 11 (km 1868–1878) appear to be the most resilient (Figure 2).

Figure 2. Vulnerability of the North Alaska Highway to permafrost thaw (%), by section



5. Summary of projected climate

Warming atmospheric temperatures lead to ground warming through heat transfer. Increasing precipitation leads to ground warming through increased insulation in winter and increased soil moisture and shallower groundwater in summer. Both warming and increased precipitation can cause permafrost to degrade.

The climate change projections in Table 3 show little variation in projected temperature between the different sections of the highway for both a1b and b1 scenarios in 2030. The only noticeable difference is a slightly greater increase in temperature between Sections 2 and 6. This may lead to slightly faster increases in ground surface temperature and permafrost thaw. According to both scenarios, the temperature would increases by 2.5°C to 4°C by 2050. Although there is no variation in the projected change in precipitation, the projected magnitude in both scenarios will contribute to permafrost degradation by affecting the speed of thaw.

This magnitude of projected warming and precipitation increase is substantial in an area where many parts of the highway section cross warm permafrost with a ground temperature close to 0°C. In fact, for Sections 2 and 3, the recorded mean permafrost temperature was between –1.5°C and –0.3°C and in Section 6 was between –1.2°C and –1. With a ground temperature that is already this warm, both scenarios could induce complete permafrost thawing along some parts of the highway between 2030 and 2050.

Table 3. SNAP climate projections for the North Alaska Highway

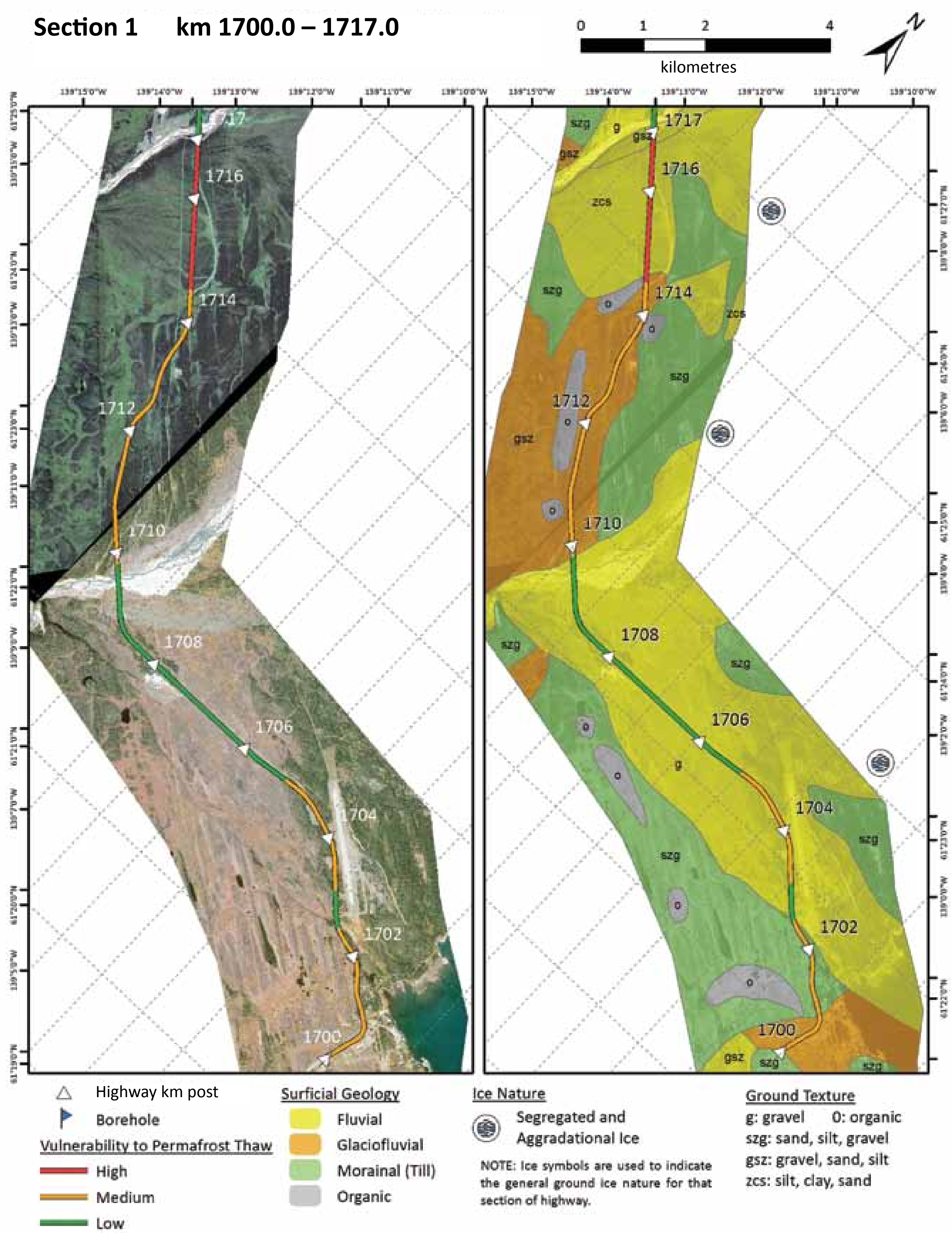
Section number and km		Temperature (°C)				Precipitation (mm)			
		2030		2050		2030		2050	
		a1b	b1	a1b	b1	a1b	b1	a1b	b1
1	**1700–1717**	1.5–2.0	2–2.5	3.5–4.0	2.5–3.0	40–50	20–30	70–80	30–40
2	**1717–1738**	1.5–2.5	2–2.5	3.5–4.0	2.5–3.0	40–50	20–30	70–80	30–40
3	**1738–1760**	1.5–2.5	2–2.5	3.5–4.0	2.5–3.0	40–50	20–30	70–80	30–40
4	**1760–1780**	1.5–2.0	2–2.5	3.5–4.0	2.5–3.0	40–50	20–30	70–80	30–40
5	**1780–1796**	1.5–2.5	2–2.5	3.5–4.0	2.5–3.0	40–50	20–30	70–80	30–40
6	**1796–1813**	1.5–2.5	2–2.5	3.5–4.0	2.5–3.0	40–50	20–30	70–80	30–40
7	**1813–1825**	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40
8	**1825–1840**	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40
9	**1840–1855**	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50
10	**1855–1868**	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50
11	**1868–1878**	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50
12	**1878–1890**	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50
13	**1890–1902**	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50

Note: Emission scenario = change from 1980–2009

The projected changes are expected to be more important in the northern and southern sections of the highway than in the middle sections. The impact of climate warming and added precipitation will be less important for limited parts of the middle sections, since the permafrost is somewhat colder.

Although the Alaska Highway is located in what is now a zone of discontinuous permafrost, the projected change in climate would be large enough to make permafrost increasingly sporadic and isolated by 2050.

5. Section Reports


Section 1 km 1700.0 – 1717.0
0 1 2 4
kilometres
1717
1716
1714
1712
1710
1708
1706
1704
1702
1700
szg
g
gsz
zcs
o
Highway km post
Borehole
Vulnerability to Permafrost Thaw
High
Medium
Low
Surficial Geology
Fluvial
Glaciofluvial
Morainal (Till)
Organic
Ice Nature
Segregated and Aggradational Ice
NOTE: Ice symbols are used to indicate the general ground ice nature for that section of highway.
Ground Texture
g: gravel
0: organic
szg: sand, silt, gravel
gsz: gravel, sand, silt
zcs: silt, clay, sand

Section 1 km 1700.0 – 1717.0 Burwash Landing

Vulnerability assessment

- This highway section is underlain by warm permafrost.
- Where present, glaciofluvial units increase the vulnerability of permafrost to thaw settlement. This will continue to be the case until the permafrost table is below potentially ice-rich layers (e.g., below a depth of 10 m).
- Glacial morainic units and fluvial units are considered to have low to medium vulnerability to thaw, due to their lesser amount of ground ice and the coarser nature of their sediment.
- In this 16.9-km section of road, 14.3% is considered highly vulnerable (2.41 km); 54.7% is considered moderately vulnerable (9.25 km); and 31% is considered to have low vulnerability (5.24 km).

Geology

The road is mostly built on fluvial and glaciofluvial sediment. Short sections are built on glacial sediment, either moraines or till.

The glacial deposit accumulated at the base of the glacier and is made up of coarsely graded and extremely heterogeneous sediments, with content varying from clays to mixtures of clay, sand, gravel and boulders. The surface of these deposits is undulating, alternating between elongated hills and depressions. Permafrost developed epigenetically, from the top to the bottom, after the glaciers retreated. This has constrained its thickness.

Fluvial or glaciofluvial deposits cover most of the area north of the Burwash Landing airport. They were deposited after the glaciers retreated (within the last 11,000 years) and buried glacial deposits at low-elevation locations. Glaciofluvial deposits often occur in the form of fluvial fans, filling the valley between the glacial hills. Fan deposits are made of fluvial sediment consisting of silt, sand, gravel and boulders. These areas are poorly drained. Where permafrost is present, it is syngenetic. Some ponds and lakes may be due to thermokarst processes; this indicates the presence of ice-rich permafrost in these deposits.

The fluvial deposits are more recent, and overlie both glacial and glacofluvial deposits. They are gravelly and therefore less likely to be thaw-sensitive when permafrost is present.

Permafrost

Where present, permafrost thaw is more likely to be problematic in the glaciofluvial sediment and fans that have accumulated in valleys and gullies. Although no permafrost cores were collected in the area, unpublished geotechnical surveys indicate that permafrost depth does not exceed 10 m in the area, with ground ice content that may not exceed 10%. For example, excess ground ice content (5–10%) was reported underneath the Burwash Landing fire hall and Tribal Council buildings. This was found at depths between 3 and 8 m.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980-2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

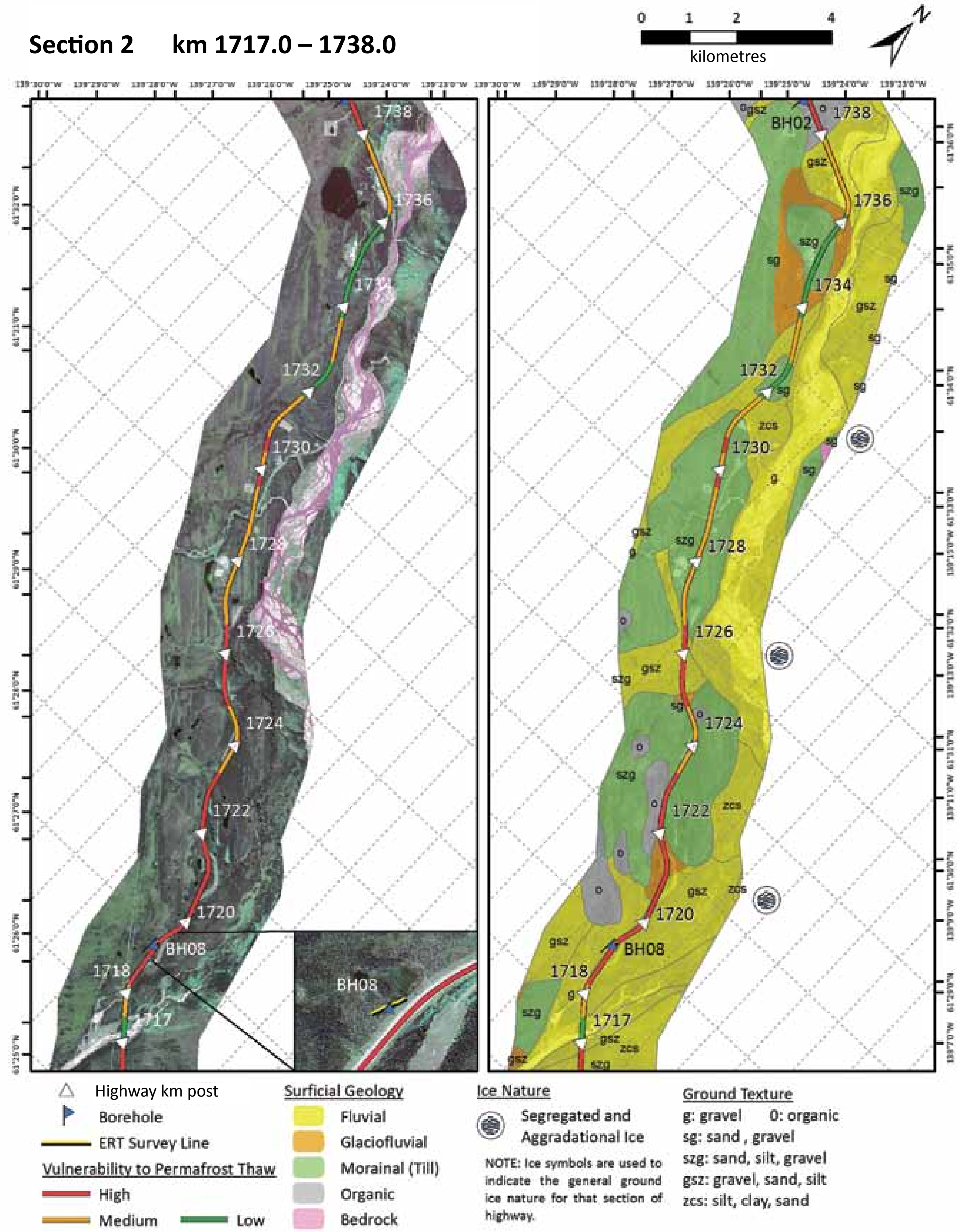
The projected increase of air temperature is expected to have more impact than projected precipitation increases, because ground temperatures are already warm. Atmospheric warming will result in a lowering of the permafrost table, with degradation proportional to the ground ice content.

Supporting data

N/A

Longitudinal cracking observed at km 1713.

Section 2 km 1717.0 – 1738.0



Section 2 km 1717.0 – 1738.0 Kluane River

Vulnerability assessment

- This highway section is underlain by warm permafrost.
- Glaciofluvial, organic and small areas of fluvial units along this section are highly vulnerable to thaw settlement. This will continue to be the case until the permafrost table is below ice-rich permafrost (below about 20 m).
- Highway sections in the glacial morainic units are considered to have low to medium vulnerability because they have lower ground ice content and the sediment is coarser.
- In this 20.97-km section of road: 36.4% is considered highly vulnerable (7.61 km); 44.6% is considered moderately vulnerable (9.36 km); and 19.0% is considered to have low vulnerability (3.97 km).

Geology

The road is built mostly on glacial (moraines or till), glaciofluvial and fluvial sediment. Short sections are built on organic sediment.

The glacial deposits, which accumulated underneath the glacier, are coarsely graded and extremely heterogeneous sediments that include clay, sand, gravel and boulders. The surface of these deposits undulates, alternating between elongated hills and depressions. Permafrost developed epigenetically, from the top to the bottom, after the glaciers retreated. This has constrained its thickness.

Glaciofluvial deposits often fill valley bottoms between the glacial hills. These are usually poorly drained areas made of silt, sand, gravel and boulders. Permafrost likely formed here through a rise in the permafrost table as additional glaciofluvial material was deposited on the ground surface.

Fluvial deposits are more recent. They overlie both glacial and glaciofluvial deposits; they also have sediment that ranges from silt to gravel, depending on the location. Finer-grained deposits are more sensitive to thaw when permafrost is present.

The organic soils developed in poorly drained depressions and overlie both morainic and fluvial material. They are made of fibric organic material that favours the aggradation of permafrost. Humidity has caused the growth of masses of almost pure ice. Highways that cross organic soils are extremely sensitive to damage from permafrost thaw.

Permafrost

Permafrost is most problematic in the organic and fluvial units, where it often consists of permafrost plateaus. Cores collected at km 1719.1 showed ice volume content as high as 59%, with ice lenses one cm thick for the full length of the profile. The sediment is mostly silty sand; the amount of coarse material increases with depth below ground.

The ERT survey conducted at the same location indicates the presence of permafrost to a depth of approximately 17 m. Because of the coarse material content at that depth, it is hard to determine how ice-rich the permafrost is there. Once permafrost has degraded below this depth, the ground surface should stabilize.

Ground temperature records show that the permafrost is relatively warm (about –1.5°C), but not as warm as that measured at other sites. This will give it more resilience, depending on the ground ice content.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2.5	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

Projected increases in winter precipitation are expected to have a greater impact on permafrost than projected temperature increases will because of the insulating effect of snow cover. Increased air temperature will increase the active layer thickness, thawing ice-rich ground close to the surface. Frost mounds and permafrost plateaus will be especially thaw-sensitive.

Supporting data

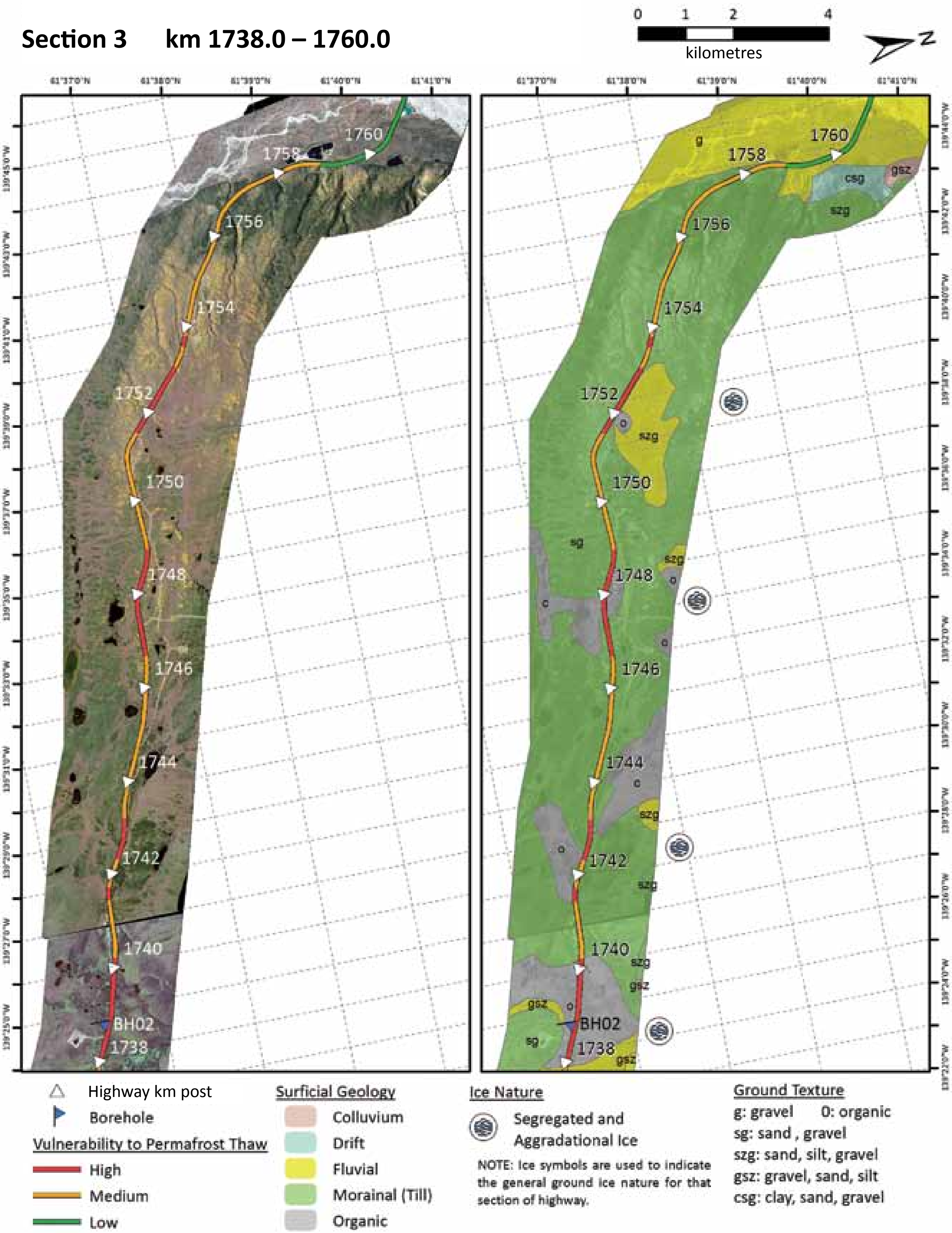
See pp. 71–73

Borehole data	BH08	depth 3.48 m; grain size, excess ice and contents
ERT	@BH08	115 m; 24 electrodes.
Ground temperature	@BH08	5 depths; July 2013–November 2014.

Permafrost core collected at BH08, km 1719.1.

Ground temperature monitoring station at BH08.

Section 3 km 1738.0 – 1760.0



Section 3 km 1738.0 – 1760.0 Swede Johnson Creek

Vulnerability assessment

- This highway section is underlain by warm permafrost.
- Highway sections built on fluvial and organic units are highly vulnerable to thaw settlement. This will continue to be the case until the permafrost table is below ice-rich permafrost (below 10–20 m).
- Highway sections built on glacial morainic units are considered to have low to medium vulnerability due to these units' lower ground ice content and the coarser nature of the sediment.
- In this 22.1 km section of road, 34.5% is considered highly vulnerable (7.61 km); 60.4% is considered moderately vulnerable (13.35 km); and 5.1% has low vulnerability (1.14 km).

Geology

This section of the road is mainly built over moraine deposits, with short lengths of fluvial deposits and organic rich soil.

Moraine deposits date to the McConnell glaciation (18,000 years ago) and consist of heterogeneous sediment (sand and mixed fragments in a finer matrix). The surface of these deposits is undulating; the depressions are filled by fluvial and/or organic rich soil.

The fluvial units have sediment ranging from silt to gravel. They are coarsest close to active fluvial areas along the Donjek River and finer in ancient deposits that overlay the moraine.

The organic soils developed in poorly drained depressions and overlie morainic material. They are made of fibric organic material and are more than 15 m thick at some locations.

The glacial deposits (moraine and drift) are comprised of coarse sediment which is unlikely to develop ground ice. Therefore, it is considered less thaw-sensitive. Permafrost developed epigenetically, from the top to the bottom, after the glaciers retreated. This has constrained its thickness.

Permafrost that aggraded in finer fluvial deposits during a colder period may have formed a significant amount of ground ice at some locations.

The thermal properties of the organic soils promoted permafrost aggradation, while their location in a wetland area provides water that supports the formation of segregated ice. Therefore, organic soils are often rich in ice, as demonstrated by the occurrence of thermokarst lakes and ponds.

Permafrost

Permafrost is more problematic in the organic unit and less so in the fluvial material. The presence of organic cover (moss and peat) has promoted the growth of ice-rich permafrost. Cores collected at km 1738.7 showed excess ice content as high as 45%. Ice lenses, with a thickness ranging from 1 cm to 1 dm, consistently occur all along the profile.

Ground temperature records show that the permafrost is very warm (about –0.3°C). Although it is currently frozen, it is located in a wet area and is prone to degradation.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2.5	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

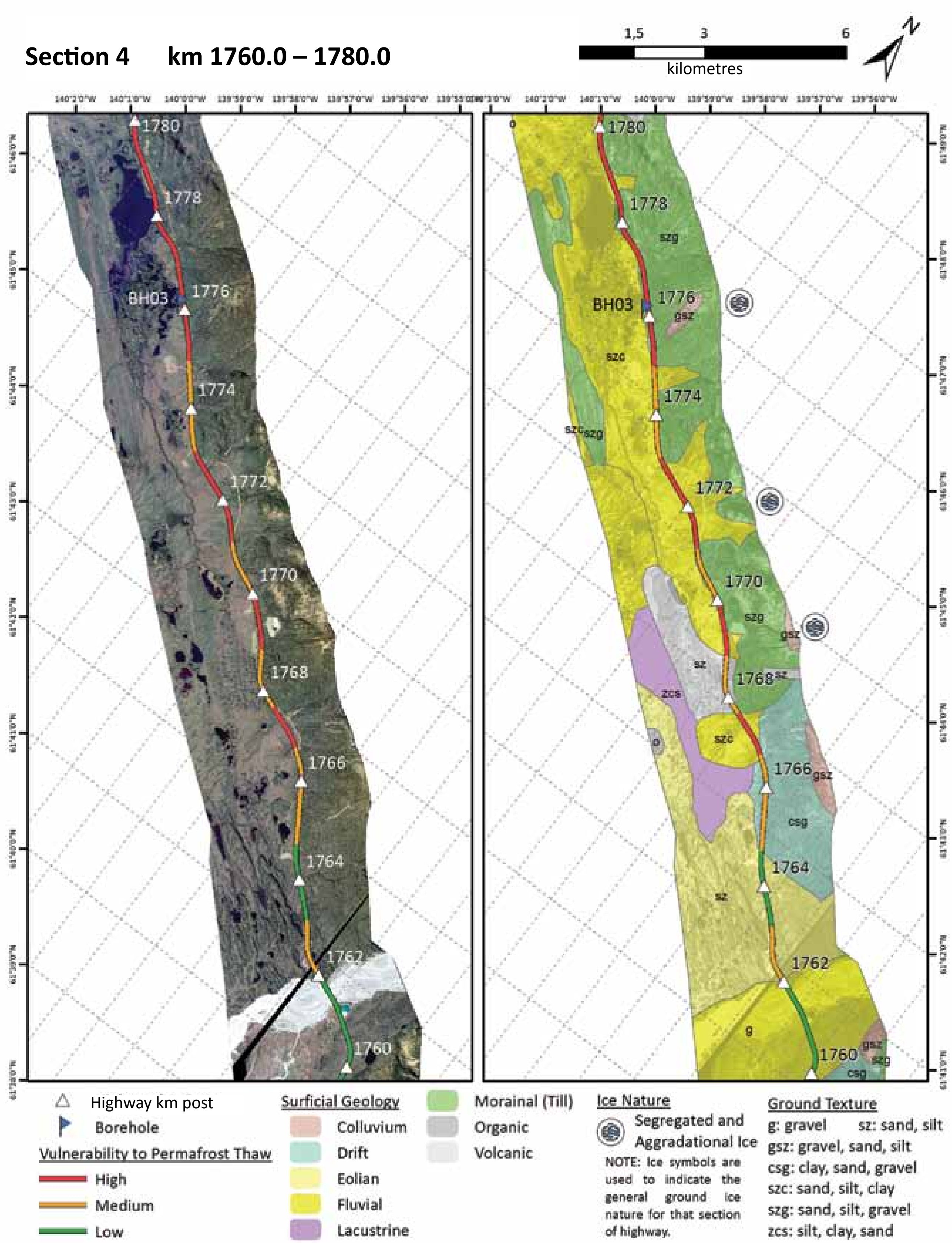
The projected increase in air temperature will have direct effects on the warm permafrost. The combined impact of warming and increased precipitation will result in higher water levels and possible flooding. As a result, permafrost located in wetlands will degrade faster than elsewhere.

Supporting data

See p. 74–75

Borehole data	BH02	depth 4.27 m; grain size, excess ice content
Ground temperature	@BH02	5 depths; July 2013–November 2014.

Permafrost core collected at Swede Johnson Creek.


Section 4 km 1760.0 – 1780.0
1,5 3 6
kilometres
1780
1778
1776
BH03
1774
1772
1770
1768
1766
1764
1762
1760
szg
gsz
szc
sz
zcs
csg
g
Highway km post
Borehole
Vulnerability to Permafrost Thaw
High
Medium
Low
Surficial Geology
Colluvium
Drift
Eolian
Fluvial
Lacustrine
Morainal (Till)
Organic
Volcanic
Ice Nature
Segregated and Aggradational Ice
NOTE: Ice symbols are used to indicate the general ground ice nature for that section of highway.
Ground Texture
g: gravel
sz: sand, silt
gsz: gravel, sand, silt
csg: clay, sand, gravel
szc: sand, silt, clay
szg: sand, silt, gravel
zcs: silt, clay, sand

Section 4 km 1760.0 – 1780.0 Donjek River

Vulnerability assessment

- Highway sections along the hill toe are highly vulnerable to thaw settlement. They are located on warm permafrost between ice-rich fluvial and glacial materials that are prone to slope processes and seepage leaching from sediment. Permafrost can be ice-rich down to a depth of 20 m.
- Although the permafrost is warm, highway sections built on glacial and eolian units are considered to have low to medium vulnerability due to the units' low amount of ground ice and the absence of thermokarst indicators.
- Sections built on drift material are more problematic because this material contains finer sediment.
- In this 20.01-km section of road, 45% is considered highly vulnerable (9.0 km); 37.0% is considered moderately vulnerable (7.40 km); and 18.0% is considered to have low vulnerability (3.61 km).

Geology

This section of the road crosses various surficial geology deposits, including fluvial, moraine, drift and eolian sediments. The road is mainly located along the base of hills, alternating between fluvial and glacial deposits.

Sediments in the fluvial units range from silt to gravel and overlie morainic and drift material at some locations. Permafrost that developed (aggraded) in finer fluvial deposits during a colder period, which formed a significant amount of ground ice, is now degrading. Air photos show many thermokarst features in the area.

The moraine and drift units are made of hetero-granular sediment (coarse material in a finer matrix) that may be overlain by colluvium and slope deposits at the foot of the hill slopes. Where present, the overlying colluvial deposits also contain a mix of coarse and fine material. In these units, permafrost may have developed syngenetically, as each layer of sediment was deposited, and therefore might be more thaw-sensitive. Note: some colluvium deposits may have been misinterpreted as drift.

The eolian deposits comprise silt and sand, and overlie drift, fluvial or other eolian deposits. Eolian deposits appear to have low vulnerability to thawing due to relatively high sand content. However, they may overlie more thaw-sensitive material, such as alluvial sediment.

The glacial deposits are comprised of coarse sediment, which is less likely to develop ground ice and is therefore less thaw-sensitive. Permafrost developed epigenetically, from the top to the bottom, after the glaciers retreated, which has constrained its thickness.

Permafrost

In this section of highway, the permafrost is most problematic in the fluvial unit. Permafrost has developed in fine-grained soil that contains organic material and coarser tephra.

Cores collected at km 1776.1 showed water content as high as 76% and excess ice content around 50%. Ice lenses, from one mm to one cm thick, consistently occur all along the vertical profile.

Ground temperature records show that the permafrost is very warm (about – 0.6°C), with a base 6 m deep. Although the permafrost is currently frozen, it is located in a wet area, which makes it more prone to degradation.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

The projected warming will have direct impacts on the very warm permafrost, such as that observed in BH03. The projected increase in precipitation will result in more frequent flooding, which will be detrimental for permafrost. It may also increase the occurrence and intensity of slope processes and seepage leaching from sediment.

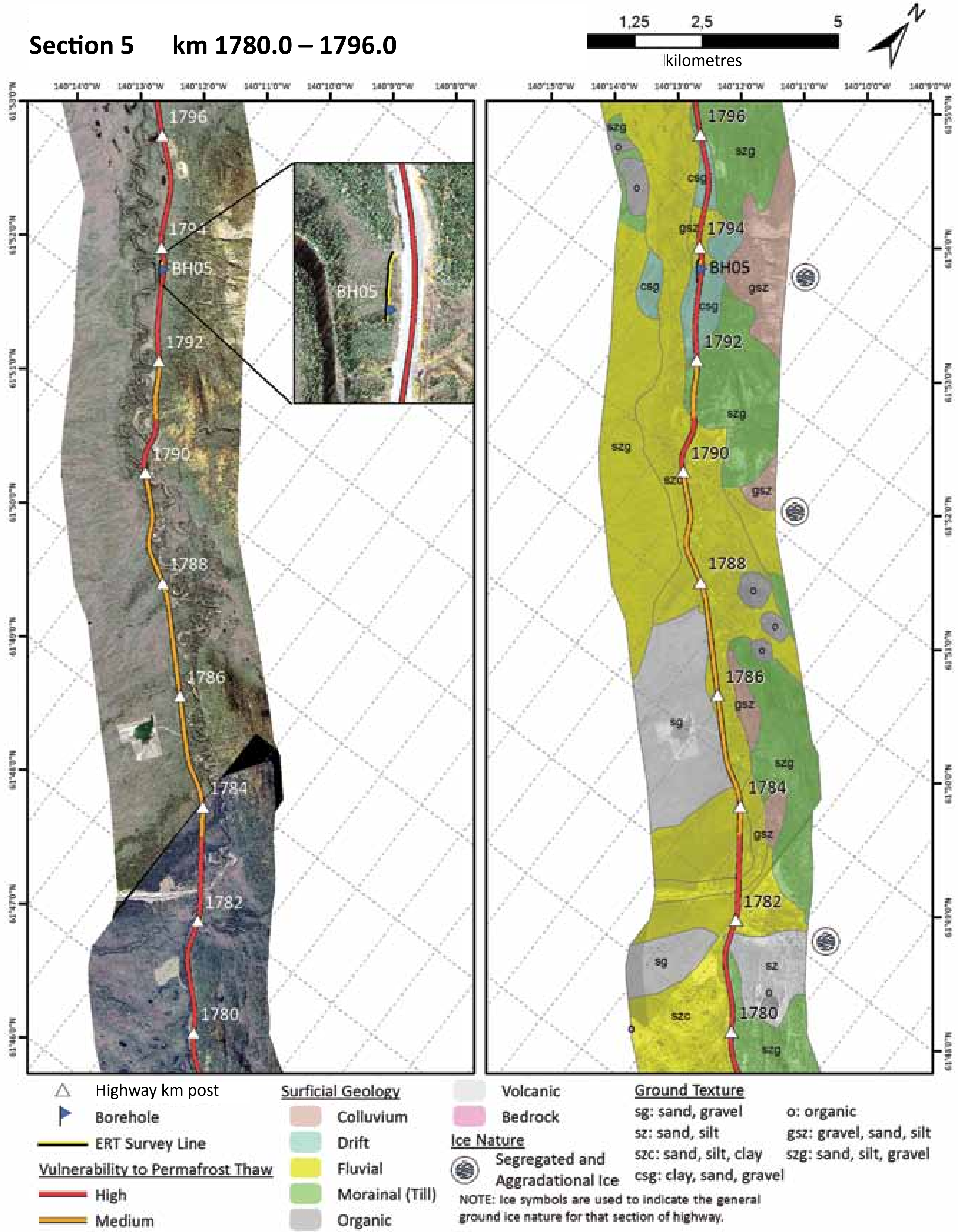
Supporting data

See p. 76–77

Borehole data	BH03	depth 4.75 m; grain size, excess ice and water contents
Ground temperature	@BH03	5 depths; July 2013–November 2014.

Permafrost core collected at BH03, km 1776.1.

Section 5 km 1780.0 – 1796.0



Section 5 km 1780.0 – 1796.0 River meanders

Vulnerability assessment

- This highway section is underlain by warm permafrost.
- Highway sections that cross fluvial units are highly vulnerable to thaw settlement until the active layer is below ice-rich permafrost (below 20 m).
- Highway sections that cross moraine units have medium vulnerability to thaw settlement due to these units' low amount of ground ice.
- Drift materials are less predictable because of their finer sediment content. They may thaw, but this will not lead to extensive road settlement. Other problems include the road being built at the hill toe, where seepage and slope processes occur in the warm permafrost.
- In this 15.99-km section of road, 52.30% is considered highly vulnerable (8.37 km); and 47.70% is considered moderately vulnerable (7.62 km). There are no areas with low vulnerability.

Geology

This section of the road alternates between various surficial geology units, comprising fluvial, moraine, drift sediment and colluvium.

The fluvial units have sediment ranging from silt to gravel that overlies moraine and drift material at some locations. In this section, the road mainly follows the relict meanders of a river system. Permafrost developed (aggraded) in these fine deposits during a colder period, and formed a significant amount of ground ice. Because of warming temperatures, thermokarst features are developing.

Moraine and drift units are made of heterogeneous sediment (coarse material in a matrix of finer material) that is overlain by colluvium and slope deposits at the foot of the hill slopes. These deposits are less favourable to the development of ground ice, and therefore have low vulnerability to thaw. In addition, permafrost developed epigenetically after the glaciers retreated, from the top to the bottom, which has constrained its thickness.

The overlying colluvial deposits also contain a mix of coarse and fine material, but permafrost has developed syngenetically, with the deposition of each new sediment layer. This increases thaw vulnerability. Note: it is possible that some colluvium deposits have been misinterpreted as drift.

Permafrost

The permafrost is most problematic in the fluvial unit. Permafrost has developed in fine-grained soil, with coarser sandy levels. Once permafrost has degraded across this fluvial deposit, the ground surface should stabilize.

Cores collected at km 1793.5 showed water content as high as 81% with ice lenses from 1 mm to 1 cm thick, consistently occurring all along the profile.

The ERT survey conducted at the same location suggests that ice-rich permafrost can be expected to be as thick as 20 m in this area.

Ground temperature records shows that the permafrost is warm (about –1.2°C). Although it is currently frozen, it is highly prone to degradation, either by increased air temperature or precipitation/meltwater.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2.5	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

The projected warming will affect the ground temperature of this warm permafrost, but because this section of the highway is located close to a meandering river, the projected increase in precipitation may have greater impact, since it will result in more frequent flooding. Sections located along the hill toe will be affected by an increase in occurrence and intensity of slope processes and seepage leaching from sediment.

Supporting data

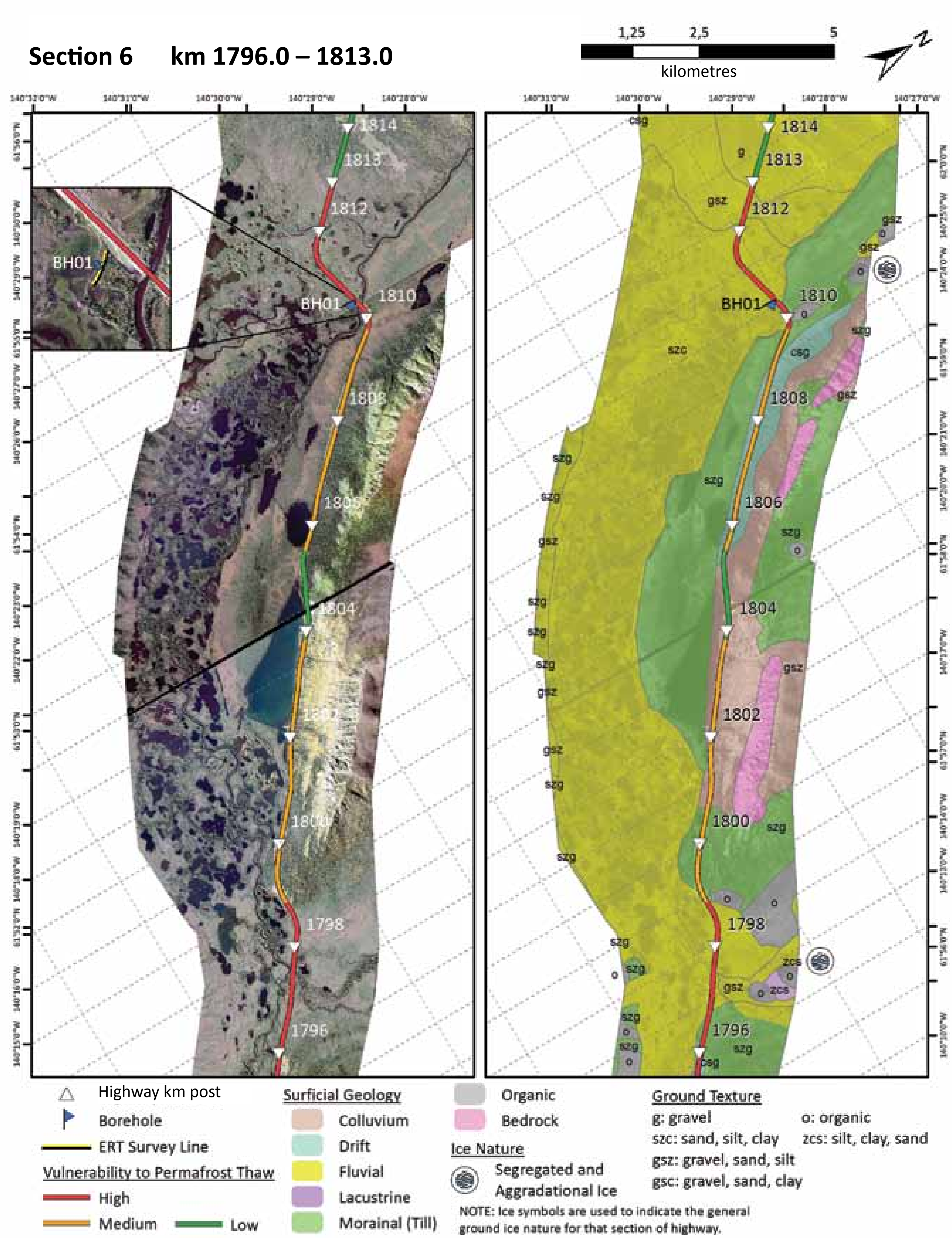
See p. 78–80

Borehole data	BH05	depth 4.75 m; grain size, water content
ERT	@BH05	115 m; 24 electrodes
Ground temperature	@BH05	5 depths; October 2013–October 2014

Drilling operation at BH05, km 1793.5.

Logger set-up at BH05, km 1793.5.

Ground temperature station at BH05, km 1793.5.


Section 6 km 1796.0 – 1813.0
1,25
2,5
5
kilometres
N
BH01
1814
1813
1812
1810
1808
1806
1804
1802
1800
1798
1796
Highway km post
Borehole
ERT Survey Line
Vulnerability to Permafrost Thaw
High
Medium
Low
Surficial Geology
Colluvium
Drift
Fluvial
Lacustrine
Morainal (Till)
Organic
Bedrock
Ice Nature
Segregated and Aggradational Ice
NOTE: Ice symbols are used to indicate the general ground ice nature for that section of highway.
Ground Texture
g: gravel
szc: sand, silt, clay
gsz: gravel, sand, silt
gsc: gravel, sand, clay
o: organic
zcs: silt, clay, sand

Section 6 km 1796.0 – 1813.0 Koidern No. 2

Vulnerability assessment

- This highway section is underlain by warm permafrost.
- Highway sections that cross fluvial units are highly vulnerable to thaw settlement until the active layer is below ice-rich permafrost (below 10 m deep).
- Highway sections that cross morainic units have low to medium vulnerability to thaw due to the low ground ice content in these units.
- Drift materials are less predictable because of their finer sediment content. They may thaw, but this will not lead to extensive road settlement. Other problems include the road being built at the hill toe, where seepage and slope processes occur in the warm permafrost.
- In this 16.97-km section of road, 35.6% is considered highly vulnerable (6.05 km); 54.5% is considered moderately vulnerable (9.24 km); and 9.9% is considered to have low vulnerability (1.67 km).

Geology

This section of the road alternates between a fluvial unit (with sediment ranging from silt to gravel that overlies drift material at some locations) and a glacial complex that comprises moraine and drift deposits. Both morainic and drift units are made of heterogenous sediment (coarse material in a finer matrix) that is overlain by colluvium and slope deposits at the foot of the hill slopes.

A meandering river system passes through the fluvial unit, leaving behind relict meanders and fine sediment deposits. Permafrost developed (aggraded) in these fine deposits during a colder period, forming a significant amount of ground ice. Because of warming temperatures, thermokarst features are developing.

The morainic unit is comprised of coarse sediment, which is less favourable to the development of ground ice and therefore less thaw-sensitive. Permafrost developed epigenetically after the glaciers retreated, from the top to the bottom, which has constrained its thickness.

The drift deposits have a higher content of fine grained sediment. The overlying colluvial deposits also contain a mix of coarse and fine material, but permafrost has developed syngenetically, with the deposition of each new sediment layer, and therefore might be more thaw-sensitive.

Permafrost

The permafrost is more problematic in the fluvial unit, which consists mostly of permafrost mounds and plateaus. Cores collected at km 1810.2 showed ice volume content as high as 59% and ice lenses 1 cm thick all along the profile. The ERT survey conducted at the same location suggests that ice-rich permafrost can be expected to be as thick as 10 m in this area. Once permafrost has degraded below this depth, the ground surface should stabilize. Ground temperature records shows that permafrost is warm (about –1°C). Although it is currently frozen, it is prone to degradation.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2.5	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

The projected increase in air temperature will affect the ground temperature of this warm permafrost, but because this section of the highway is close to a meandering river, the increase of precipitation may have more impact. Ground temperature records indicate that permafrost is sensitive to variations in water levels. Permafrost started to thaw from its base between summer 2013 and summer 2014. This is interpreted to be a result of the large amount of precipitation at the end of July 2013, which raised the water level close to the monitoring site. Sections located at the hill toe will be affected by the increase in occurrence and intensity of slope processes and seepage leaching from sediment.

Supporting data

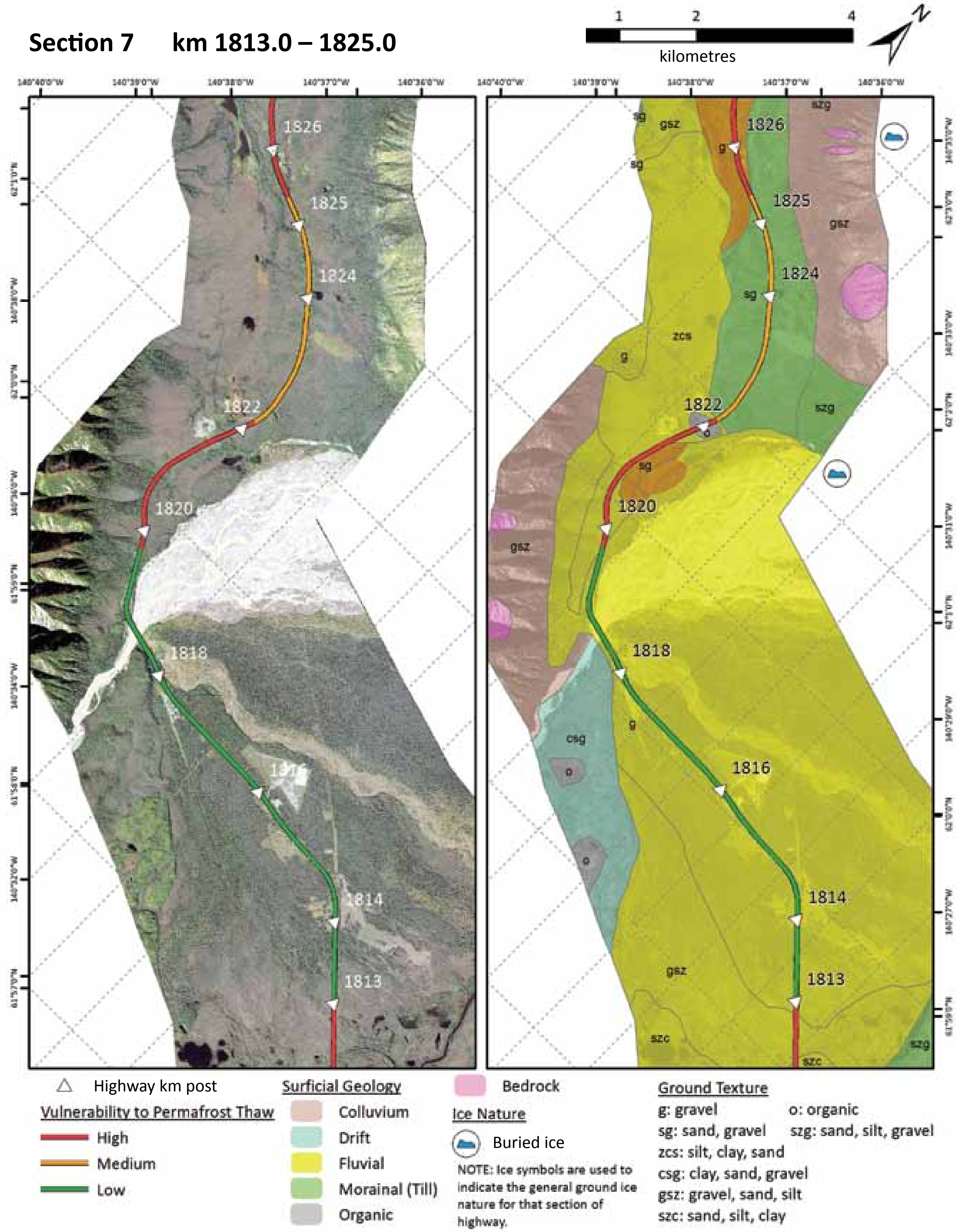
See p. 81–83

Borehole data	BH01	depth 6.13 m; grain size, ice volume content
ERT	@BH01	117.5 m; 48 electrodes
Ground temperature	@BH01	11 depths; October 2013–November 2014

Permafrost core at BH01, km 1810.2.

Downloading climate and ground temperature data at BH01, km 1810.2.

Section 7 km 1813.0 – 1825.0



Section 7 km 1813.0 – 1825.0 White River

Vulnerability assessment

- This highway section is underlain by warm permafrost.
- Highway sections that cross glaciofluvial and fluvial units are highly vulnerable to thaw settlement.
- Highway sections that cross morainic units have low to medium vulnerability to thaw settlement due to the units’ low ground ice content. The morainic units may thaw, but road settlement should be limited.
- Highway sections that cross active or coarse fluvial deposits are not expected to be on permafrost or thaw-sensitive permafrost.
- In this 12.01-km section of road, 20.3% is considered highly vulnerable (2.44 km); 23.1% is considered moderately vulnerable (2.78 km), and 56.6% is considered to have low vulnerability (6.79 km).

Note: Interpretations of thaw vulnerability for this section are based on data from the surveys in Section 9. See page 34.

Geology

This section of the road alternates between two major surficial geology components: a glacial complex and a fluvial complex. The glacial complex comprises moraine and glaciofluvial material. Morainic units are made up of heterogenous sediment (coarse material in a fine matrix) overlain by glaciofluvial sediments at some locations. Glaciofluvial units are more gravelly. The fluvial complex has sediment ranging from silt to gravel.

The morainic unit is comprised of coarse sediment that is less favourable to the development of ground ice, and therefore less thaw-sensitive. In addition, permafrost developed epigenetically after the glaciers retreated, from the top to the bottom, which has constrained its thickness.

The fluvial deposits vary in nature. If they are part of an active system, the sediment is gravelly and permafrost is absent, such as areas near the White River channel, where there are no thermokarst indicators. At some locations, fluvial deposits have finer sediment (clay, silt and sand) and they also overlie glaciofluvial material; deeply buried ground ice may also occur here.

Some organic rich soils occur; they are made of fibric organic material that favours permafrost aggradation. In addition, humidity has led to the growth of segregated ice, making these soils fairly thaw-sensitive.

Permafrost

Permafrost is absent from most of the fluvial units in this area. However, some of the units have finer sediment and overlie glaciofluvial material. This material can be problematic; as has been observed in other sections (see Section 9, km 1840.0–1855.0), massive ice can be present deep in the profile. The moraine units have permafrost and are expected to be moderately thaw-sensitive due to the coarse nature of the sediment and the recent age of permafrost in these deposits. Considering the neighbouring sections, permafrost is expected to be warm.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

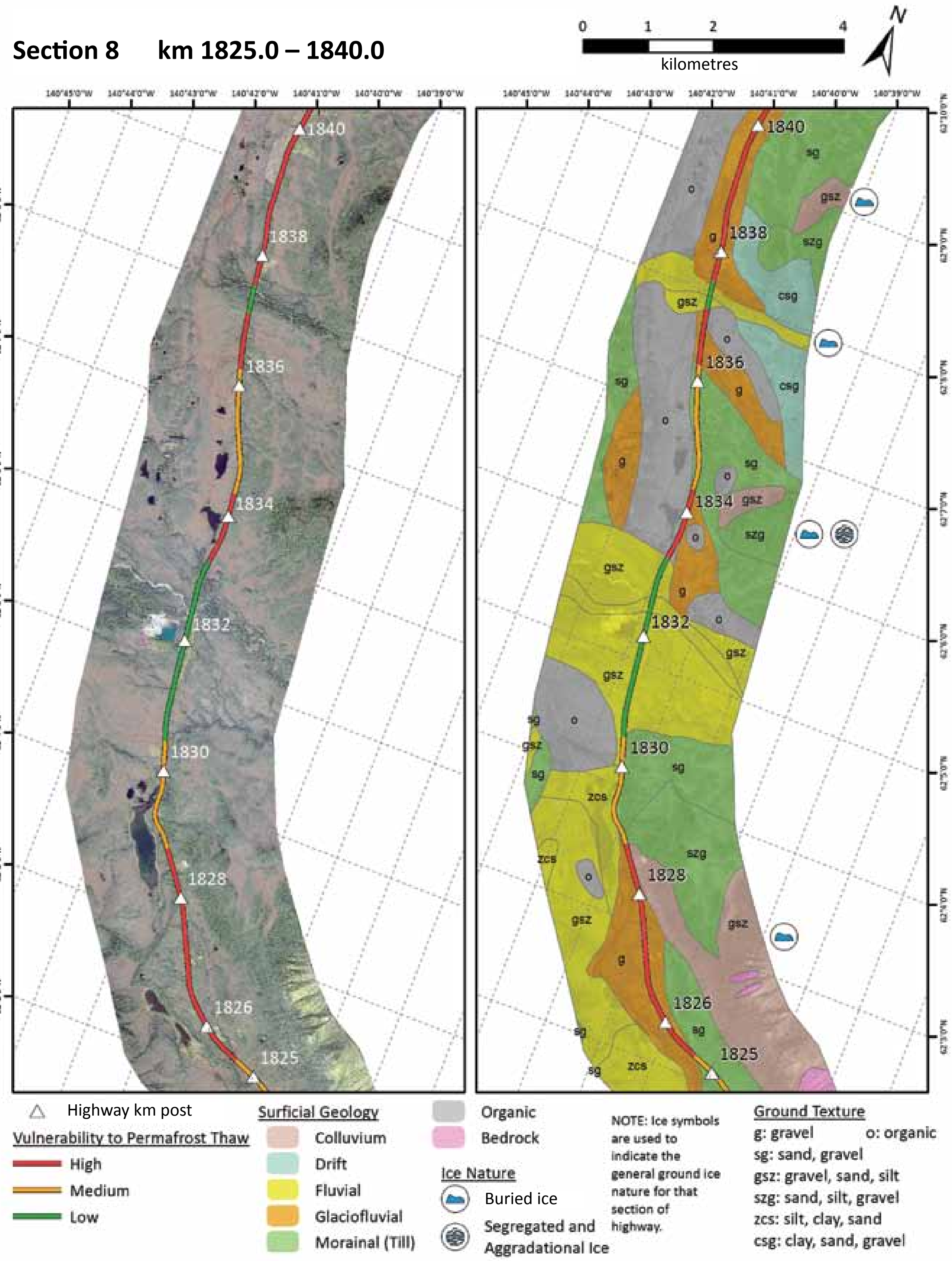
Large portions of this section have a low vulnerability to permafrost thaw and therefore climate change should not affect them. Where permafrost is considered highly vulnerable, climate warming may not have an immediate effect because ground ice can be buried deep in the ground. Once the permafrost table has lowered down to these depths, however, degradation will be intense and long-lasting.

Supporting data

N/A

IRIS electrical resistivity system, a one-channel imaging unit.

Section 8 km 1825.0 – 1840.0



Section 8 km 1825.0 – 1840.0 South of Dry Creek

Vulnerability assessment

Note: Interpretations of thaw vulnerability for this section are based on data from the surveys in Section 9, page 34.

- This highway section is underlain by warm permafrost.
- Highway sections that cross fluvial and glacial units are highly vulnerable to thaw settlement, even though degradation indicators are absent. This is due to the potential presence of massive ice up to 10 m below the ground surface (partially documented by consultants' reports). Colluvial material may also have high ground ice content below 5 – 7 m deep.
- Highway sections that cross morainic units are considered to have low to medium vulnerability due to the units' low ground ice content.
- For this 15.06-km section of road, 52.4% is considered highly vulnerable (7.89 km); 26.1% is considered moderately vulnerable (3.93 km); and 21.5% is considered to have low vulnerability (3.24 km).

Geology

This section of the road alternates between various surficial geology materials including glacial (moraines), glaciofluvial, fluvial and organic sediment as well as colluvium.

The glacial morainic complex was laid by ancient glaciers and consists of heterogeneous sediment (sand and mixed fragments in a finer matrix). The glacial deposits are less thaw-sensitive, because of the coarse nature of sediments and because permafrost has developed epigenetically after the glaciers retreated, from the top to the bottom, which has constrained its thickness.

Glaciofluvial deposits are formed when glacial sediments are washed out of the terminus of a glacier by meltwater and deposited; they are indicated along in this section by the presence of kettle holes. The glaciofluvial outwash consists mainly of gravel and sand and is typically assumed to have low vulnerability to thaw. However, as discussed in the Sections 9 and 10, these deposits may become highly problematic from km 1825 (in this section) to km 1860 (in Section 10) due to the presence of deeply buried ice.

Fluvial units deposited after the glaciers retreated have sediments ranging from silt and sand to gravel. Coarser sediments in more active fluvial zones have low vulnerability to thaw.

Fluvial, morainic and glaciofluvial units can be overlain by colluvium and other slope deposits that contain a mix of coarse and fine material. The colluvial deposits may have developed syngenetically, with permafrost forming with the each additional sediment layer. This increases the vulnerability to thaw of colluvium.

Organic soils have developed in poorly drained depressions. The thermal properties of the organic soil have favoured permafrost aggradation, and wetlands provide water that supports the formation of segregated ice. These soils have high vulnerability, but are isolated in extent along this highway section.

Permafrost

Although there are few signs of major degradation, the permafrost in this area is especially problematic in the glaciofluvial unit. Data collected in Section 9 (km 1840–1855) indicates that these deposits can contain bodies of massive ice that are hard to detect because they are deeper than 10 m. Although they have been stable since the construction of the highway, an increase in temperature or changes in precipitation, and resulting groundwater, may trigger degradation. If this occurs, the impact on the road will be substantial and long-lasting.

Climate

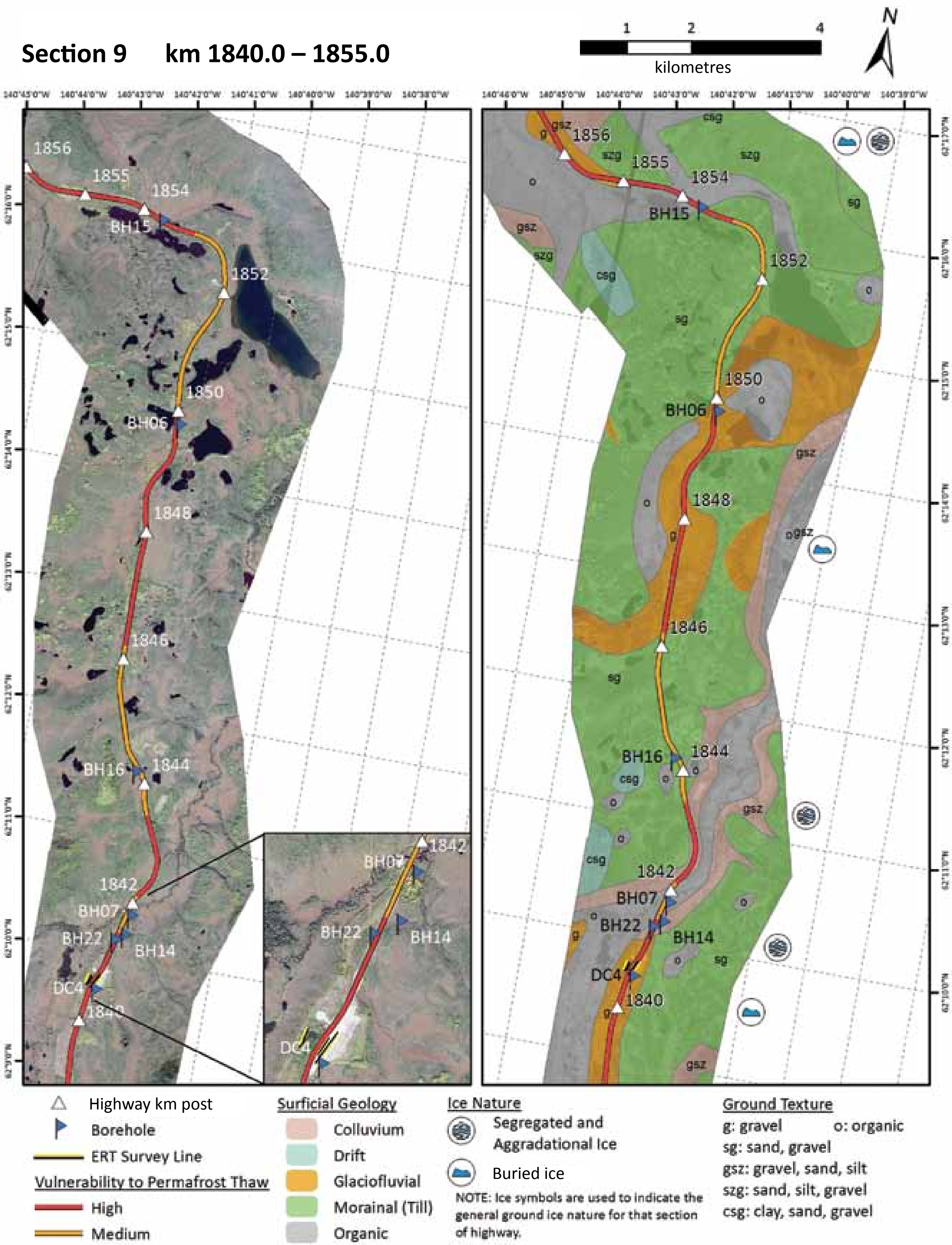
	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	30–40

The high vulnerably of portions of this section is related to the occurrence of buried ice below the glaciofluvial units. The warming climate may not have an immediate effect on permafrost, because it will take some time before the deepening permafrost table reaches the massive buried ice. However, once the permafrost table has lowered to these depths, degradation will be intense and long-lasting.

Supporting data

N/A

Cross-section of an ice wedge along an interceptor ditch near km 1894.


Section 9 km 1840.0 – 1855.0
1 2 4
kilometres
N
1856
1855
1854
1852
1850
1848
1846
1844
1842
1840
BH15
BH06
BH16
BH07
BH22
BH14
DC4
gsz
szg
csg
sg
o
g
Highway km post
Borehole
ERT Survey Line
Vulnerability to Permafrost Thaw
High
Medium
Surficial Geology
Colluvium
Drift
Glaciofluvial
Morainal (Till)
Organic
Ice Nature
Segregated and Aggradational Ice
Buried ice
NOTE: Ice symbols are used to indicate the general ground ice nature for that section of highway.
Ground Texture
g: gravel
o: organic
sg: sand, gravel
gsz: gravel, sand, silt
szg: sand, silt, gravel
csg: clay, sand, gravel

Section 9 km 1840.0 – 1855.0 Dry Creek

Vulnerability assessment

Note: Interpretations of thaw vulnerability for this section are also applied to nearby sections with similar surficial geology deposits.

- This highway section is underlain by warm permafrost.
- Highway sections that cross glaciofluvial units are highly vulnerable to thaw settlement, even though degradation indicators are absent. This is due to the presence of massive ice observed 10 m below the ground surface. Colluvial material may also have high ground ice content below 5–7 m.
- Highway sections that cross morainic units have low to medium vulnerability to thaw due to the units' low ground ice content.
- In this 14.93-km section of road, 57.1% is considered highly vulnerable (8.52 km); and 42.9% is considered moderately vulnerable (6.41 km). There are no areas with low vulnerability.

Geology

This section of the road alternates among various surficial materials, including glacial (moraines), glaciofluvial, and organic sediments and colluvium.

The glacial morainic complex was laid by an ancient glacier and consists of heterogeneous sediment (sand and mixed fragments in a finer matrix). The complex is comprised of coarse sediment that does not favour the development of ground ice; this limits thaw vulnerability. Permafrost developed epigenetically after the glaciers retreated, from the top to the bottom, which has constrained its thickness.

The glaciofluvial deposits of the Dry Creek area were deposited at the margin of a melting glacier. Glaciofluvial deposits are formed when glacial sediments are washed out of the terminus of a glacier by meltwater and deposited. The glaciofluvial outwash consists mainly of gravel and sand, and is typically assumed to have low vulnerability to thaw. However, as discussed below, these deposits are quite problematic in the Dry Creek area, and may be subject to severe degradation processes.

The organic soils developed in poorly drained depressions and overlie glaciofluvial material. They are made of fibric organic material (peat) and can be more than 14 m thick at some locations. The thermal properties of the organic soils favour permafrost aggradation, and their location in wetlands provides the water that supports the growth of segregated ice. Therefore, organic soils are often the most ice-rich, as demonstrated in this section by the occurrence of thermokarst lakes and ponds.

The glacial deposits described above can be overlain by colluvium and other slope deposits, and by glaciofluvial material. Colluvial deposits also contain a mix of coarse and fine material, but permafrost has developed syngenetically, with each new sediment layer, and it therefore might be more thaw-sensitive.

Permafrost

In this section, the permafrost has the potential to be highly problematic in several units. The following ice-rich cores have been documented, all in close proximity to one another:

- BH22 (km 1841.3), recovered from the Alaska Pipeline survey project, is located in a colluvial unit. It contains ice-rich clay sediments that start at about 7.5 m deep.

- BH07 (km 1841.8) is located in an organic unit. It showed icy organic silt (up to 54% of excess ice) down to 1.7 m deep before the drilling was stopped in gravelly sediment.
- BH16 (km 1844.1) is located in the moraine. It displayed ice-rich fine sediment (up to 80% of excess ice) in the first 2 m of the profile before hitting gravel.
- BH06 (km 1849.8) is located in a glaciofluvial unit. It had 2 m of icy silty sand (up to 49% of excess ice) before hitting gravelly sediment.
- BH15 (km 1853.6) is located in an organic unit that overlies glaciofluvial sediment. It showed icy organic silt (up to 80% of excess ice) down to 3 m deep.

Moraine and organic units seem ice rich in their upper levels, while colluvium appears to be ice rich at deeper levels. The latter may cause problems in the long term.

The glaciofluvial unit is potentially more problematic. When gravel was extracted from the slope facing the rest area at Dry Creek, it almost immediately triggered thermokarst processes. This is surprising, because such coarse material would normally contain very little ground ice. However, the following ERT surveys showed the occurrence of highly resistive material, which is a possible indicator of ice:

- At S1, west of a developing thermokarst pond that is west of the road, highly resistive material was observed, starting at about 8–20+ m deep. Resistivity values are in the range of frozen till, but thermokarst processes are an indicator of a significant amount of ground ice.
- At S2, east of the road, a highly resistive material was observed from about 6–20+ m depth. Resistivity values are in the range of frozen till, but thermokarst processes indicate a significant amount of ground ice.
- S3, performed closer to the bluff to the east of the road, showed a highly resistive body between about 10 and 25 m deep. Resistivity values have a magnitude of up to 107 Ohm.m, which is typical of a massive ice body.

Ground temperature records from BH14 and BH22 in the colluvial material show that the permafrost is warm (about –1.3°C at BH14 and –1.0°C at BH22). Although it is currently frozen, it is prone to degradation. However, the degradation may take time to manifest, especially in the glaciofluvial units, because the ice-rich levels and massive ground ice underneath and within this material are deep underground.

Origin of the ground ice: why is the glacial fluvial material so problematic?

Several hypotheses have been suggested to explain the unusual occurrence of ground ice in such coarse fluvial sediment. For example, the longitudinal shape of the observed deformation suggested an ice-wedge origin as a probable cause.

The ERT data collected at Dry Creek showed the highest resistivity measured along the highway, in the order of 10^7 Ohm.m. At the other sites, including those with confirmed ice wedges, values never exceeded 10^5 Ohm.m or the lower bracket of 10^6 Ohm.m. In the literature, resistivity values can be in the 10^8 Ohm.m magnitude in temperate glacier ice (Reynolds 1997); permafrost and sedimentary ice rarely exceed 10^6 Ohm.m (Gibas, Rachlewicz and Szczuciński 2005).

In May 2014, borehole DC4, performed by Guy Doré's team, found approximately 7 m of ice below the glaciofluvial gravel (Benoît Loranger, pers. comm.).

Given the results of the ERT surveys, the observation from borehole DC4, and the general geomorphological context of Dry Creek area, it can be assumed that the Dry Creek area is underlain by buried ice, rather than ice wedges, at some locations.

This report presents the hypothesis that the highly resistive material observed in the ERT profiles is relict glacial ice that has been buried since the glaciers retreated (Annex 1, page 91). The Dry Creek area was located at the margin of a melting glacier that has since disappeared. At the time of the glacial retreat, residual ice blocks, or even icebergs transported by glacial meltwater, became grounded and were subsequently buried — either partially or completely — by glacial outwash (see Annex 1, page 91). Glacial outwash is generated when streams of meltwater flow away from the glacier and deposit sediment; this forms a broad outwash plain called a sandur. When the ice blocks melt, circular depressions called kettle holes are left in the sandur.

Kettle holes can also form as the result of a flood when an ice-dammed lake suddenly drains. These floods often rapidly deposit large quantities of sediment onto the sandur surface, which buries glacial ice. The kettle holes are formed by the melting blocks of sediment-rich ice that were transported and consequently buried by the flood.

Numerous kettle holes can be observed in the Dry Creek area on satellite imagery and surficial geology maps. Either of the mechanisms for kettle hole formation described above could apply in the Dry Creek area. The glaciofluvial deposit is an outwash, and what was mapped as colluvium is the relict deposit of a proglacial lake. The fine-grained sediment, silt and clay that was observed in the borehole BH22 (see log, p. 84) in the colluvium north of the rest area indicates a former lacustrine environment, and tends to support the glacial flood mechanism. The rest of the sediment would have been eroded during the flood.

When the lake drained, the buried ice — instead of melting — was incorporated within the aggrading permafrost, which was able to aggrade quickly in the coarse, well-drained material of the glaciofluvial/outwash deposits. In this context, the thermokarst pond observed south of the rest area may be a forming kettle hole.

Longitudinal deformation observed in the area would attribute to buried ice that is beside and/or enclosed in an esker. Some eskers can be observed southeast of the area.

Regardless of the mechanism that formed the kettle holes, relict glacial ice may remain, insulated by the sediments above it. The high resistivity values, surficial geology and amount of time since the last glaciation (which is too short for ice wedges to develop at this scale) all suggest that the observed ice is unlikely to have an ice wedge origin.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50

The high vulnerably of portions of this section is related to the occurrence of buried ice below the glaciofluvial units. The warming climate may not have an immediate effect on permafrost, because it will take some time before the deepening permafrost table reaches the massive buried ice. However, once the permafrost table has lowered to these depths, degradation will be intense and long-lasting.

Supporting data **See p. 84–91**

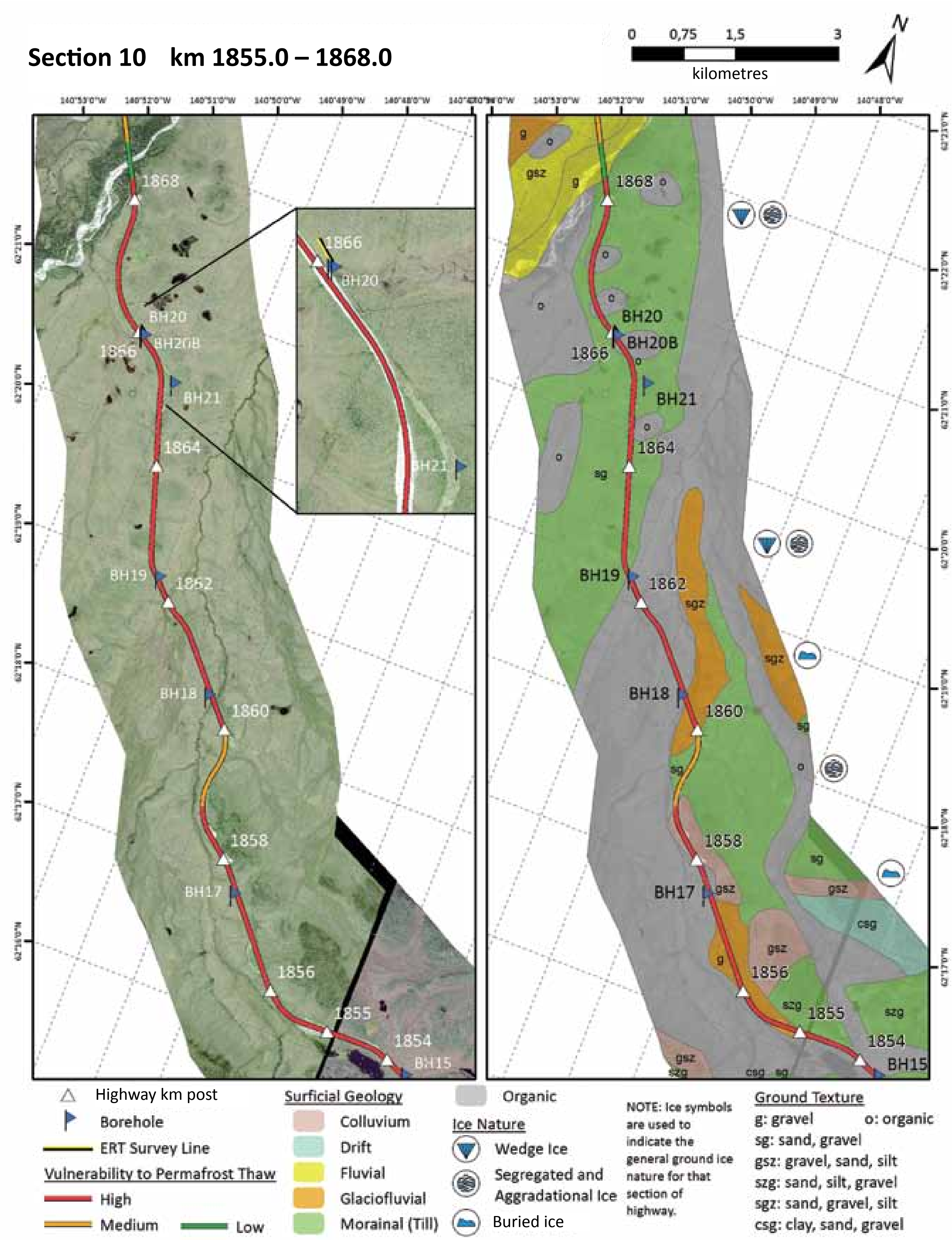
Borehole data (from south to north)	BH22	depth 9.9 m; log observation, ice volume content
	BH07	depth 1.67 m; grain size, ice volume content
	BH16	depth 2.02 m; grain size, ice volume content
	BH06	depth 2.06 m; grain size, ice volume content
	BH15	depth 3.0 m; grain size, ice volume content
ERT	S1	west to the thermokarst pond; 117.5 m – 48 electrodes
	S2	east to the road embankment; 117.5 m – 48 electrodes
	S3	east to the road, close to the cut; 230 m – 48 electrodes
Ground temperature	@BH14	8 depths; October 2013–July 2014
	@BH22	4 depths; August–November 2014

Thermokarst pond near the Dry Creek rest area.

Thermokarst pond near the Dry Creek rest area.

Restored gravel pit east of Dry Creek rest area.

Section 10 km 1855.0 – 1868.0



Section 10 km 1855.0 – 1868.0 Southern Beaver Creek

Vulnerability assessment

- This highway section is underlain by relatively cold permafrost.
- Most of the geomorphic units along this highway section are highly vulnerable to thaw settlement. In the glaciofluvial units, massive ice could be present from 10 m below the ground surface. In glacial and organic material, the first 15 m are ice-rich.
- Highway sections on the McConnell morainic unit are considered to have medium vulnerability due to the unit's low ground ice content.
- In this 13.01-km section of road, 91.5% is considered highly vulnerable (11.91 km); and 8.5% is considered moderately vulnerable (1.10 km). There are no areas with low vulnerability.

Note: Interpretations of thaw vulnerability for this section are based on data from the surveys in Section 9, page 34.

Geology

This section of the road alternates among various surficial geology materials including colluvium and glacial (moraines), glaciofluvial and organic sediment.

The glacial morainic complex was laid by ancient glaciers. The southern units date to the McConnell glaciation (18,000 years ago); the northern units were probably laid by an older glaciation. Both units consist of heterogeneous sediment (sand and mixed fragments in a finer matrix). The McConnell glacial deposits are less thaw-sensitive because of their coarse nature and because permafrost developed epigenetically, from the top to the bottom, which has constrained its thickness. The more ancient moraine seems more problematic; permafrost has had more time to develop within the unit and depressions have been filled by finer material from various origins.

Glaciofluvial deposits are formed when glacial sediments are washed out of the terminus of a glacier by meltwater and deposited. The glaciofluvial outwash consists mainly of gravel and sand, and is therefore assumed to have little vulnerability to thaw. Yet, as discussed in Sections 8 and 9, these deposits may be quite problematic from km 1825–1860.

Both glacial and glaciofluvial deposits can be overlain by colluvium and other slope deposits that also contain a mix of coarse and fine material. The overlying colluvial deposits may have developed syngenetically, with the deposition of each new sediment layer, which increases their thaw vulnerability.

The organic soils have developed in poorly drained depressions. Their thermal properties favoured permafrost aggradation, while wetlands provide water supply that supported the growth of segregated ice.

Permafrost

Permafrost is problematic in most of the section. The section of highway that crosses the glaciofluvial unit may have few signs of major degradation at this time, but as discussed in Sections 8 and 9, the glaciofluvial sediment may cover buried ice. In addition, boreholes showed high excess ice, which will lead to higher thaw vulnerability:

- BH17 (km 1857.2) and BH18 (km 1860.4) showed excess ice content up to 86% in organic material.

- BH19 (km 1862.3), located at the boundary between organic and glacial sediment, showed a fine-grained material and wedge ice with 99% of excess ice content at some levels.
- BH20 (km 1866) was drilled in an ancient morainic unit. Similarly to BH19, it also contains fine-grained sediment and up to 89% of excess ice content. BH20b is a duplicate of BH20 that was not analysed.
- BH21 (km 1865.2) is an Alaska Pipeline Project borehole drilled at the toe of an abandoned section of the highway. The warm ground temperature recorded in the borehole, about –0.6°C, is symptomatic of the disturbance of the road embankment at the toe. Grain-size, cryostructure and ice-volume analyses were not available for this core.

An ERT survey at the site of BH20 suggests that 15 m of ice-rich material is underlain by less resistive material, possibly ancient taliks.

Ground temperature records at BH20 show that the permafrost is around –2.4°C, which is colder than permafrost found south of this section.

Climate

	Temperature (°C)				**Precipitation (mm)**			
	2030		**2050**		**2030**		**2050**	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50

The high vulnerability of portions of this section is related to the occurrence of buried ice below the glaciofluvial units. Therefore, the warming climate may not have an immediate effect on permafrost; it will take some time before the deepening permafrost table reaches the massive buried ice. However, once the permafrost table has lowered to these depths, degradation will be intense and long-lasting. At other locations, ground ice content is located higher in the profile; therefore, degradation will be more systematic over time.

Supporting data

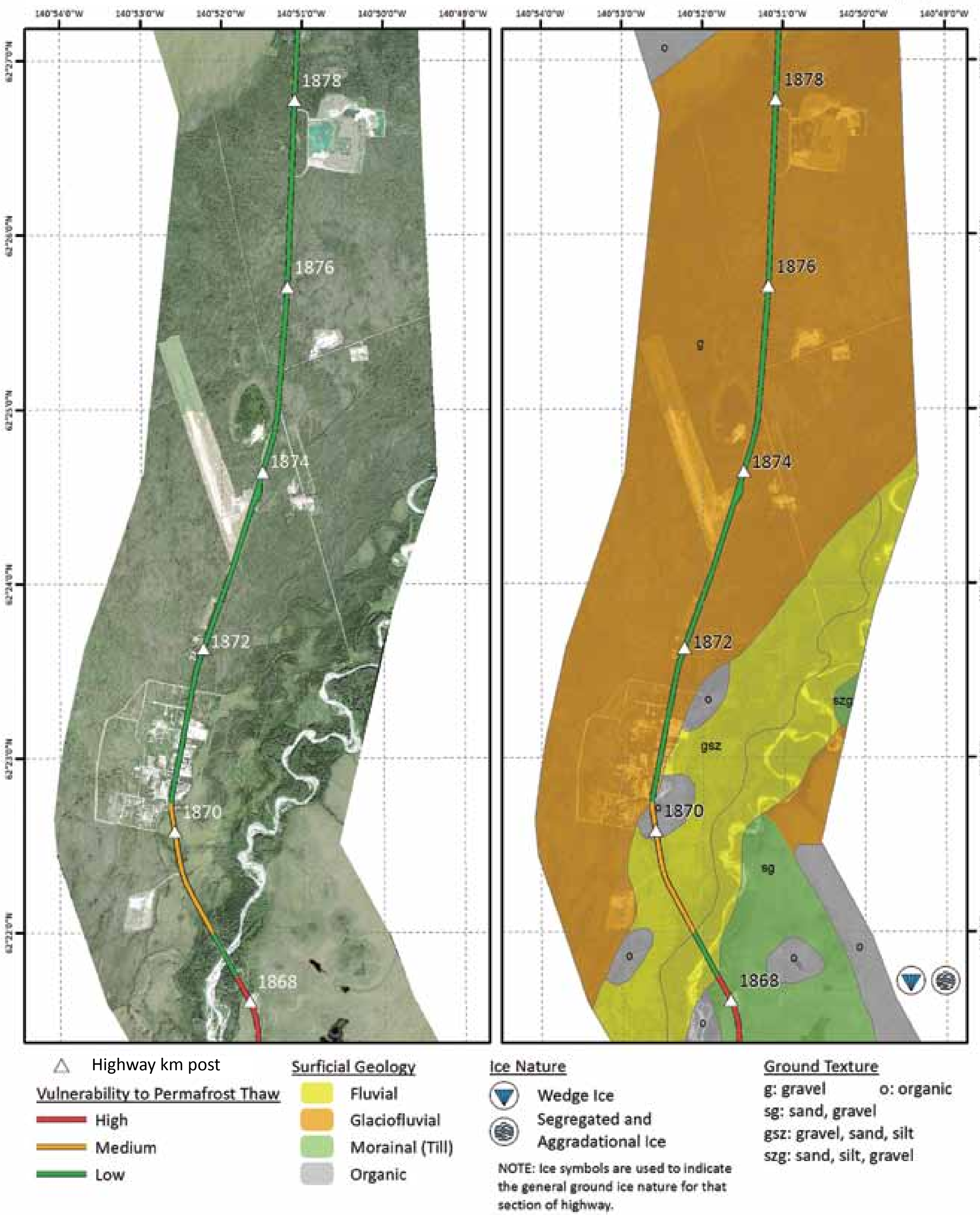
See p. 92–99

Borehole data	BH17	depth 2.74 m; grain size, ice content
	BH18	depth 3.08 m; grain size, ice content
	BH19	depth 2.61 m; grain size, ice content
	BH20	depth 4.77 m; grain size, ice content
	BH20b	depth 5.08 m; log
ERT	@BH20	235 m – 48 electrodes
Ground temperature	@BH20	5 depths; May–July 2014
	@BH20b	5 depths; July–November 2014
	@BH21	5 depths; August–November 2014

Drilling operation at BH20, km 1866.

Wedge ice from BH19, km 1862.3.

Section 11 km 1868.0 – 1878.0



Section 11 km 1868.0 – 1878.0 Beaver Creek

Vulnerability assessment

- Highway sections that cross glacial morainic materials are highly high vulnerable to thaw settlement, with the first 15 m below ground having the most ice-rich materials.
- Highway sections on glaciofluvial material and fluvial units are considered to have low to medium vulnerability due to the gravelly texture and low ground ice content of these units.
- In this 10.18-km section of road, 3.6% is considered highly vulnerable (0.36 km); 14.5% is considered moderately vulnerable (1.48 km); and 81.9% is considered to have low vulnerability (8.34 km).

Geology

This section of the road passes over glacial (moraines), fluvial, organic and glaciofluvial sediment.

The area was not glaciated during the McConnell glaciation (18,000 years ago); the moraine was laid by an earlier glacier. It consists of sand and mixed fragments. However, as shown in Section 10 (km 1855–1868; BH20 and 20b), this material could be fine grained. The moraine is ancient and permafrost has had significant time to develop. In addition, some depressions have been filled by finer material from various origins. These filled depressions can be highly vulnerable to thaw.

The glaciofluvial deposits are formed of glacial sediments that were deposited by meltwater. The glaciofluvial outwash consists of gravel and is therefore assumed to have little to no vulnerability to thaw.

Fluvial deposits are gravelly in the active riverbed, and there is sandy and silty content along the periphery of the river. The active fluvial system is gravelly and not thaw-sensitive, but the fine content of the peripheral deposits might be more thaw-sensitive.

An organic rich unit that was mapped at km 1870 may have developed in a low wetland area. The organic soils are thaw-sensitive because they have developed in poorly drained depressions. The thermal properties of the organic soils favour permafrost aggradation, while wetlands provide water that supports the growth of segregated ice.

Permafrost

Because this section is outside of but near the boundary of the McConnell glaciated area, it is not expected that there is any buried ice under the glaciofluvial deposits. To date, the borrow pits that have been dug in the area have not triggered thermokarst processes. Consequently, this area generally appears to have little vulnerability to thaw.

As discussed in Section 10 (km 1855–1868), drilling and geophysics in the pre-McConnell moraine and the organic soils showed the presence of fine-grained materials and wedge ice, and a permafrost temperature of approximately –2.4°C.

The fluvial deposits for this section are gravelly and do not indicate the presence of thermokarst processes. Permafrost is probably not present in this material or in the overlying organic unit.

Climate

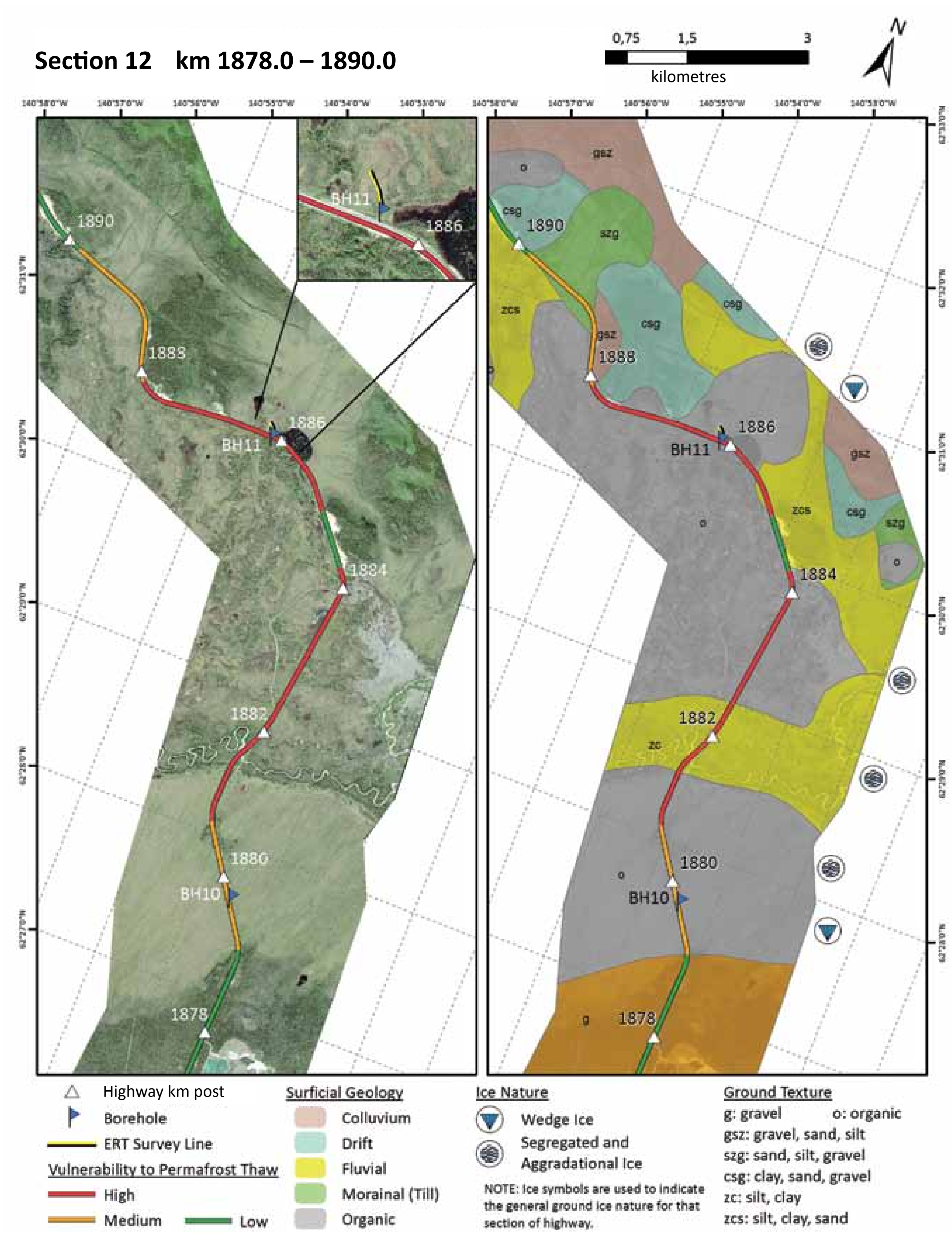
	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50

Climate change is not expected to have a major impact on this section of the highway.

Supporting data

N/A

A camera crew films as the research crew extracts and field-logs a permafrost core.


Section 12 km 1878.0 – 1890.0
0,75
1,5
3
kilometres
N
1890
1888
1886
1884
1882
1880
1878
BH11
BH10
gsz
o
csg
szg
zcs
zc
g
Highway km post
Borehole
ERT Survey Line
Vulnerability to Permafrost Thaw
High
Medium
Low
Surficial Geology
Colluvium
Drift
Fluvial
Morainal (Till)
Organic
Ice Nature
Wedge Ice
Segregated and Aggradational Ice
NOTE: Ice symbols are used to indicate the general ground ice nature for that section of highway.
Ground Texture
g: gravel
o: organic
gsz: gravel, sand, silt
szg: sand, silt, gravel
csg: clay, sand, gravel
zc: silt, clay
zcs: silt, clay, sand

Section 12 km 1878.0 – 1890.0 Thermokarst area

Vulnerability assessment

- This highway section is underlain by warm permafrost.
- The highway crosses fluvial and organic units that are highly vulnerable to thaw settlement. Ice-rich permafrost can be expected as deep as 15 m or more.
- Highway sections on glaciofluvial and glacial material and colluvium have low to medium vulnerability due to lower ground ice content and the thickness of the deposits.
- In this 11.91-km section of road, 48.3% is considered highly vulnerable (5.76 km); 35.7% is considered moderately vulnerable (4.25 km); and 16% has low vulnerability (1.90 km).

Geology

This section of the road is located on terrains that were not glaciated during the McConnell glaciation. It alternates among various surficial geology units, including glacial (drift and moraine), glaciofluvial, fluvial and organic sediment and colluvium.

The glacial complex is located at the southern end of the section. It includes drift made of clay, silt, sand and mixed fragments, and moraine consisting of silt, sand and mixed fragments. Glaciofluvial deposits are found at the southern end of the section. They consist of gravel that is sometimes covered by organic soil.

Colluvial deposits containing silt, sand and mixed fragments are associated with higher-relief topography. They often overlie glacial deposits. The colluvium is more thaw-sensitive and is mostly located on slopes. In addition, colluvium may overlie more thaw-sensitive material at some locations. Slope movements and solifluction may cause problems for the road.

The fluvial complex in this area consists of silt and clay. It is also covered by organic sediment in areas of low relief where conditions are wetter. Both fluvial and organic units are problematic. Fluvial deposits are fine grained and thick, at least in the first metres of the profile, while organics overlie fluvial or glaciofluvial deposits in poorly drained areas.

The thermal properties of the fibric organic material have favoured ice-rich permafrost development. Wetlands have provided water that supports the growth of segregated ice and the formation of frost mounds. Extensive thermokarst processes, including pond and lake formation, are occurring.

Drift material contains finer sediment than the moraine, so it might be considered more thaw-sensitive. Because of the coarse nature of both materials, however, they can be considered to have relatively low thaw vulnerability.

Permafrost

Permafrost is the most problematic in the fluvial and organic units. BH10 (km 1879.7), which is located in organic material, showed fine ice-rich organic sediment in the first 1.5 m of the profile, before reaching gravel in the underlying glaciofluvial deposit. BH11 (km 1886), which is located on a frost mound near a thermokarst lake, alternated between sandy silt and silty sand sediments; the excess ice content is high in both materials. Ice content reaches a maximum of 85% in silty sand.

An ERT survey was performed at the site of BH11 from the frost mound outward into the adjacent field. It suggests that ice-rich permafrost may extend down to at least 20 m and possibly farther.

Ground temperatures at BH11 are relatively warm (around –1.5°C at 8.5 m deep). Because the permafrost can be particularly ice-rich and is relatively thick and warm, it is expected to be highly thaw-sensitive.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50

The projected increase in air temperature will have direct impacts on the warm permafrost in locations such as BH11. The projected increase in precipitation will result in higher water levels and possible flooding. Permafrost located in wetland areas will degrade faster here than elsewhere along the highway. Frost mounds and permafrost plateaus will be especially vulnerable.

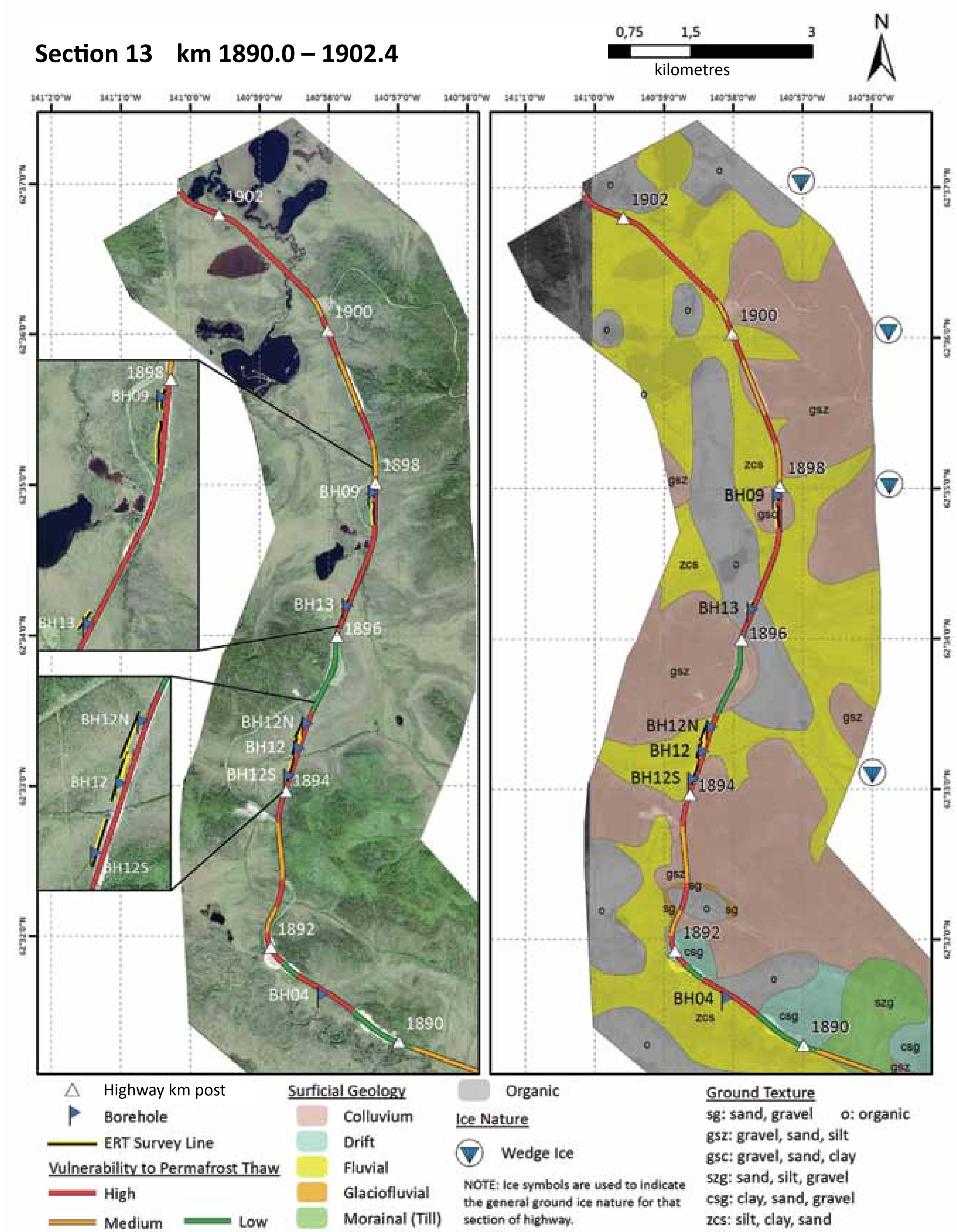
Supporting data

See p. 100–103

Borehole data	BH10	depth 1.48 m (log)
	BH11	depth 5.90 m (grain size, ice content)
ERT	@BH11	117.5 m – 48 electrodes.
Ground temperature	@BH11	5 depths from October 2013–November 2014

Degradation observed at km 1881.

Permafrost core collected at BH11, km 1886.


Section 13 km 1890.0 – 1902.4
0,75
1,5
3
kilometres
N
1902
1900
1898
BH09
BH13
1896
BH12N
BH12
BH12S
1894
1892
BH04
1890
gsz
zcs
gsc
o
sg
csg
szg
Highway km post
Borehole
ERT Survey Line
Vulnerability to Permafrost Thaw
High
Medium
Low
Surficial Geology
Colluvium
Drift
Fluvial
Glaciofluvial
Morainal (Till)
Organic
Ice Nature
Wedge Ice
NOTE: Ice symbols are used to indicate the general ground ice nature for that section of highway.
Ground Texture
sg: sand, gravel
o: organic
gsz: gravel, sand, silt
gsc: gravel, sand, clay
szg: sand, silt, gravel
csg: clay, sand, gravel
zcs: silt, clay, sand

Section 13 km 1890.0 – 1902.4 U.S. border

Vulnerability assessment

- This highway section is underlain by relatively cold permafrost.
- Highway sections that cross fluvial and organic units are highly vulnerable to thaw settlement. Ice-rich permafrost can be expected as deep as 20–25 m. The permafrost base could be as deep as 60 m.
- Highway sections that cross glacial and colluvium units have low to medium vulnerability to thaw due to lower ground ice content and the thickness of the deposits.
- In this 12.75-km section, 63% is considered highly vulnerable (8.03 km); 19.9% is considered moderately vulnerable (2.54 km); and 17.1% is considered to have low vulnerability (2.18 km).

Geology

This section of the road is located on terrain that was not glaciated during the McConnell glaciation. It alternates among various surficial geology materials, including glacial (drift), glaciofluvial, colluvial, fluvial and organic sediments.

The glacial drift complex was laid by glaciers older than the McConnell glaciation. Located at the south of this section, its materials are heterogeneous, consisting of sand and fragments in a mix of silt and clay. Glaciofluvial sediment is encountered in only one location (km 1892.5) and contains sand and gravel covered by an organic unit. Colluvium is present on the relief or close by. They are comprised of silt, sand and mixed fragments. The fluvial complex fills the valley bottoms in this area and consists of sand, silt and clay. Some organic soils overlie fluvial material.

Because of its coarse nature and its position directly over the bedrock, glacial (drift) material can be considered to have low vulnerability to thaw. The colluvial units are more thaw-sensitive, but their thickness can be assumed to be relatively limited because of their location on slopes. However, because the colluvium may overlie more sensitive material at some locations, slope movements and solifluction might cause problems for the road.

The fluvial and organic units are the most problematic. Fluvial deposits are fine grained and thick. Air photos and field observation show that they contain ice wedge networks. In addition, organic soils often overlie fluvial deposits, having developed in poorly drained depressions. The thermal properties of the organic soils favoured permafrost aggradation, and wetlands provide water that supports the growth of segregated ice. Organic units also display ice-wedge networks. Both fluvial and organic units show the development of thermokarst processes such as water ponding.

Permafrost

Permafrost is most problematic in fluvial and organic units. For example, BH04 (km 1891.1), BH 12S, 12 and 12N (between km 1894.2 and 1894.8), and BH13 (km 1896.3), were located in either fluvial or organic deposits. They all display ice-rich fine-grained material; some of them pass through ice wedges. Alaska pipeline boreholes (unpublished) and stratigraphic sections 4-A07, 4-A08 and 4-A09 from the surficial geology map show that such conditions can be encountered as deep as 20 m. BH09 (km 1897.8), located in colluvium landslide deposits, showed the same characteristics.

An ERT survey at the sites of BH12 and BH13 suggest ice-rich (probably wedge ice) permafrost down to at least 20 m, and surveys at BH09 indicate that it could occur as deep as 25 m.

Ground temperature records at BH12 and BH13 show a relatively cold permafrost temperature compared to highway sections farther south (–3.2°C and –2.2°C, respectively). BH09 has a warmer permafrost temperature (–1.2°C).

In this area, temperature profiles and literature suggest than permafrost could be as thick as 60 m. It is expected that permafrost degradation will be both long-lasting and large in magnitude.

Climate

	Temperature (°C)				Precipitation (mm)			
	2030		2050		2030		2050	
Emission scenario	a1b	b1	a1b	b1	a1b	b1	a1b	b1
Change from 1980–2009	1.5–2	2–2.5	3.5–4	2.5–3	40–50	20–30	70–80	40–50

Permafrost is especially thick and ice rich in the valleys. Therefore, an increase in snowfall will have the most detrimental effect where its accumulation will prevent permafrost cooling during the winter. Because permafrost is colder along some portions of this section, the effect of the climate warming may be delayed in comparison with the southern section of the highway. However, once it has warmed up, permafrost degradation will have an intensity that is proportional to its ground ice richness and a duration commensurate with its thickness.

Supporting data

See p. 104–115

Borehole data	BH04	depth 2.88 m; grain size, ice content
	BH12S	depth 5.86 m; grain size, ice content
	BH12	depth 4.36 m; grain size, ice content
	BH12N	depth 5.83 m; grain size, ice content
	BH13	depth 4.85 m; grain size, ice content
	BH09	depth 5.44 m; grain size, ice content
ERT	@BH12S	235 m – 48 electrodes
	@BH12	235 m – 48 electrodes
	@BH12N	235 m – 48 electrodes
	@BH13	117.5 m – 48 electrodes
	@BH09	cut 235 m – 48 electrodes
	@BH09	station 117.5 m – 48 electrodes
Ground temperature	@BH12	11 depths; August 2013–November 2014
	@BH13	5 depths; October 2013–November 2014
	@BH09	5 depths; July 2013–November 2014

Top of an ice wedge collected at BH13, km 1896.3.

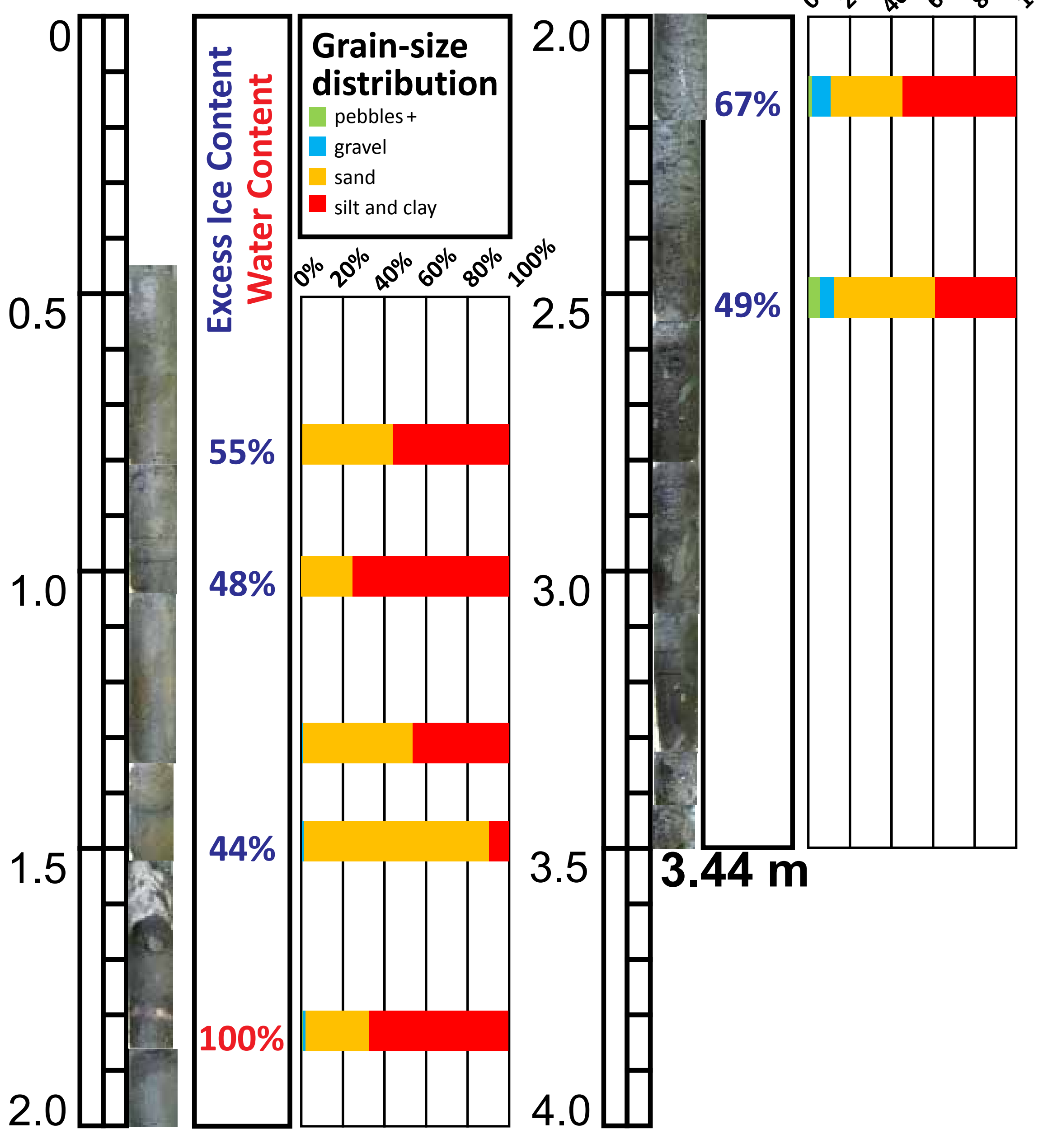
Water jet drilling at BH13, km 1896.3

Annexes

Annex 1. Supporting Data

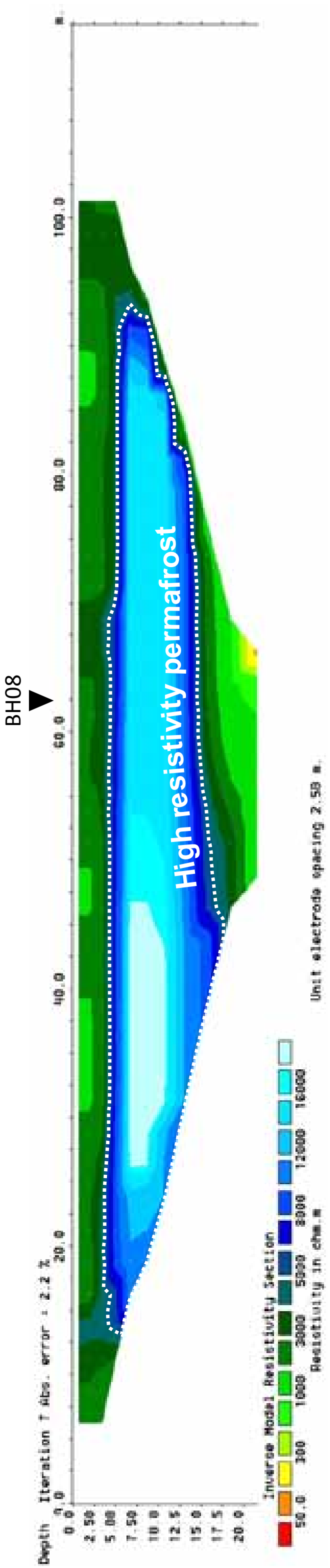
Section 2 km 1717.0 – 1738.0 Kluane River

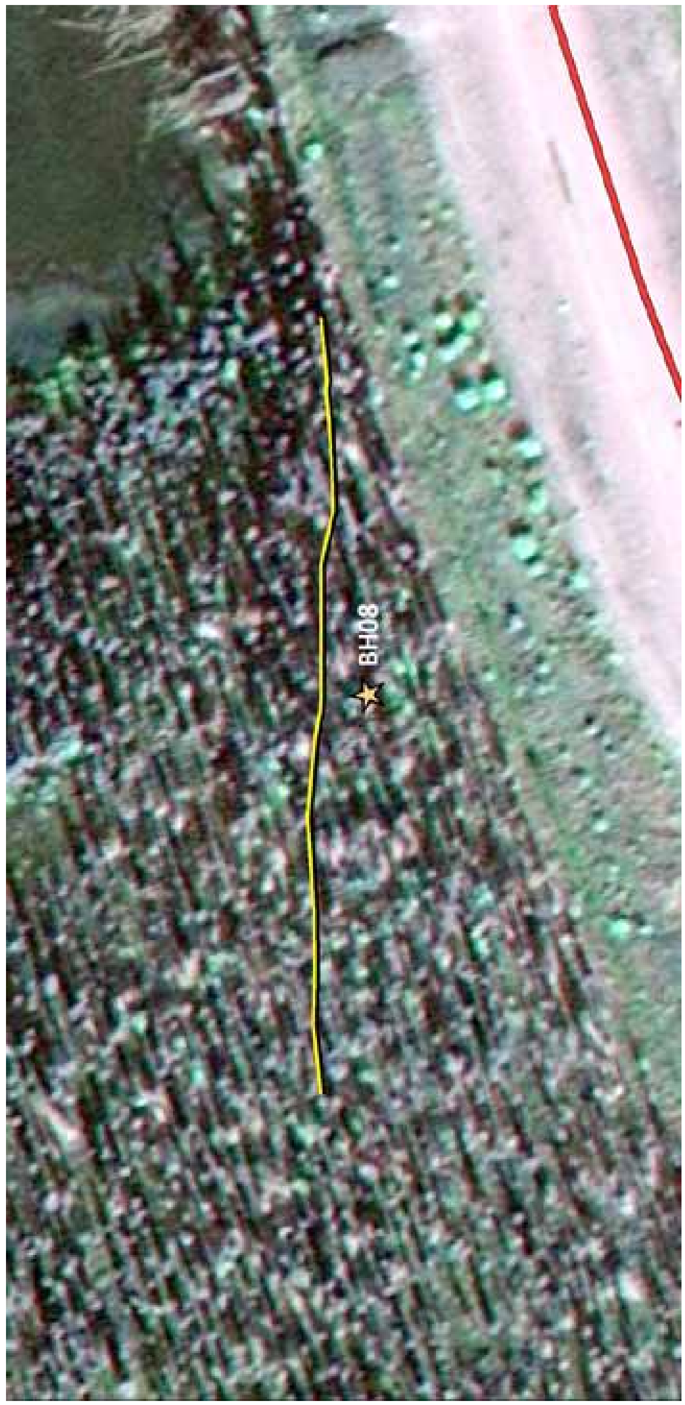
BH08, km 1719.1



Section 2 (continued)

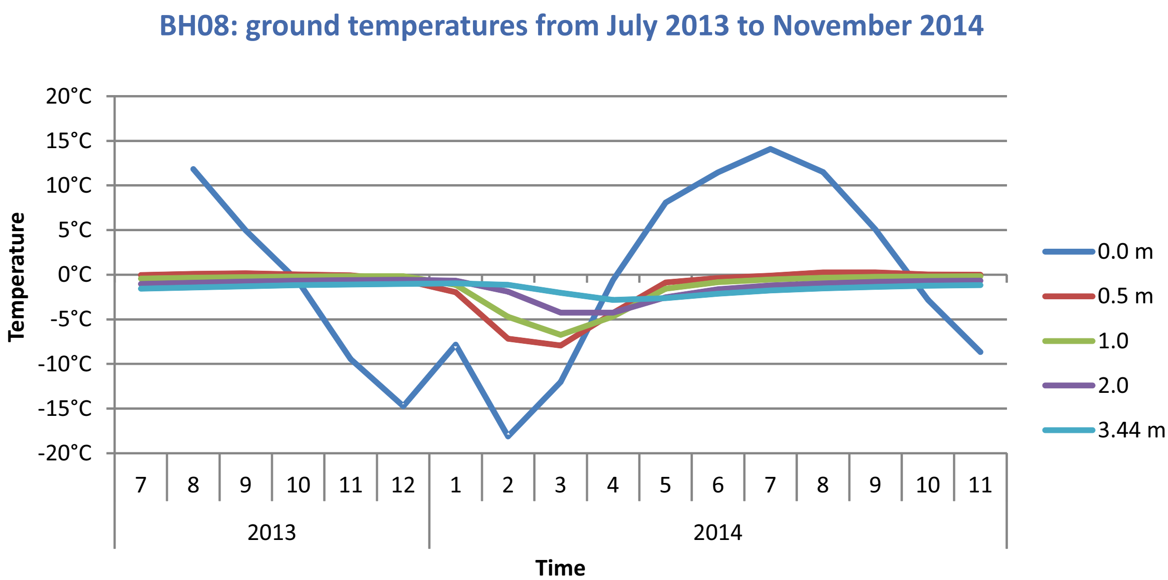
BH08, km 1719.1



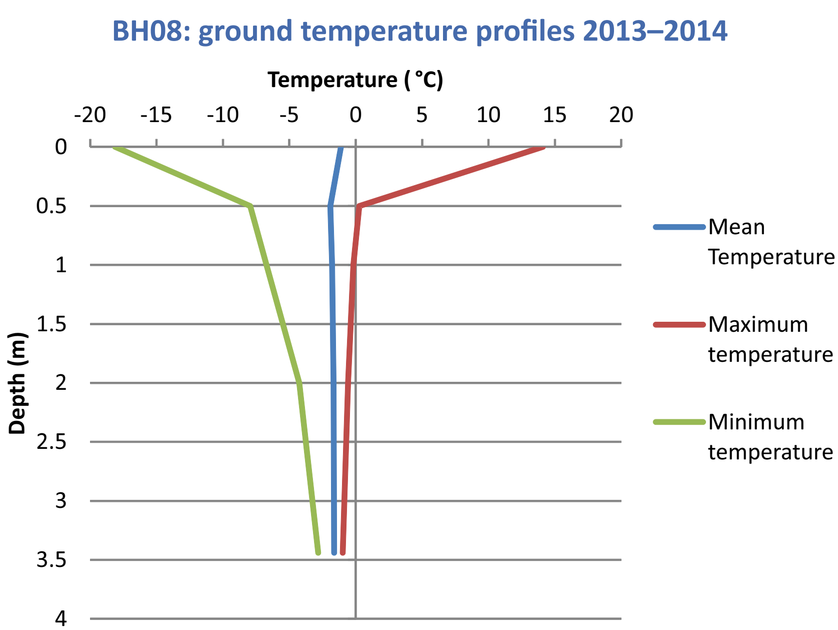


Section 2 (continued)

BH08, km 1719.1

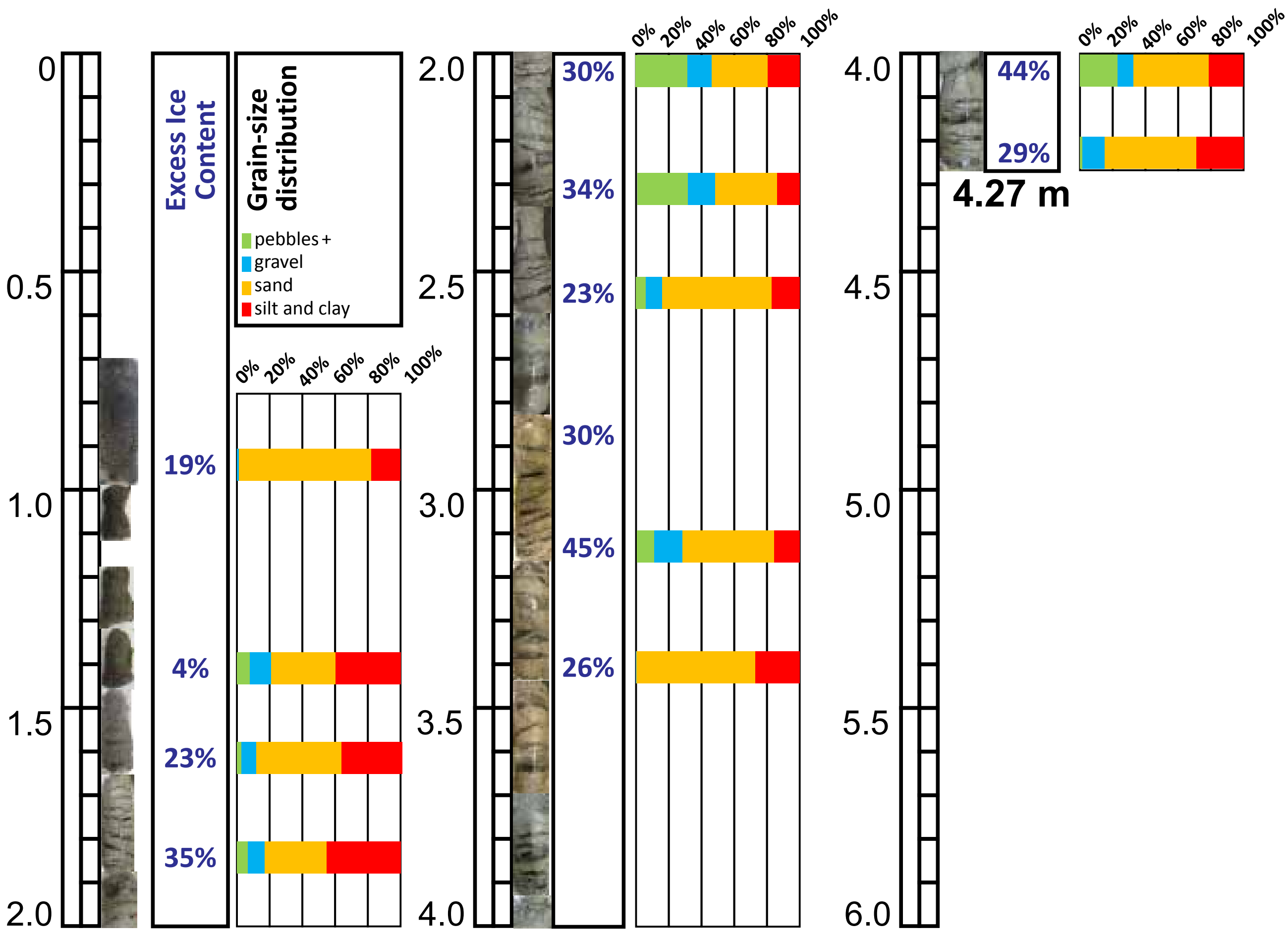


Depth (m)	0	0.5	1	2	3.44
Mean Monthly Temperature	-1.1°C	-1.9°C	-1.8°C	-1.7°C	-1.6°C
Maximun Monthly Temperature	14.1°C	0.3°C	-0.2°C	-0.6°C	-1.0°C
Minimum Monthly Temperature	-18.1°C	-7.9°C	-6.7°C	-4.3°C	-2.8°C



Section 3 km 1738.0 – 1760.0 Swede Johnson Creek

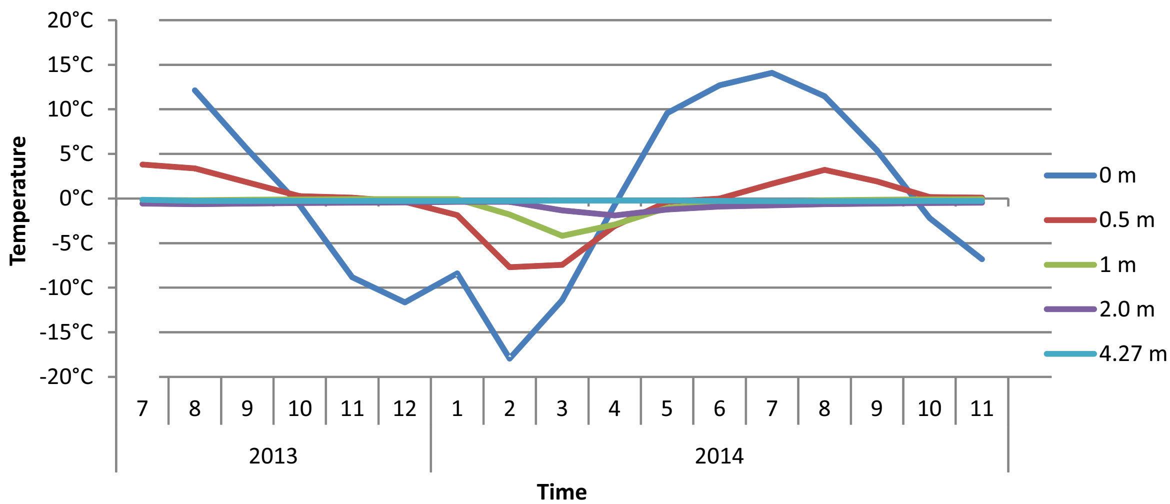
BH02, km 1738.7



Section 3 (continued)

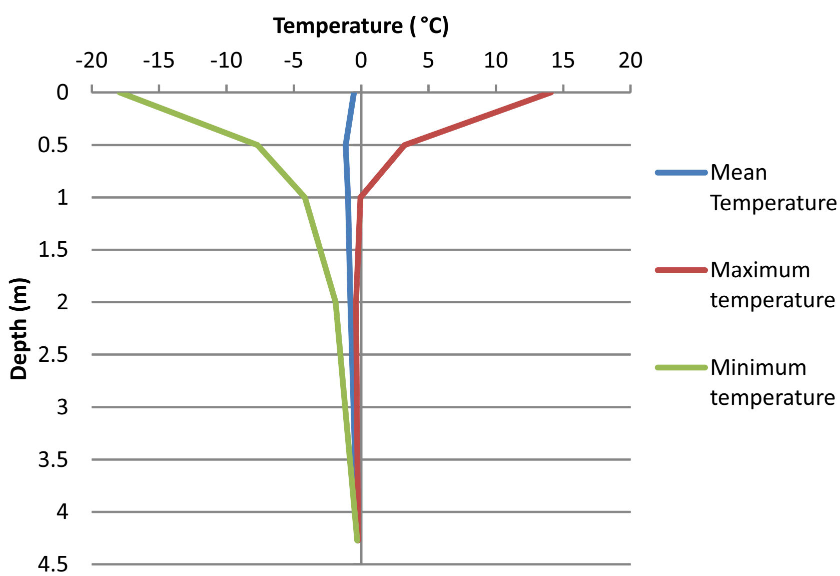
BH02, km 1738.7

BH02: ground temperatures from July 2013 to November 2014



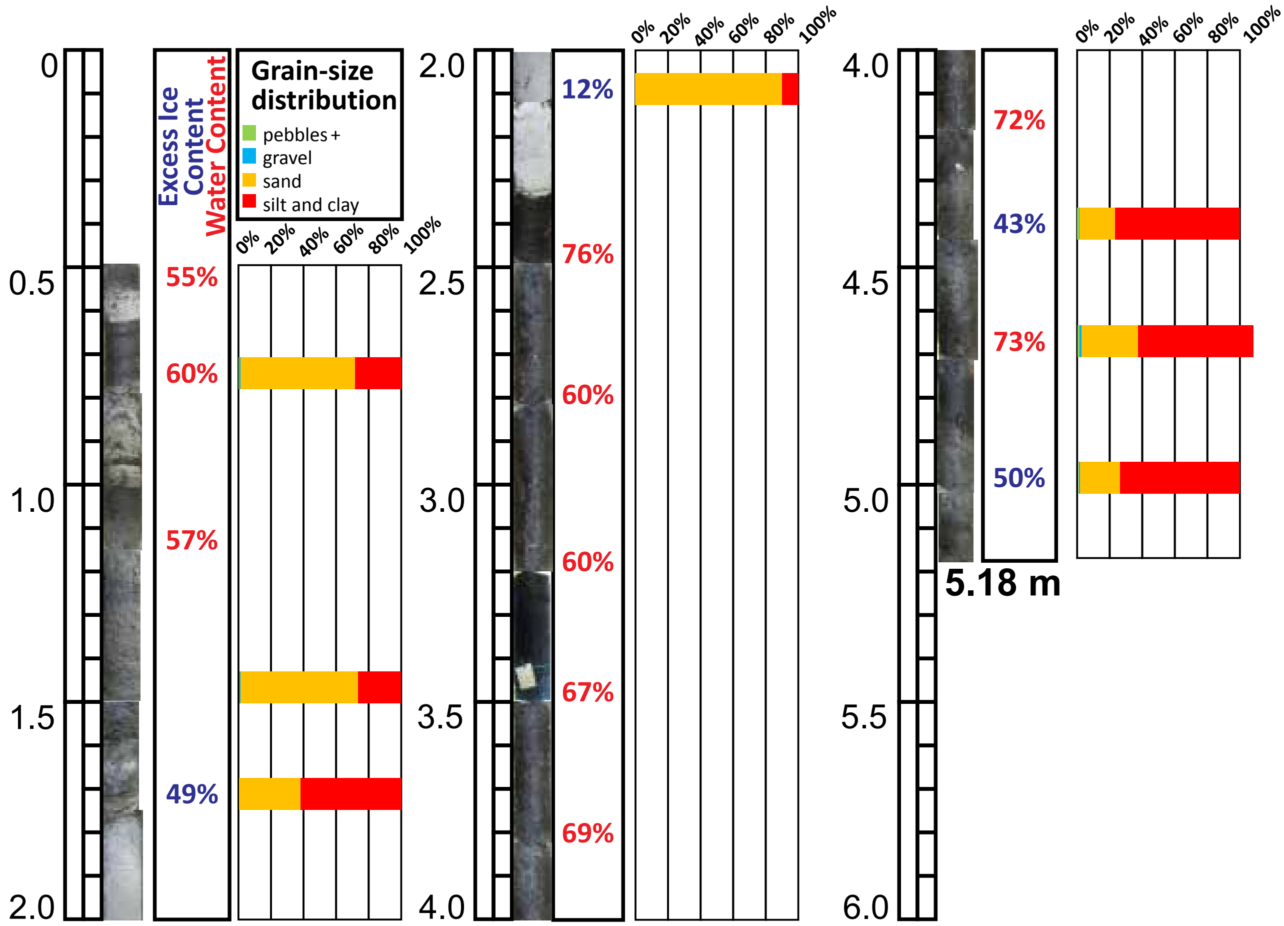
Depth (m)	0	0.5	1	2	4.27
Mean Monthly Temperature	-0.5°C	-1.1°C	-1.0°C	-0.8°C	-0.3°C
Maximun Monthly Temperature	14.1°C	3.2°C	-0.1°C	-0.4°C	-0.2°C
Minimum Monthly Temperature	-17.9°C	-7.7°C	-4.2°C	-1.9°C	-0.3°C

BH02: ground temperature profiles 2013–2014



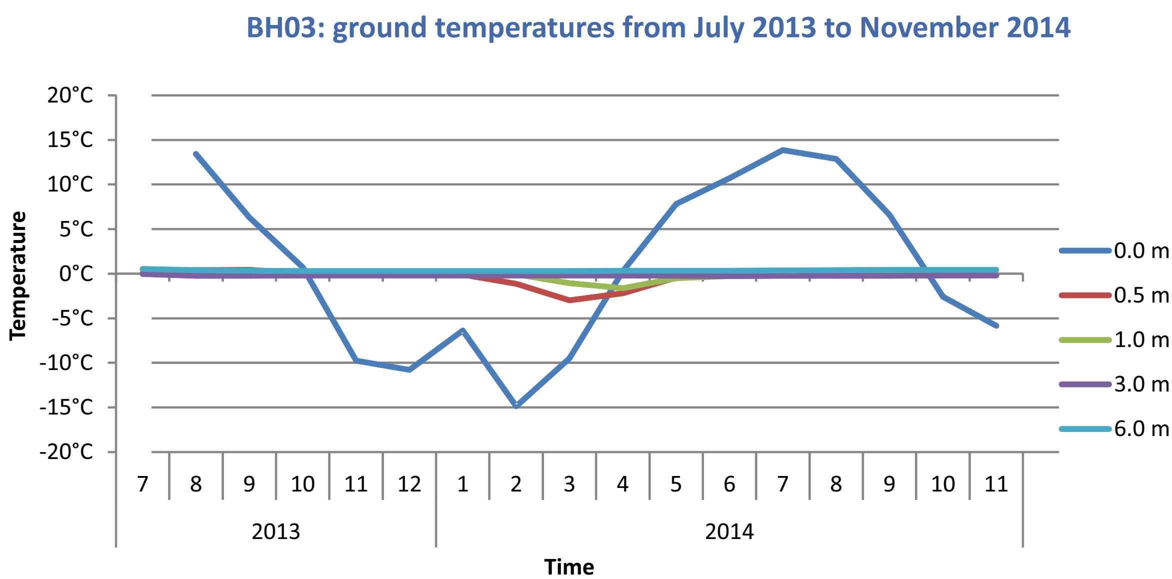
Section 4 km 1760.0 – 1780.0 Donjek River

BH03, km 1776.1

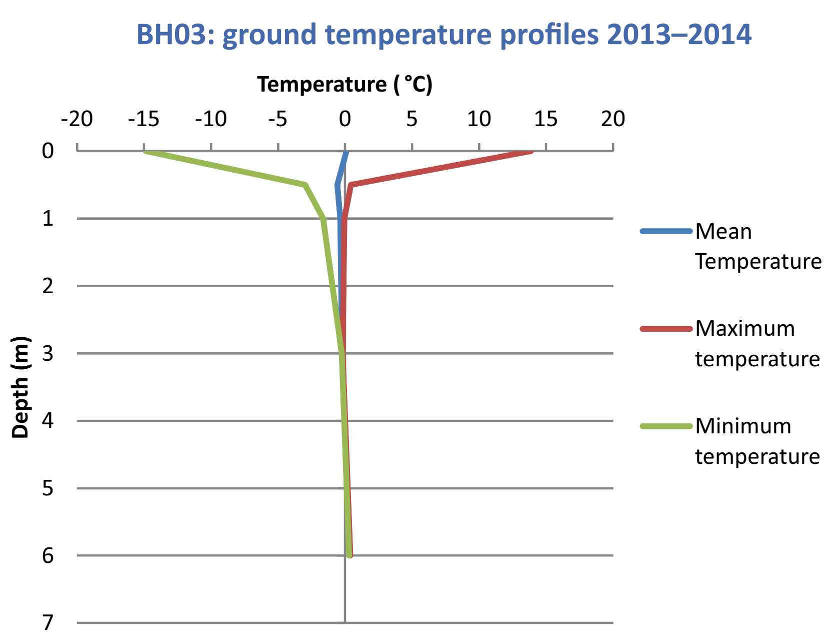


Section 4 (continued)

BH03, km 1776.1

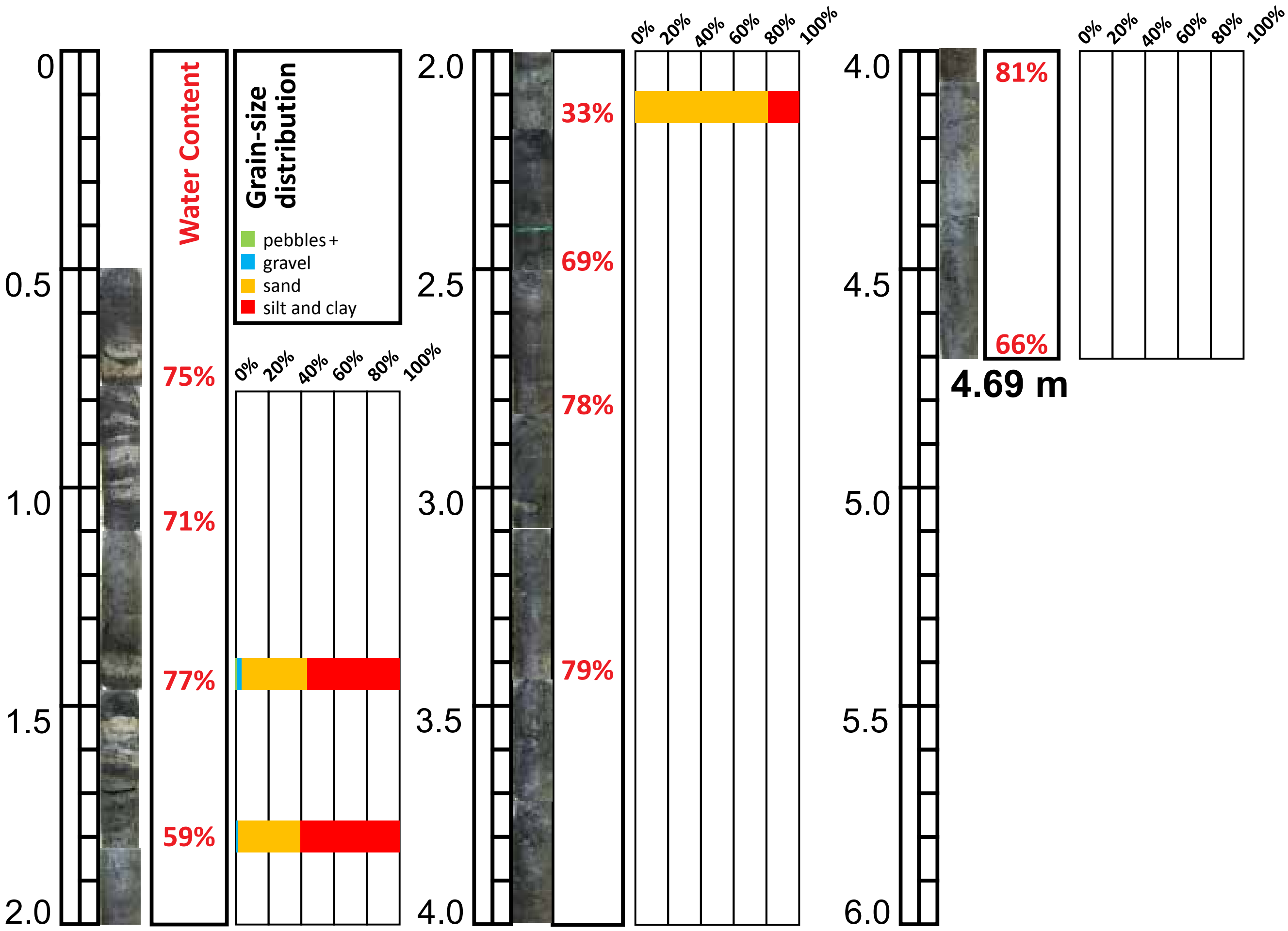


Depth (m)	0	0.5	1	3	6
Mean Monthly Temperature	0.1°C	-0.6°C	-0.4°C	-0.2°C	0.3°C
Maximun Monthly Temperature	13.9°C	0.4°C	-0.1°C	-0.2°C	0.4°C
Minimum Monthly Temperature	-14.9°C	-3.0°C	-1.6°C	-0.3°C	0.3°C



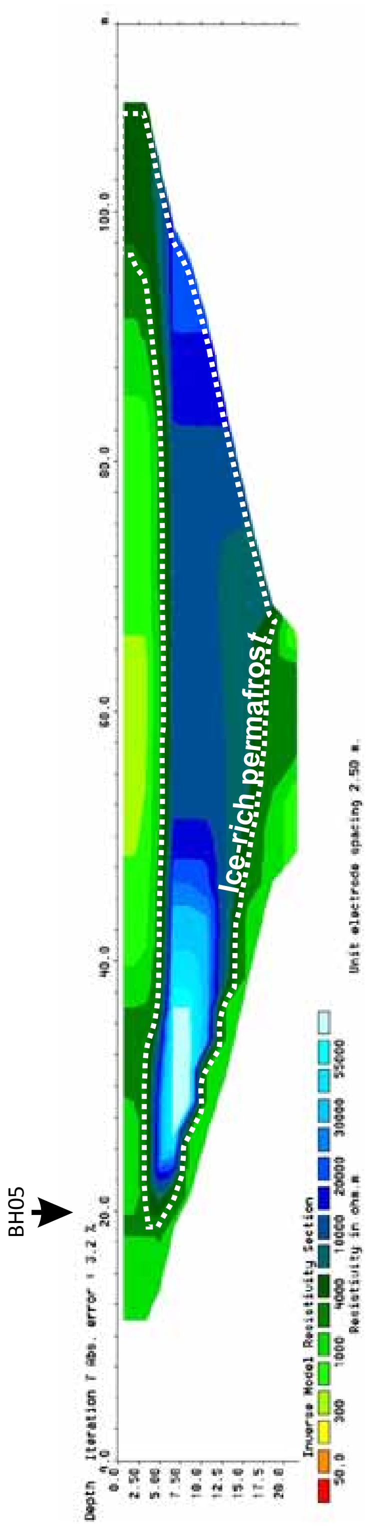
Section 5 km 1780.0 – 1796.0 **River meanders**

BH05, km 1793.5



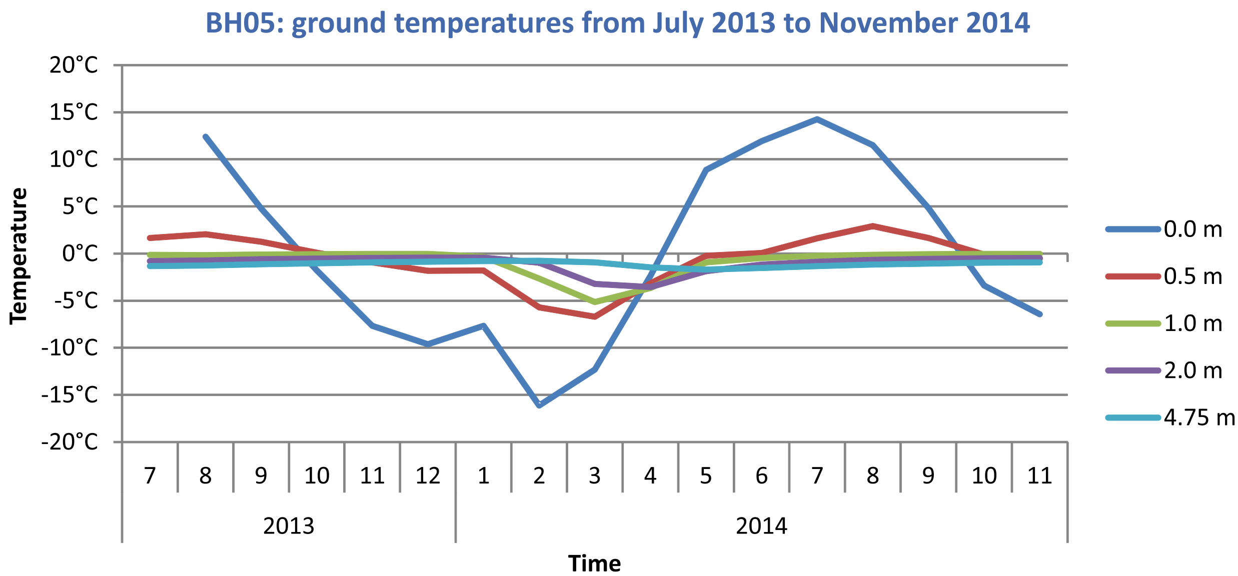
Section 5 (continued)

BH05, km 1793.5

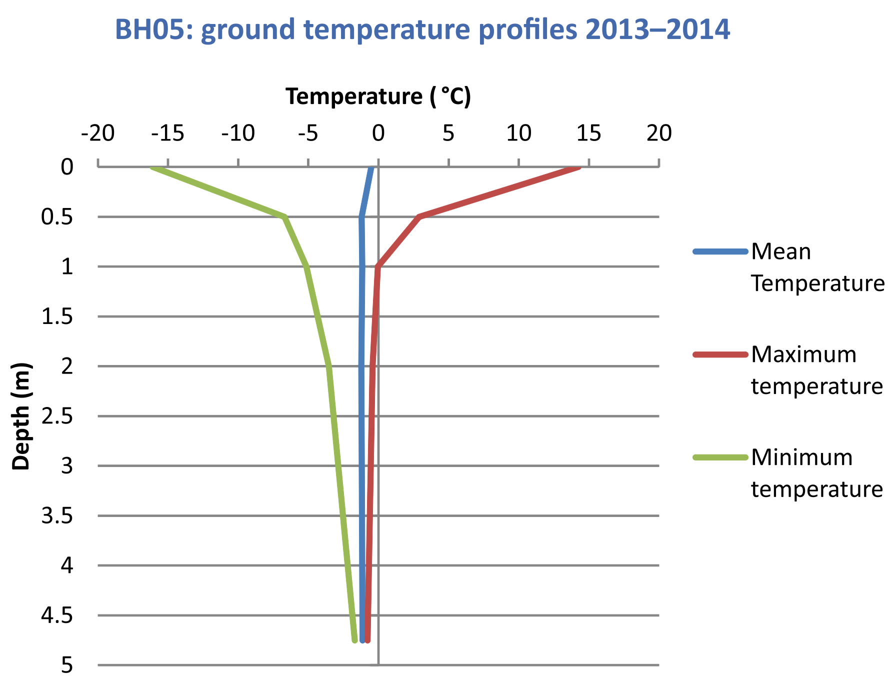


Section 5 (continued)

BH05, km 1793.5

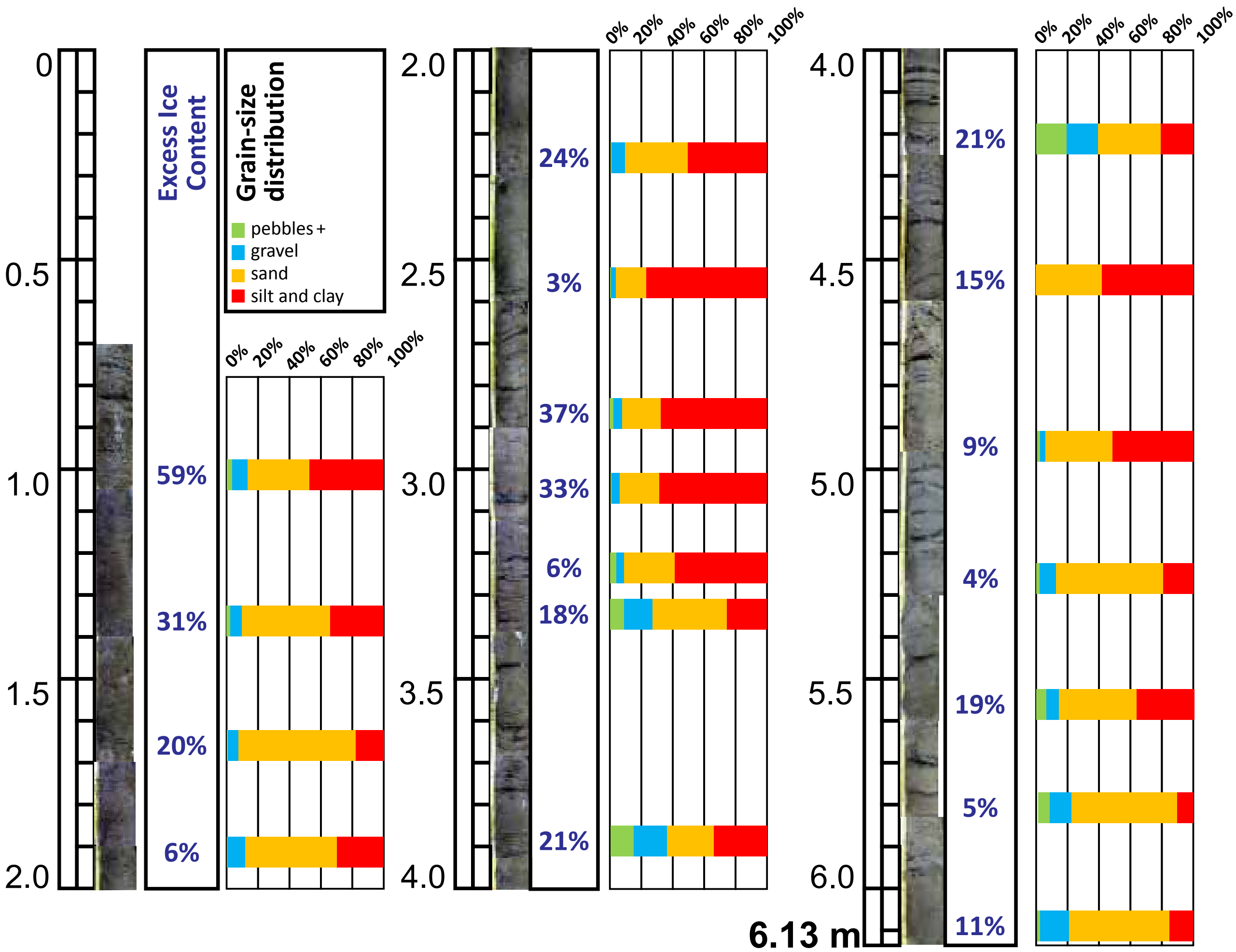


Depth (m)	0	0.5	1	2	4.75
Mean Monthly Temperature	-0.5°C	-1.2°C	-1.2°C	-1.2°C	-1.1°C
Maximun Monthly Temperature	14.3°C	2.9°C	0.0°C	-0.4°C	-0.8°C
Minimum Monthly Temperature	-16.1°C	-6.7°C	-5.1°C	-3.5°C	-1.7°C



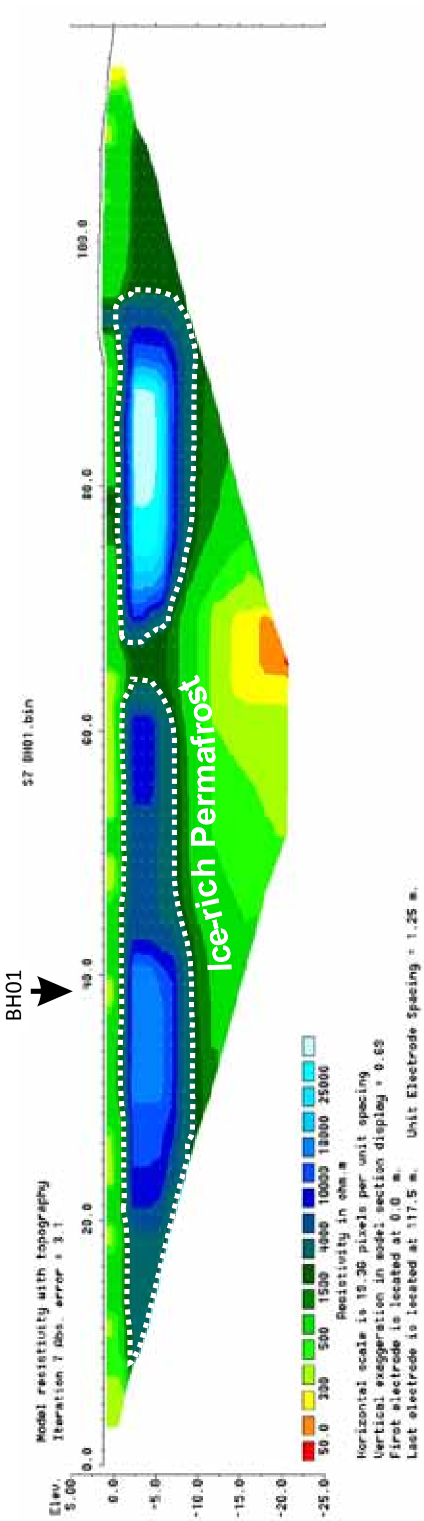
Section 6 km 1796.0 – 1813.0 **Koidern No. 2**

BH01, km 1810.2



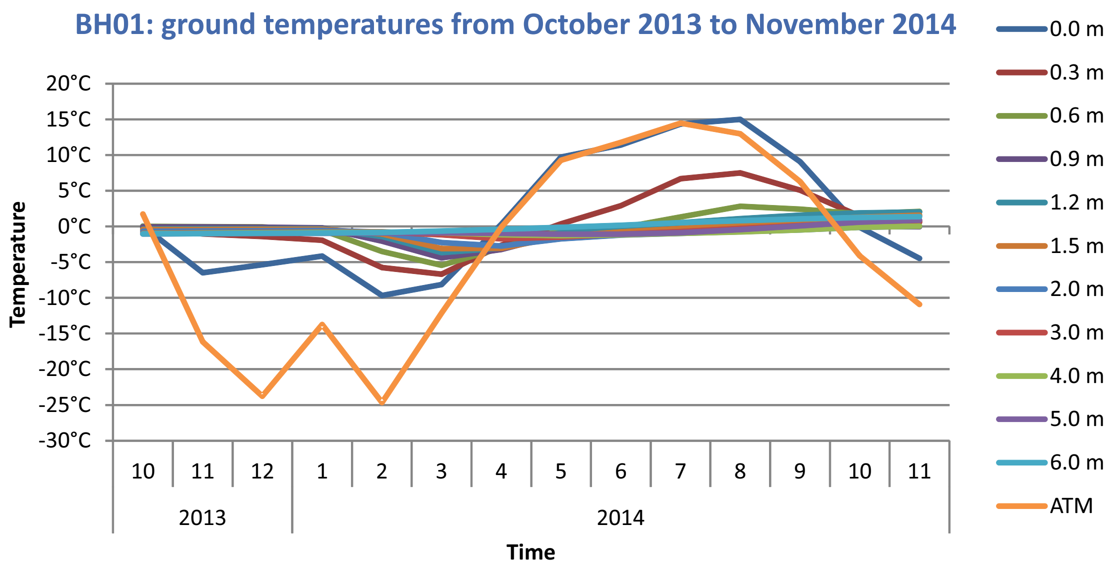
Section 6 (continued)

BH01, km 1810.2

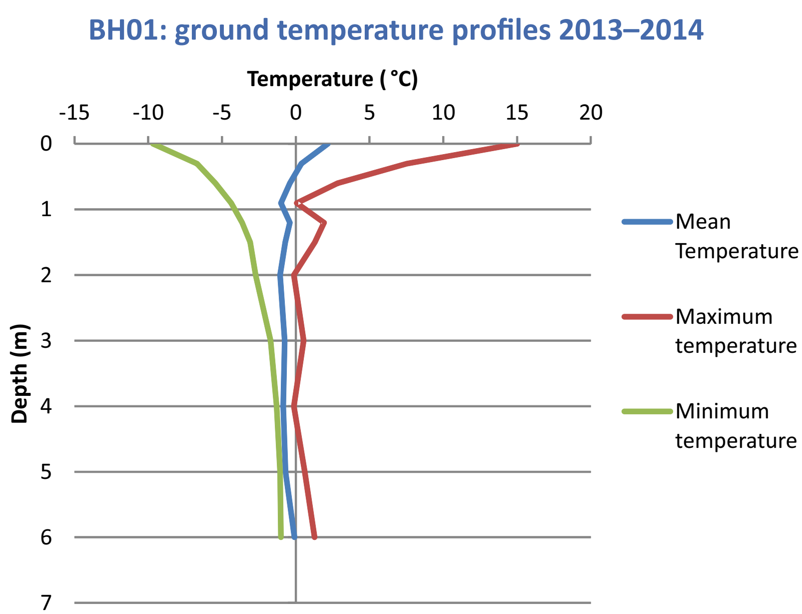


Section 6 (continued)

BH01, km 1810.2

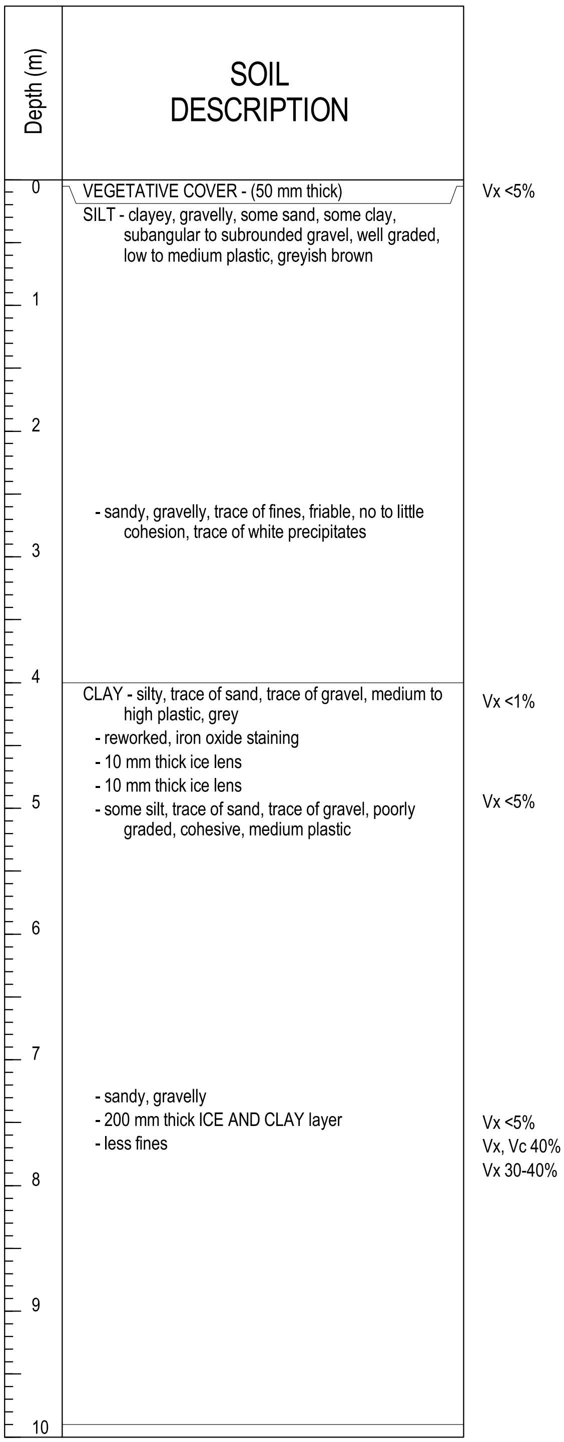


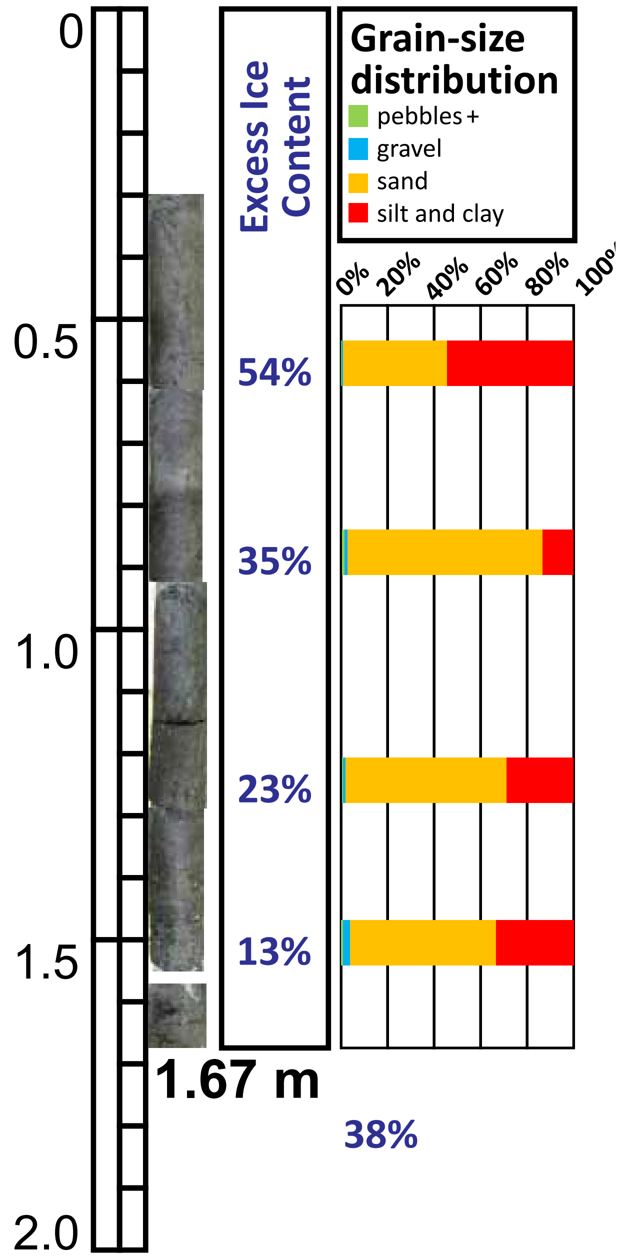
Depth (m)	0	0.3	0.6	0.9	1.2	1.5	2	3	4	5	6	Air
Mean Monthly Temperature	2.2°C	0.4°C	-0.4°C	-1.0°C	-0.4°C	-0.7°C	-1.1°C	-0.8°C	-0.9°C	-0.7°C	-0.1°C	-3.3°C
Maximun Monthly Temperature	15.0°C	7.5°C	2.8°C	0.1°C	1.9°C	1.3°C	-0.1°C	0.5°C	-0.1°C	0.6°C	1.3°C	14.5°C
Minimum Monthly Temperature	-9.7°C	-6.7°C	-5.4°C	-4.4°C	-3.6°C	-3.1°C	-2.7°C	-1.7°C	-1.3°C	-1.1°C	-1.0°C	-24.6°C



Section 9 km 1840.0 – 1855.0 Dry Creek

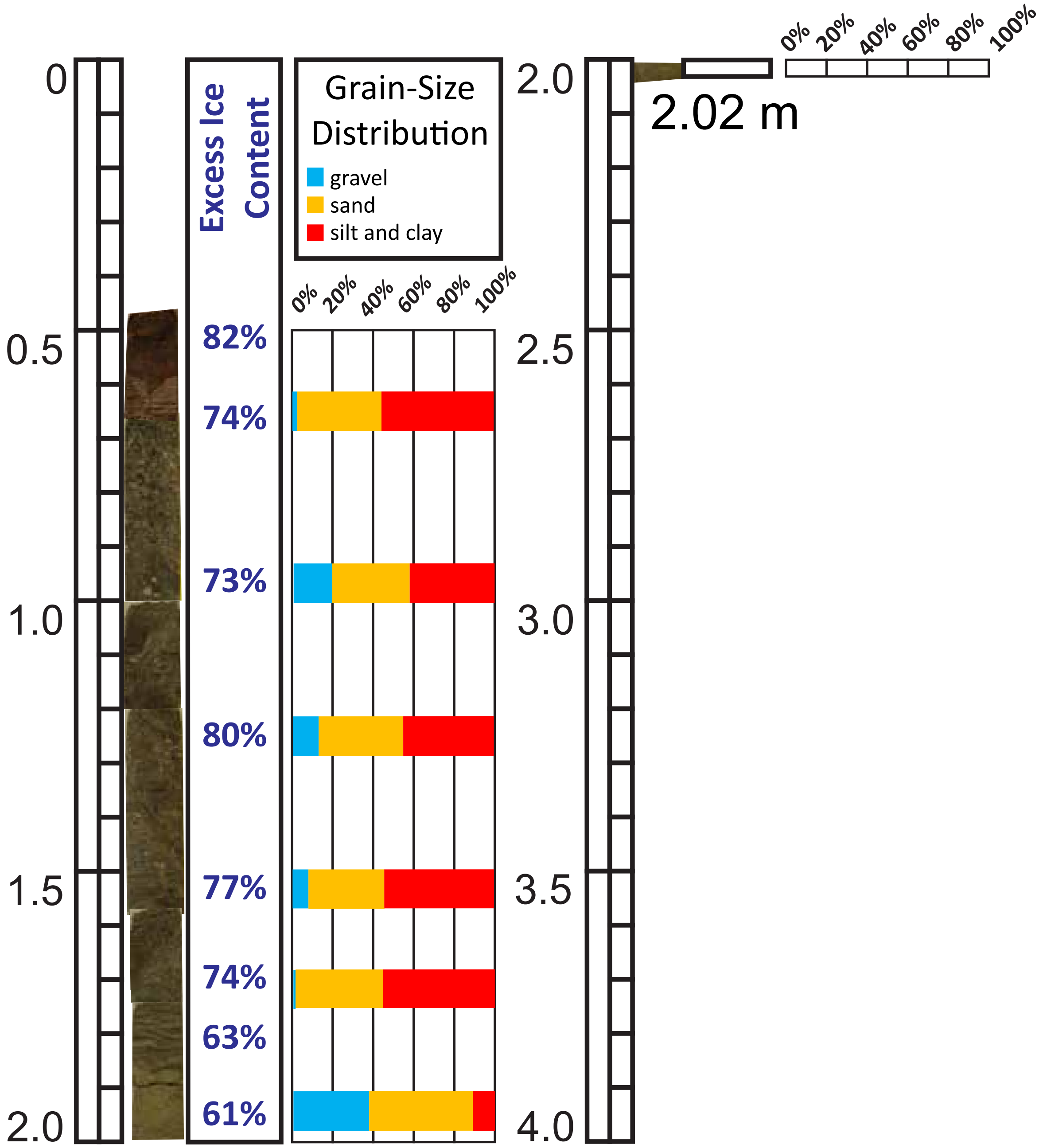
BH22, km 1841.3 and BH07, km 1841.8





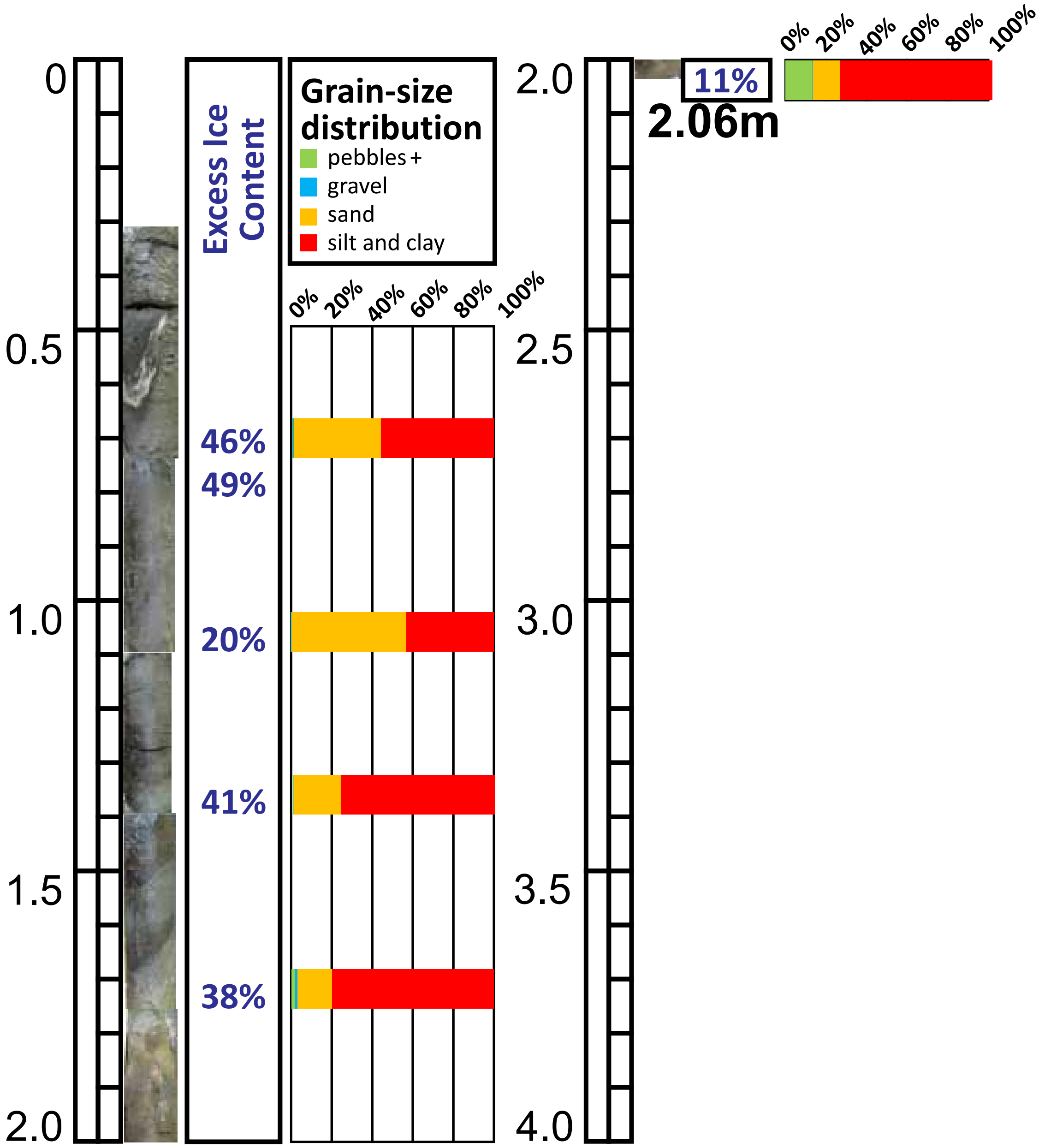
Section 9 (continued)

BH16, km 1844.1



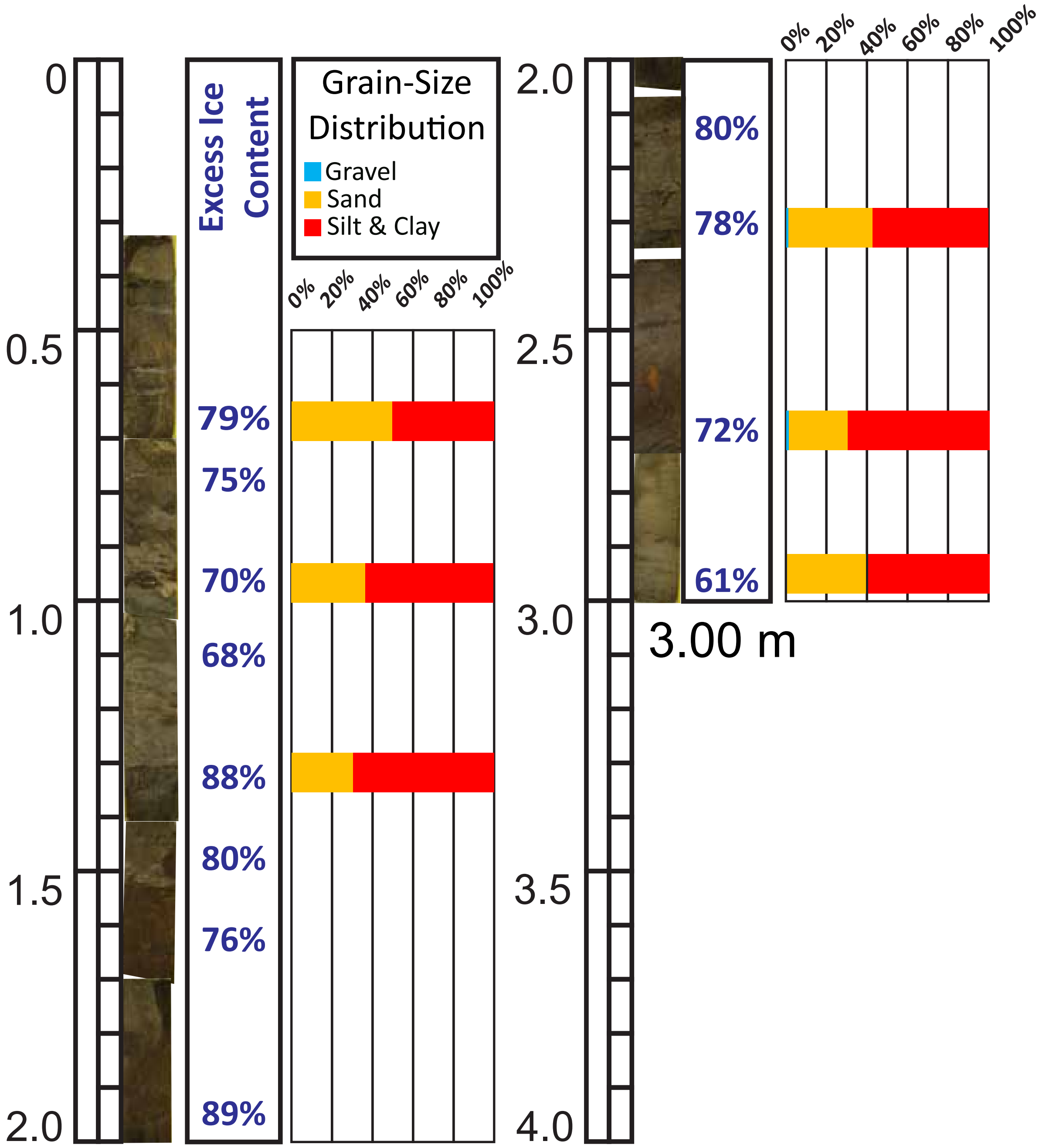
Section 9 (continued)

BH06, km 1849.8, Snag Junction



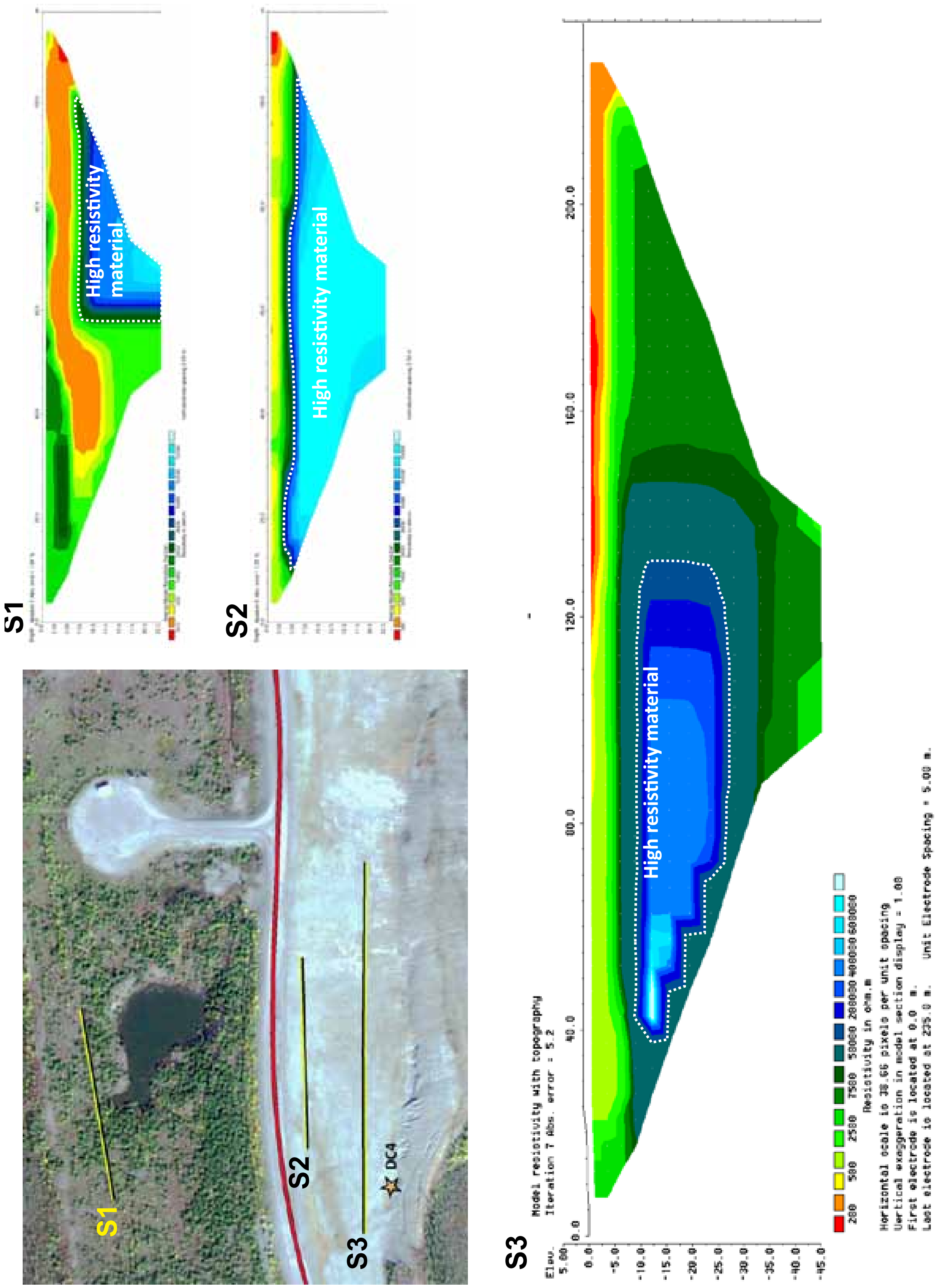
Section 9 (continued)

BH15, km 1853.6



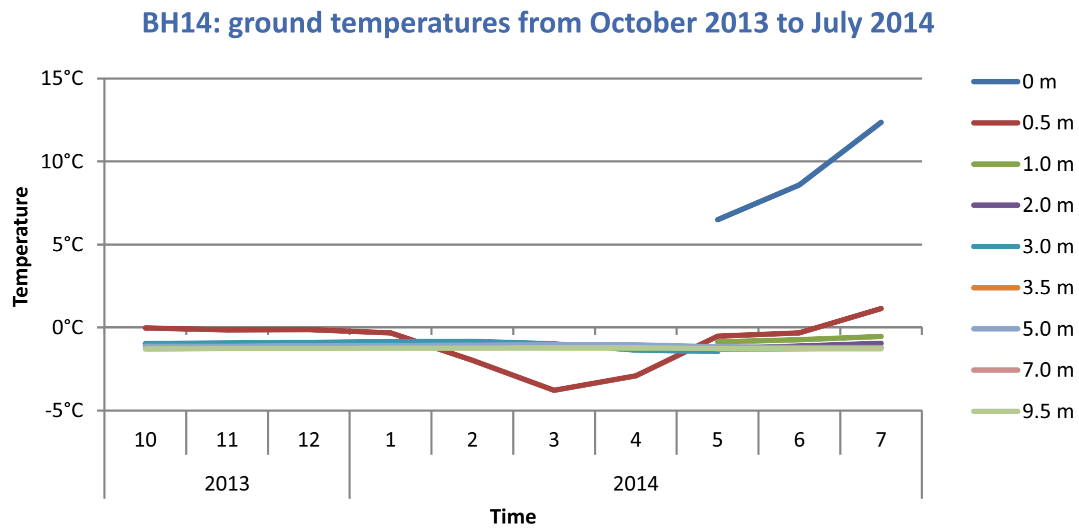
Section 9 (continued)

S1, S2 and S3, km 1840.6

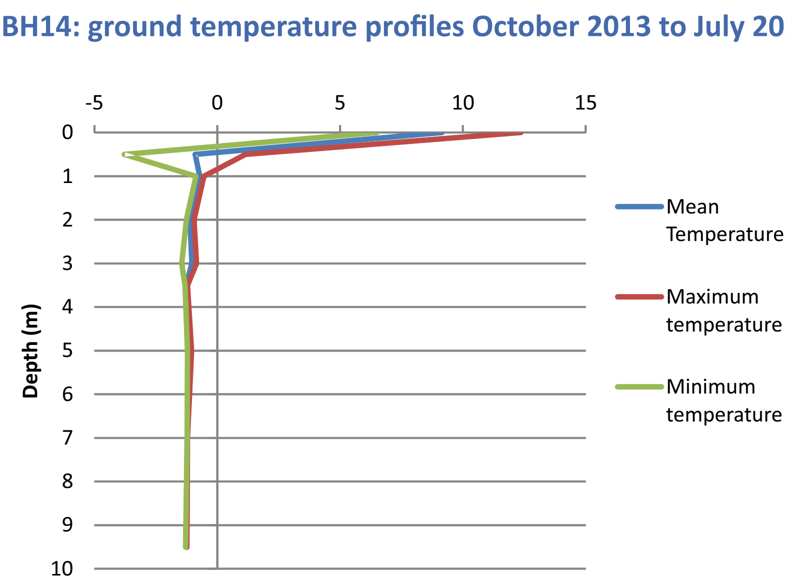


Section 9 (continued)

BH14, km 1841.5

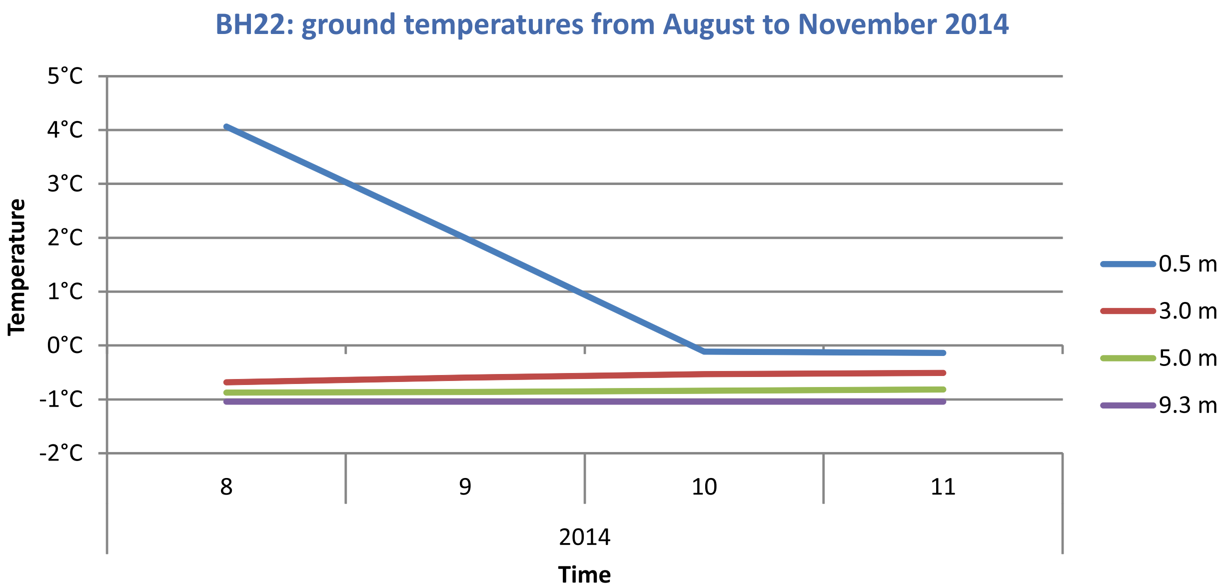


Depth (m)	0	0.5	1	2	3	3.5	5	7	9.5
Mean Monthly Temperature	9.1°C	-0.9°C	-0.7°C	-1.1°C	-1.0°C	-1.3°C	-1.1°C	-1.2°C	-1.3°C
Maximun Monthly Temperature	12.4°C	1.1°C	-0.5°C	-1.0°C	-0.8°C	-1.2°C	-1.0°C	-1.2°C	-1.2°C
Minimum Monthly Temperature	6.5°C	-3.8°C	-0.9°C	-1.3°C	-1.4°C	-1.3°C	-1.2°C	-1.2°C	-1.3°C

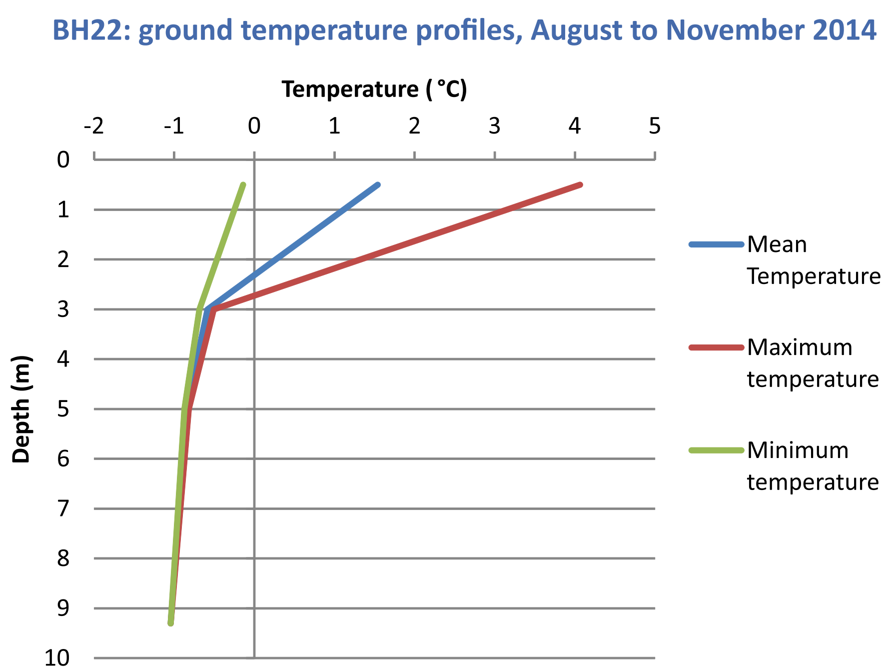


Section 9 (continued)

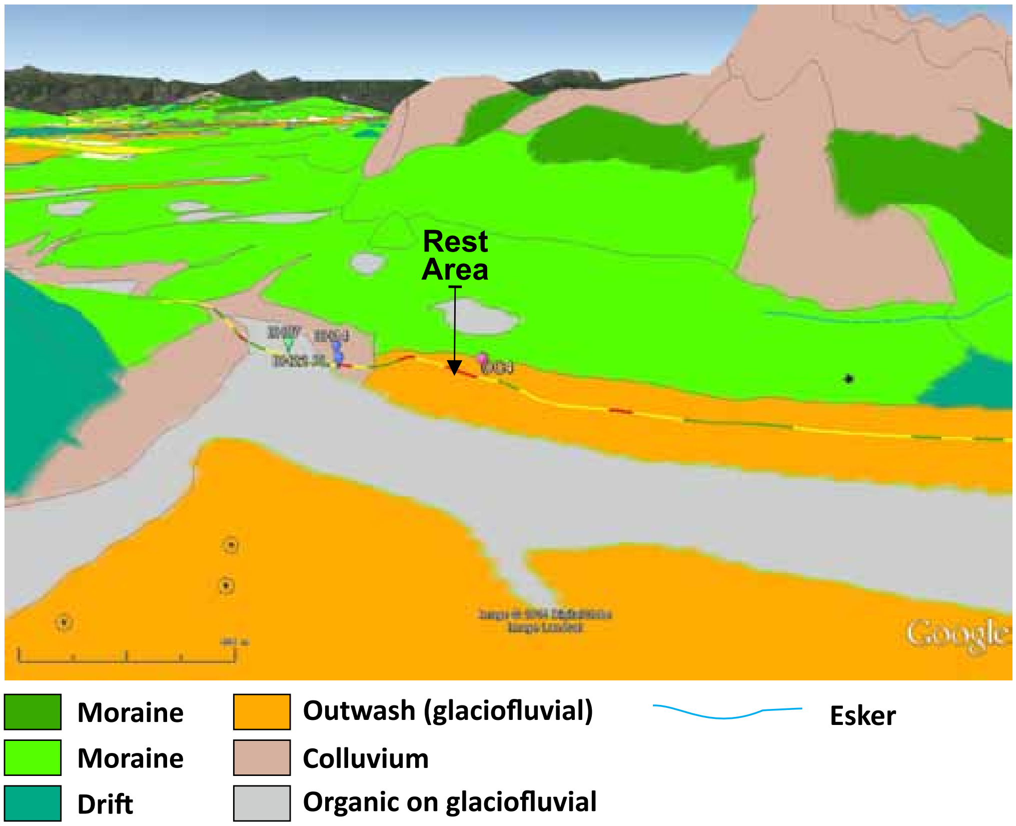
BH22, km 1841.3

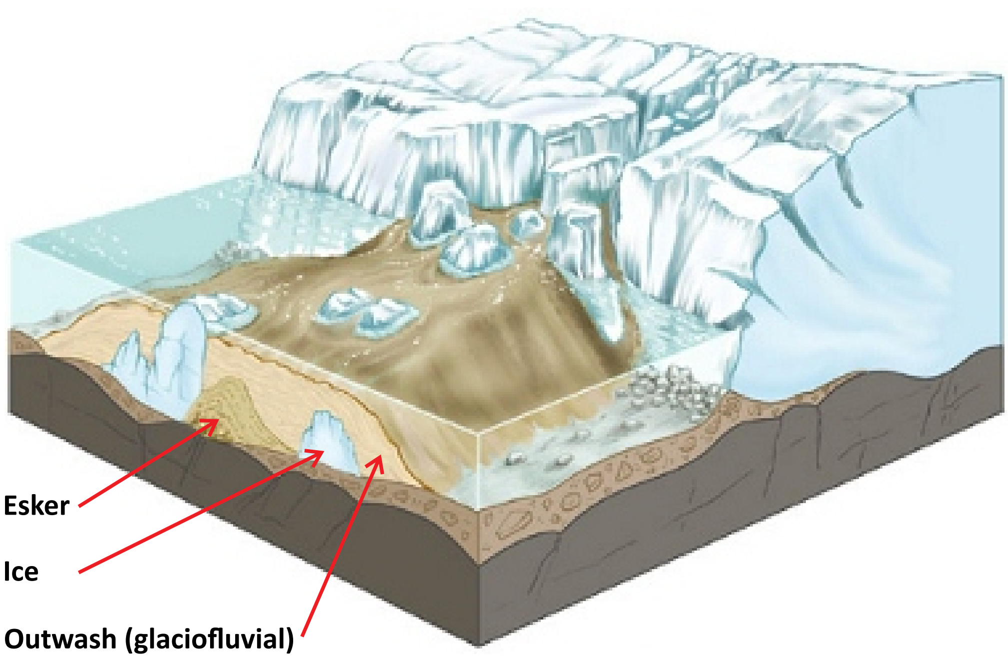


Depth (m)	0.5	3	5	9.3
Mean Monthly Temperature	1.5°C	-0.6°C	-0.8°C	-1.0°C
Maximun Monthly Temperature	4.1°C	-0.5°C	-0.8°C	-1.0°C
Minimum Monthly Temperature	-0.1°C	-0.7°C	-0.9°C	-1.0°C



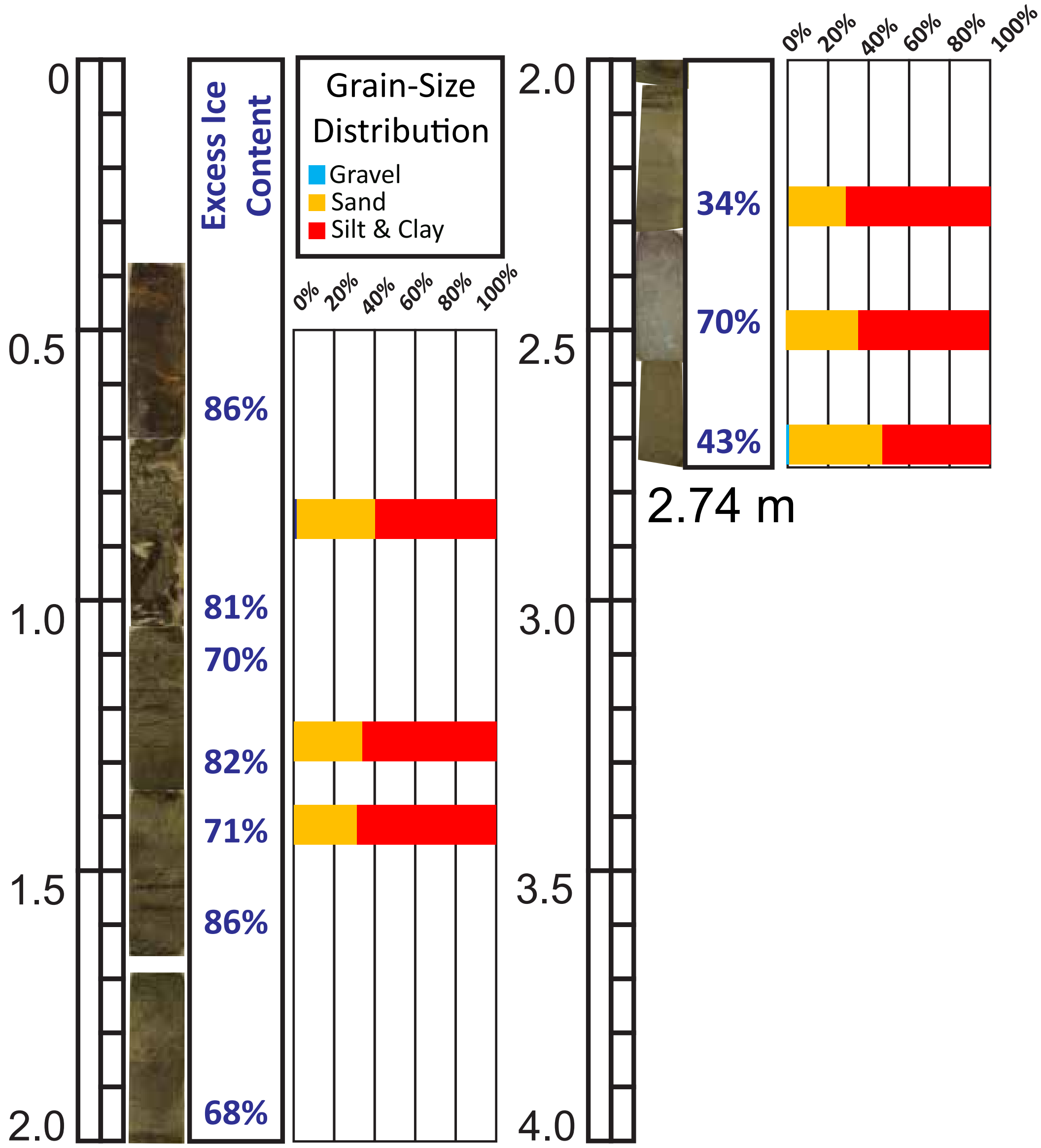
Section 9 (continued)





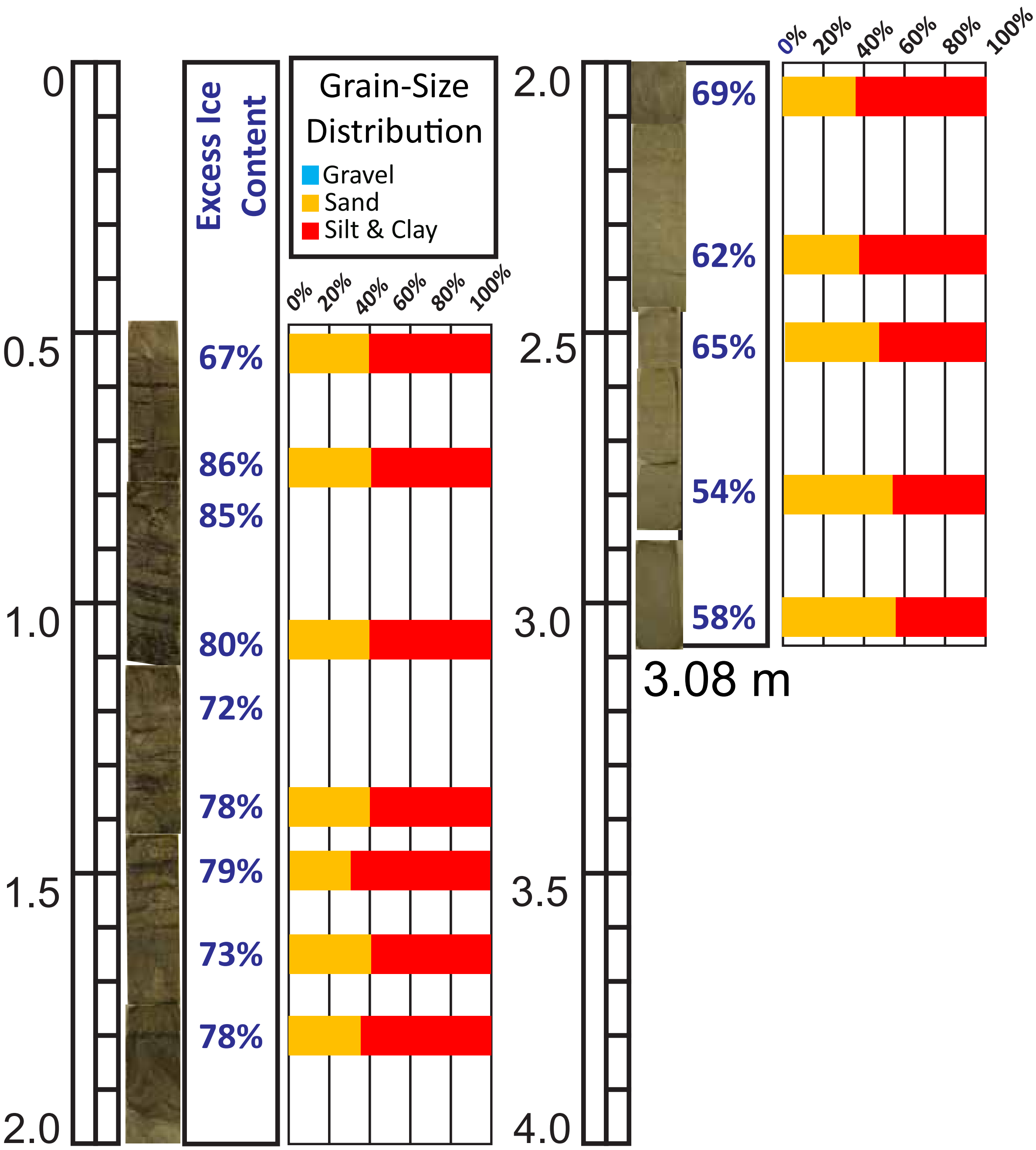
Section 10 km 1855.0 – 1868.0 **Southern Beaver Creek**

BH17, km 1857.2



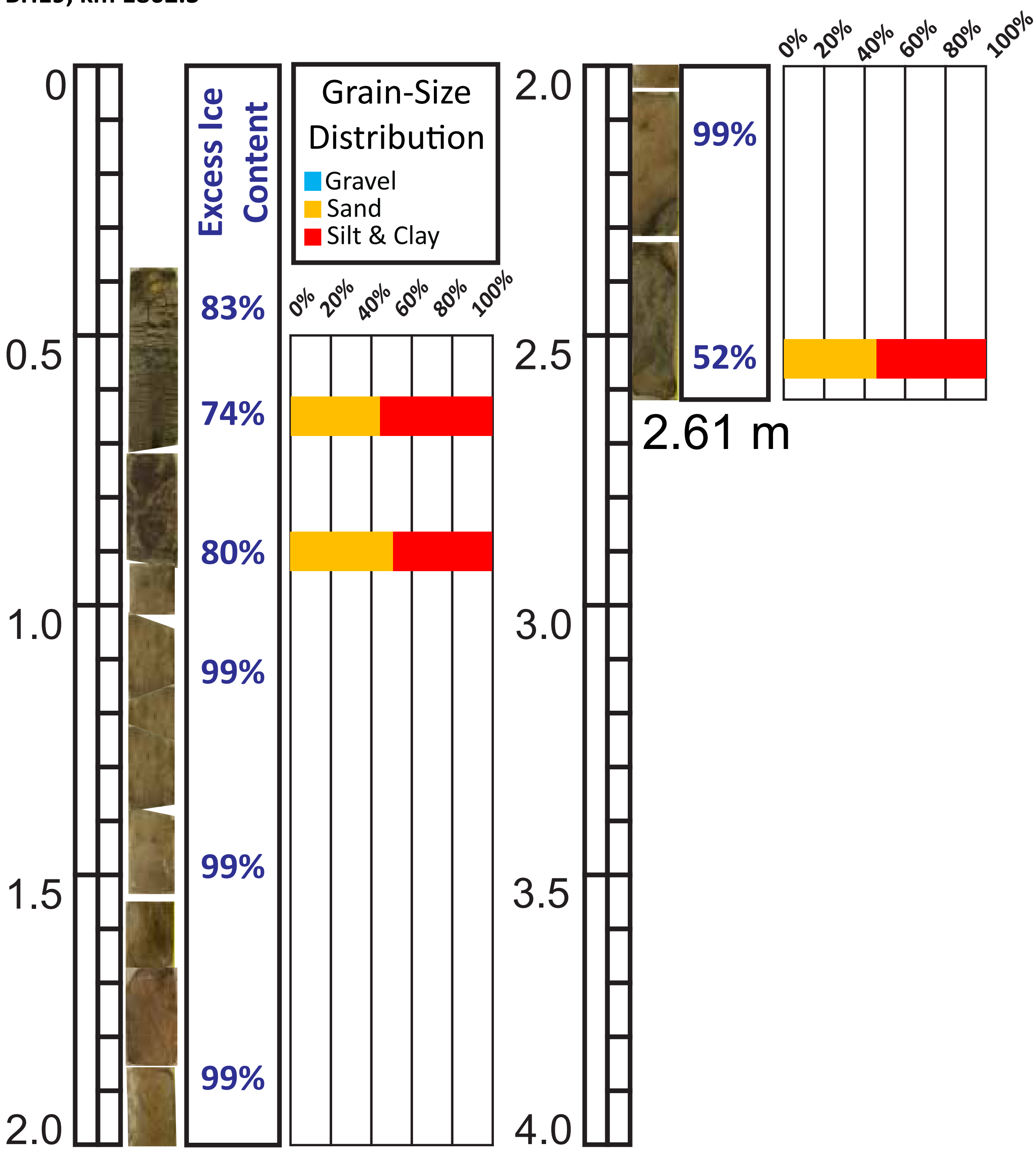
Section 10 (continued)

BH18, km 1860.4



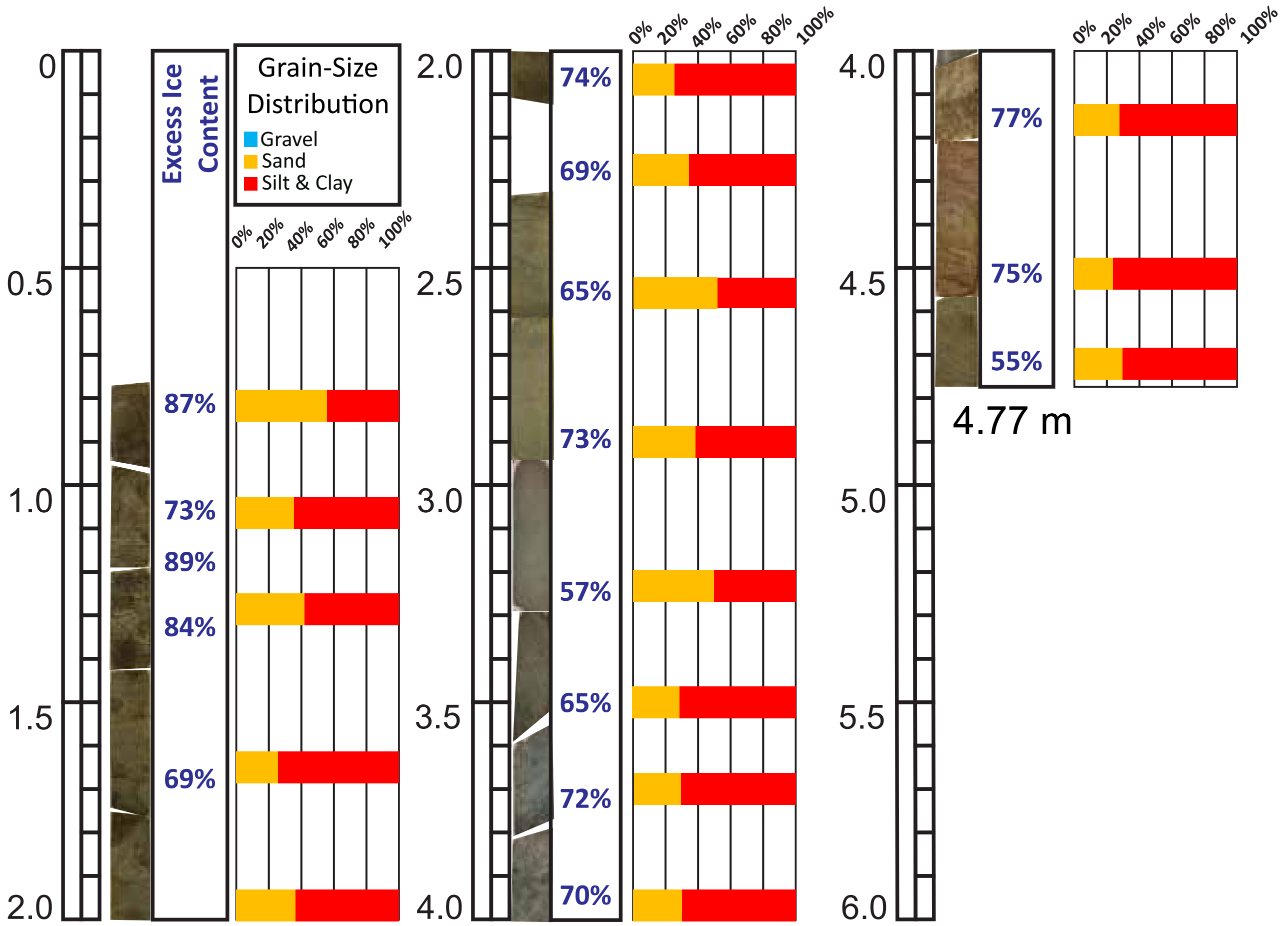
Section 10 (continued)

BH19, km 1862.3



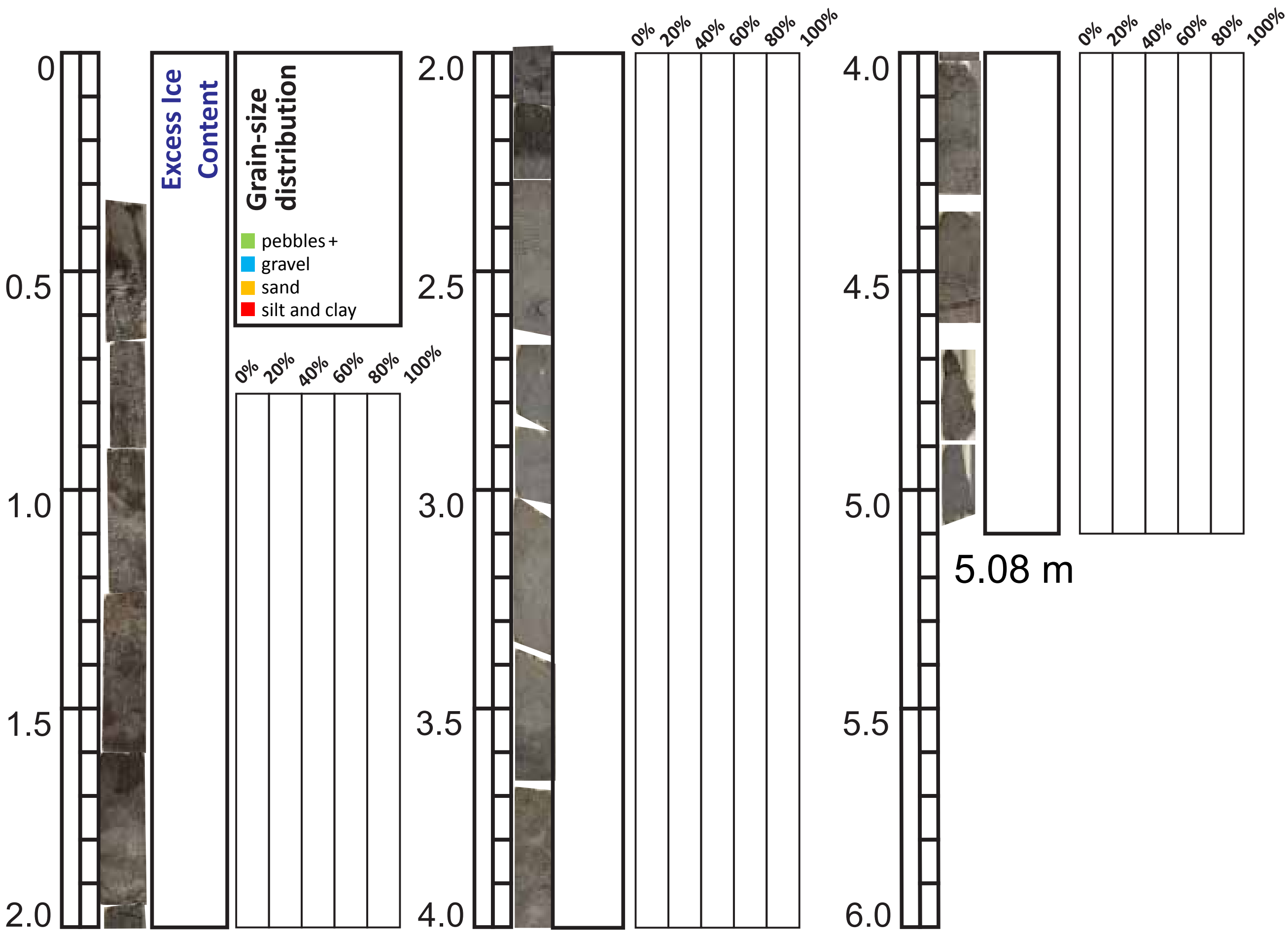
Section 10 (continued)

BH20, km 1866 **Thermokarst site close to test section**



Section 10 (continued)

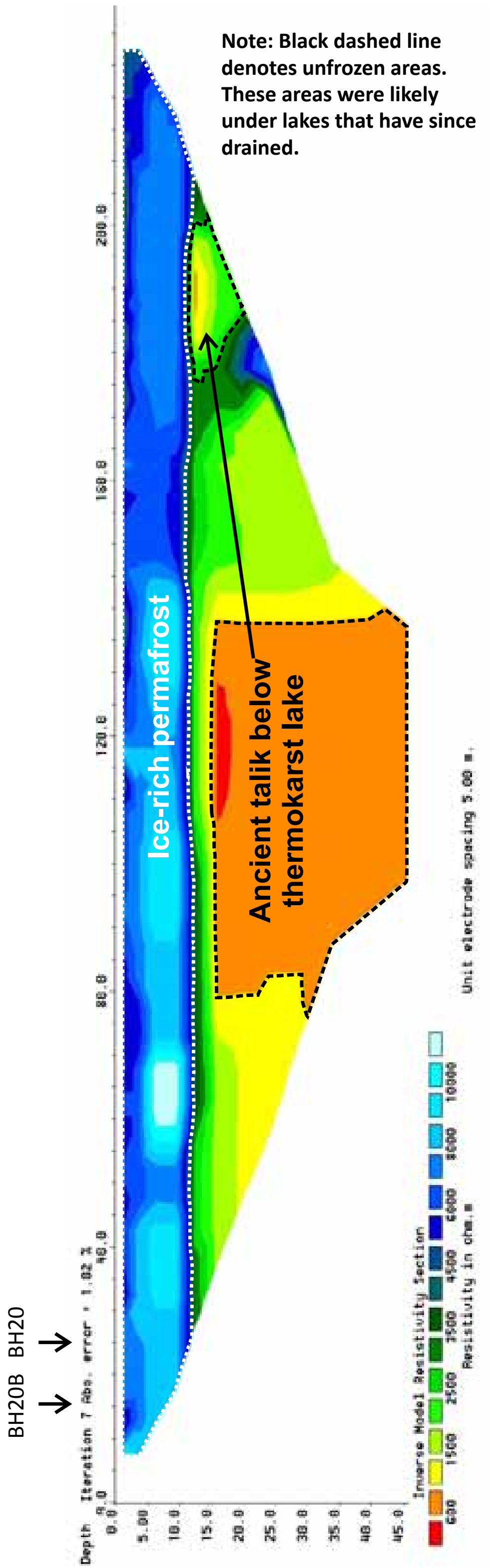
BH20B, km 1866, close to pond



Note: BH20B is a duplicate of BH20 that was not analysed.

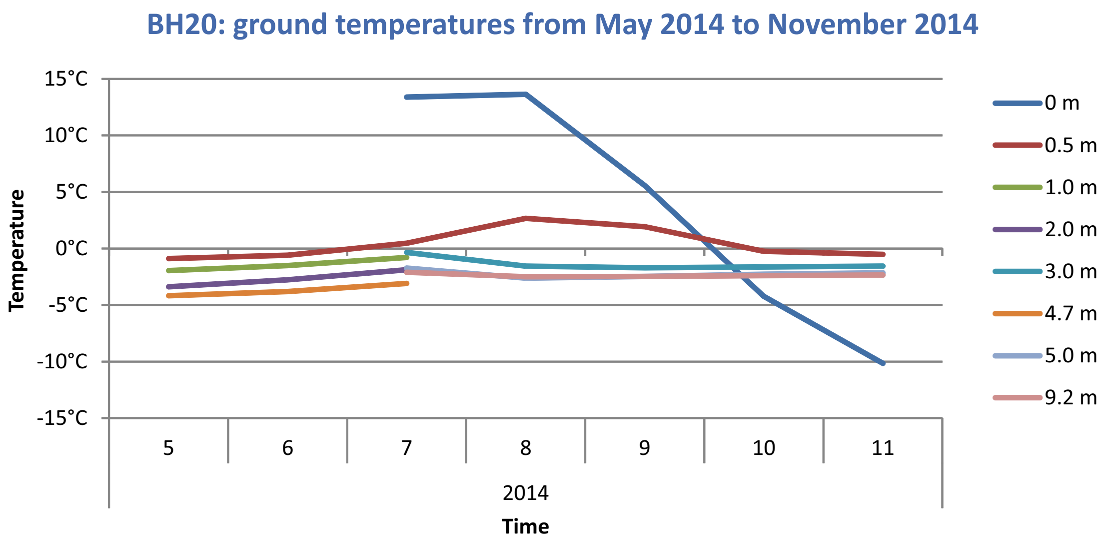
Section 10 (continued)

BH20 and BH20B, km 1866

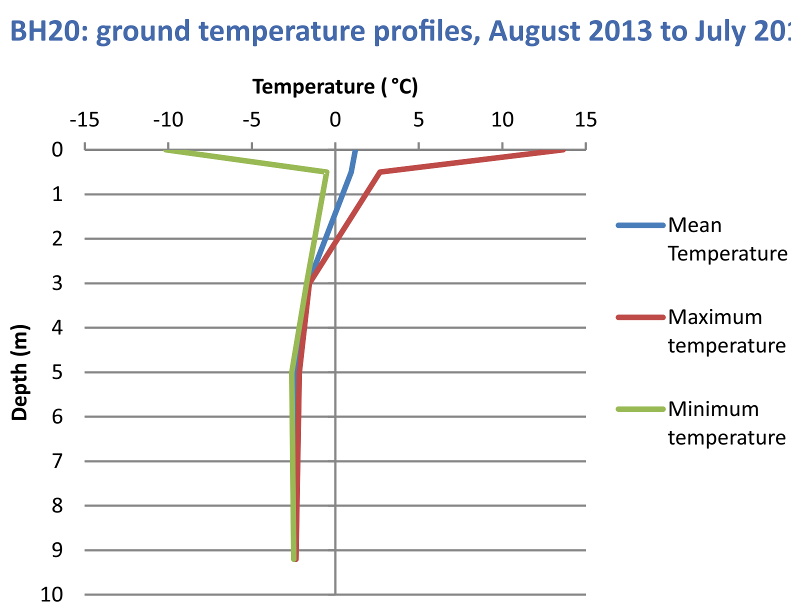


Section 10 (continued)

BH20B, km 1866

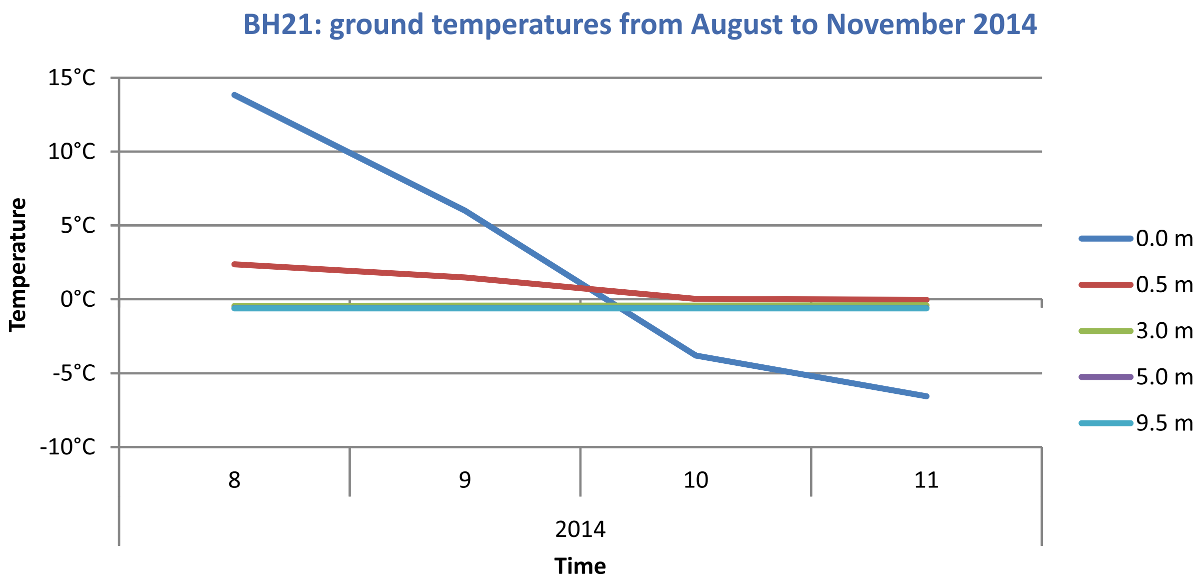


Depth (m)	0	0.5	1	2	3	4.7	5	9.2
Mean Monthly Temperature	3.6°C	0.4°C	-1.4°C	-2.7°C	-1.4°C	-3.7°C	-2.2°C	-2.4°C
Maximun Monthly Temperature	13.6°C	2.7°C	-0.8°C	-1.9°C	-0.3°C	-3.1°C	-1.7°C	-2.1°C
Minimum Monthly Temperature	-10.2°C	-0.9°C	-1.9°C	-3.4°C	-1.7°C	-4.2°C	-2.6°C	-2.5°C

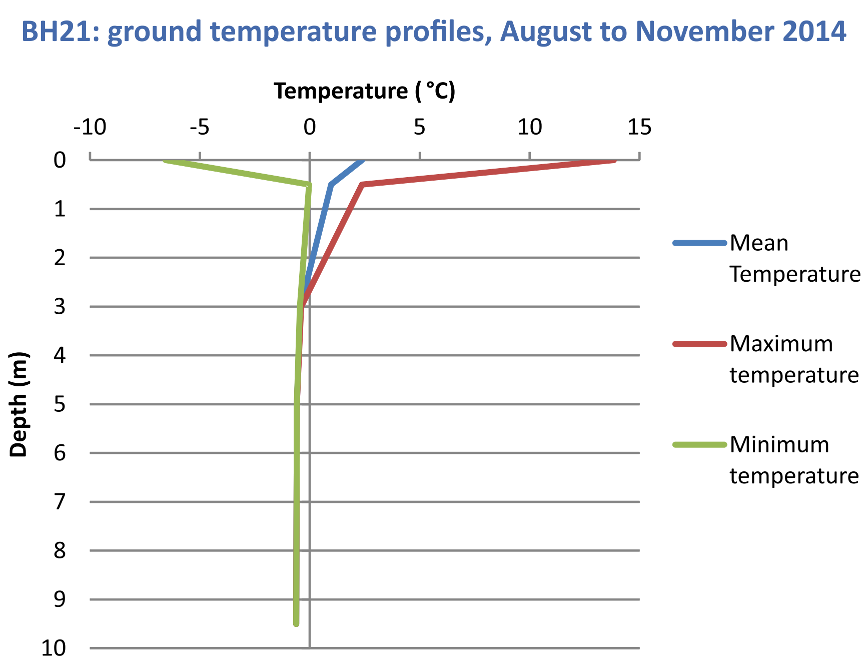


Section 10 (continued)

BH21, km 1865.2

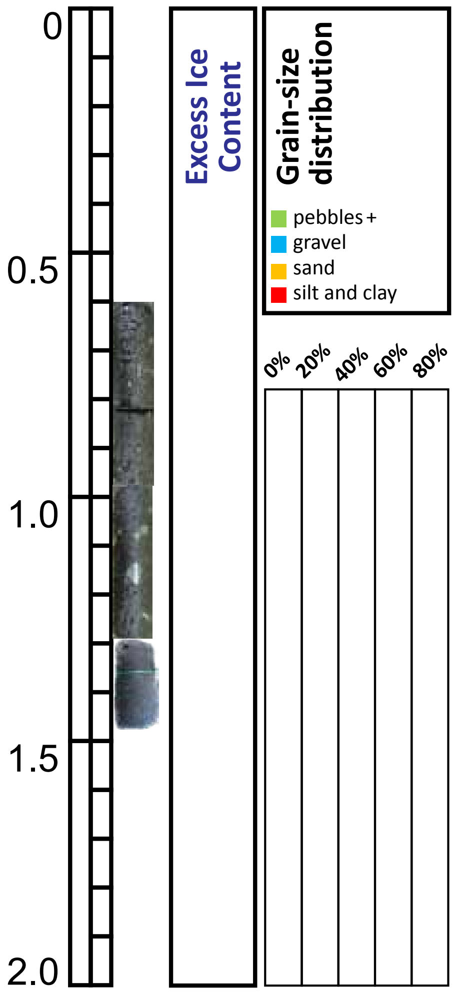


Depth (m)	0	0.5	3	5	9.5
Mean Monthly Temperature	2.4°C	1.0°C	-0.4°C	-0.6°C	-0.6°C
Maximun Monthly Temperature	13.8°C	2.4°C	-0.4°C	-0.6°C	-0.6°C
Minimum Monthly Temperature	-6.6°C	0.0°C	-0.4°C	-0.6°C	-0.6°C



Section 12 km 1878.0 – 1890.0 Thermokarst area

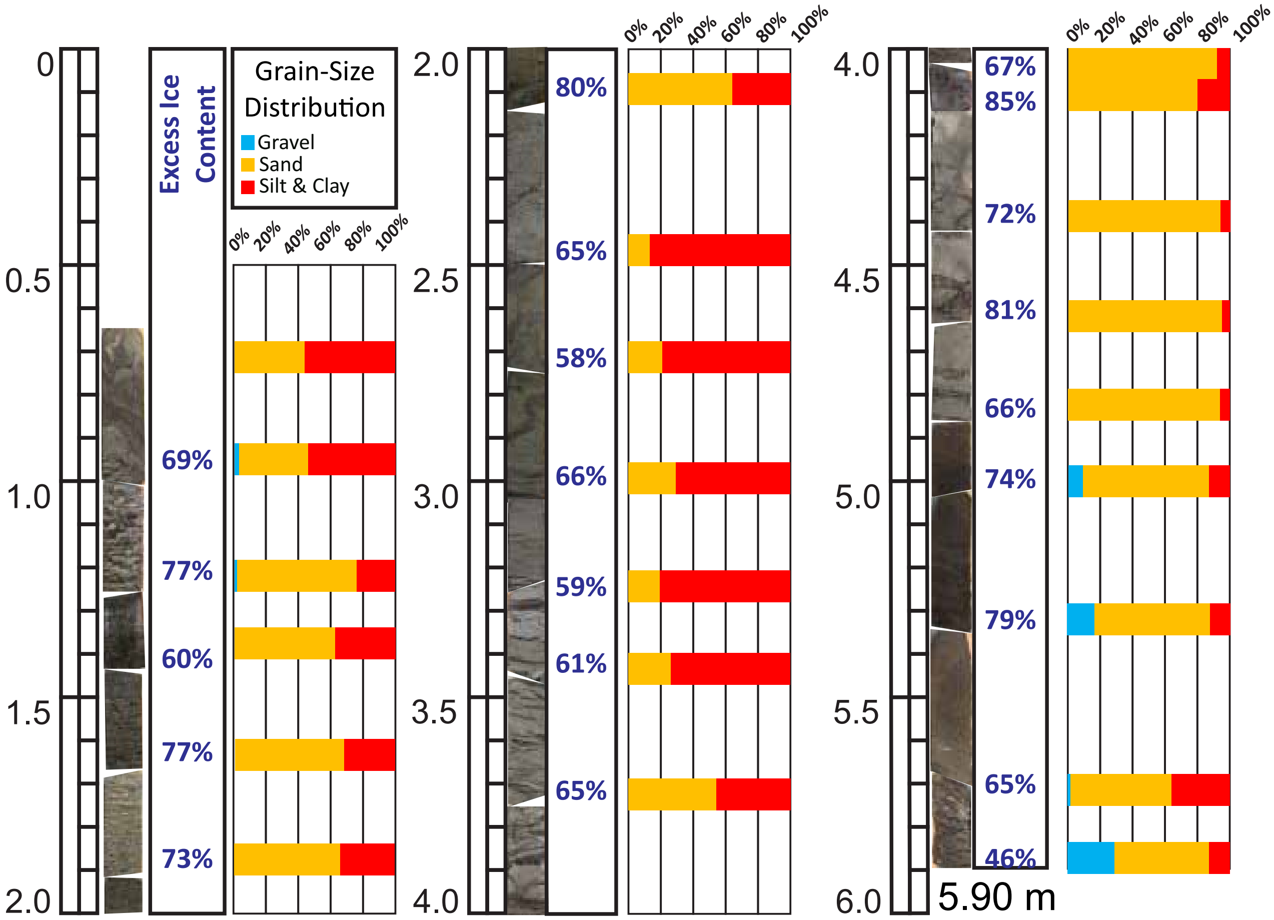
BH10, km 1879.7



Note: The core was not sufficiently representative to justify analyses.

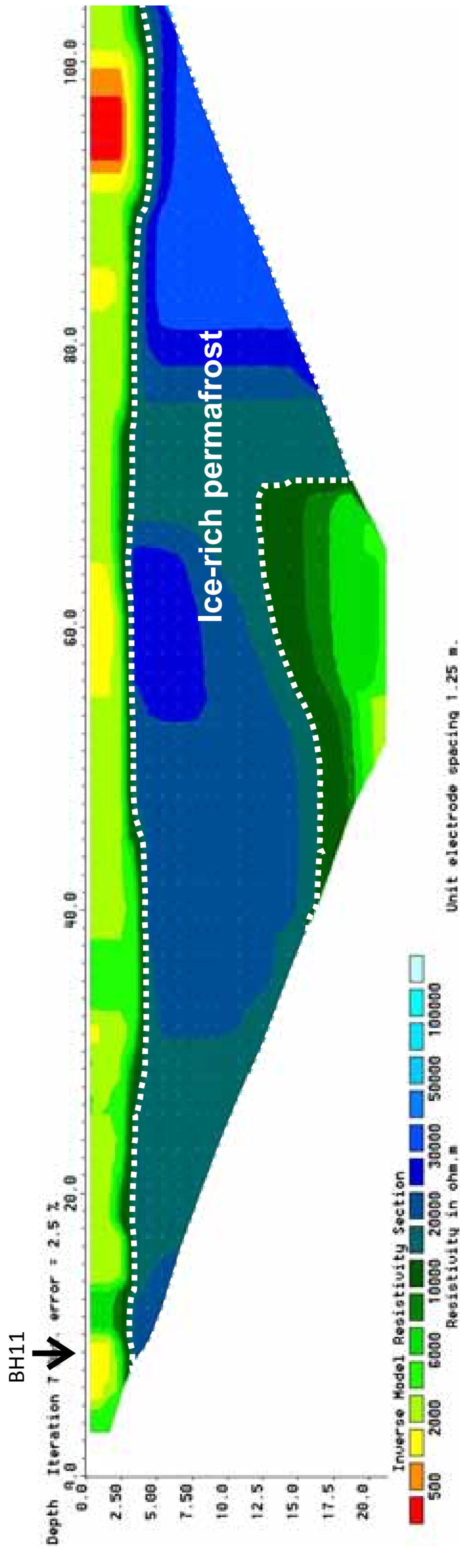
Section 12 (continued)

BH11, km 1886, Palsa site



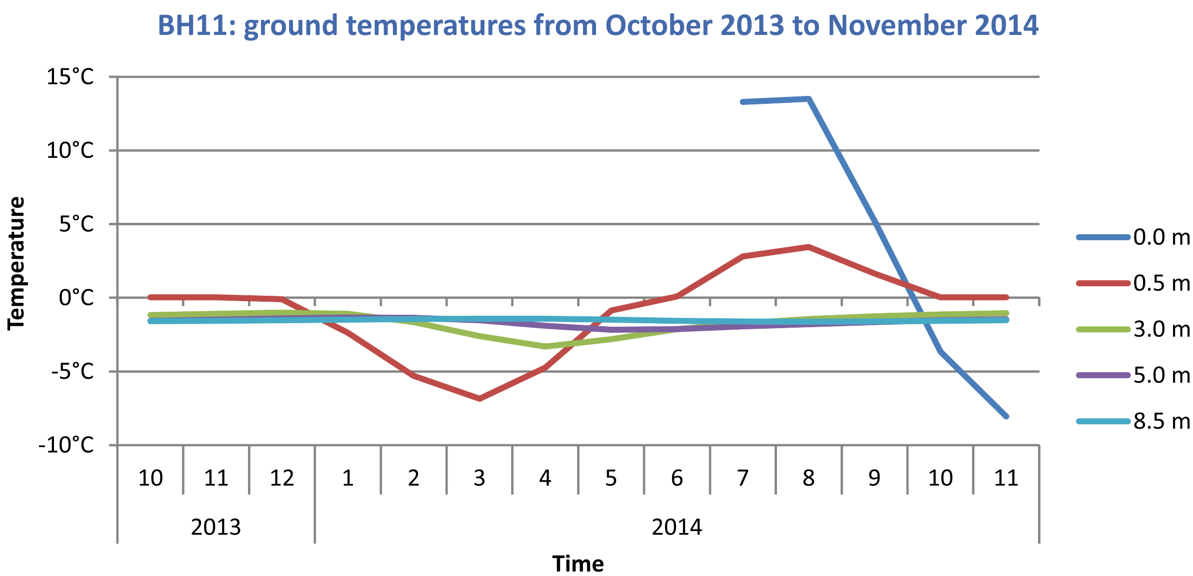
Section 12 (continued)

BH11, km 1886

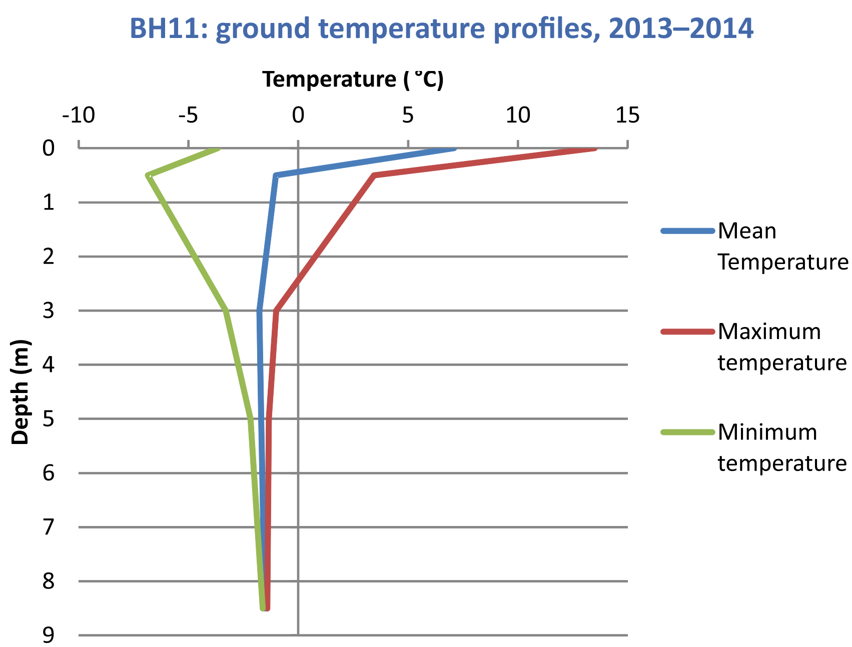


Section 12 (continued)

BH11, km 1886

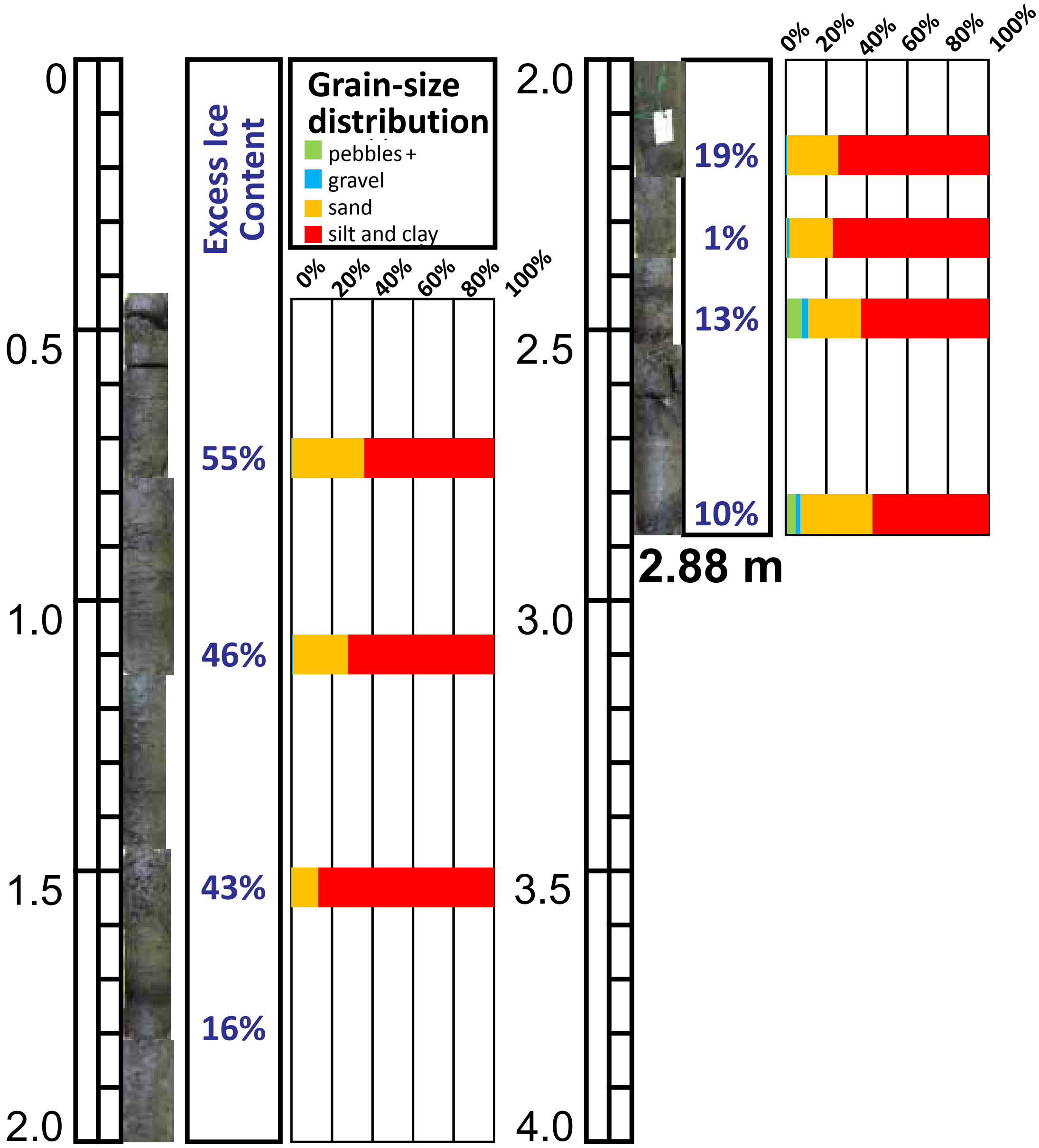


Depth (m)	0	0.5	3	5	8.5
Mean Monthly Temperature	7.1°C	-1.0°C	-1.8°C	-1.7°C	-1.5°C
Maximun Monthly Temperature	13.5°C	3.4°C	-1.0°C	-1.3°C	-1.4°C
Minimum Monthly Temperature	-3.7°C	-6.9°C	-3.3°C	-2.2°C	-1.6°C



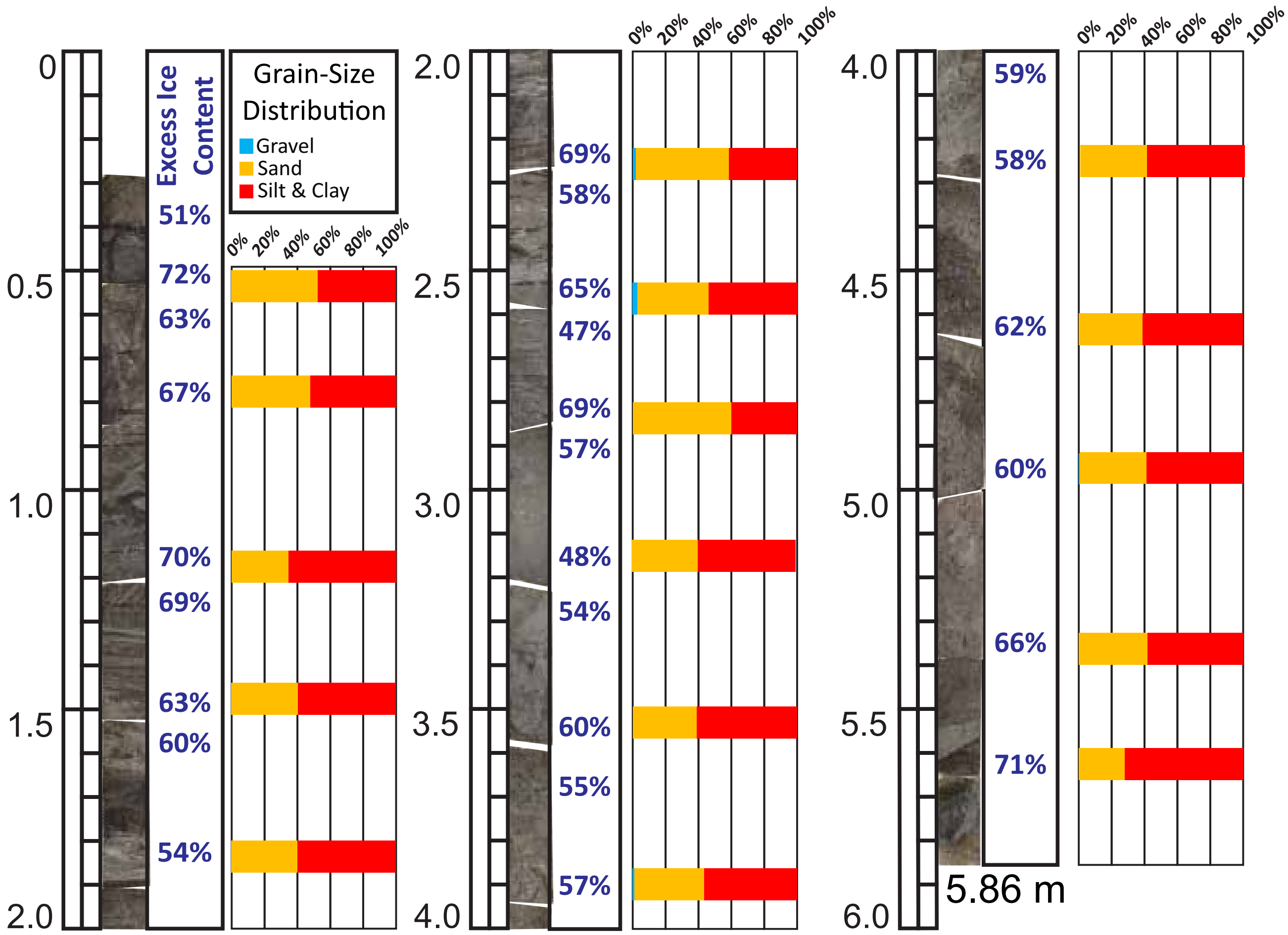
Section 13 km 1890.0 – 1902.4 **U.S. border**

BH04, km 1891.1



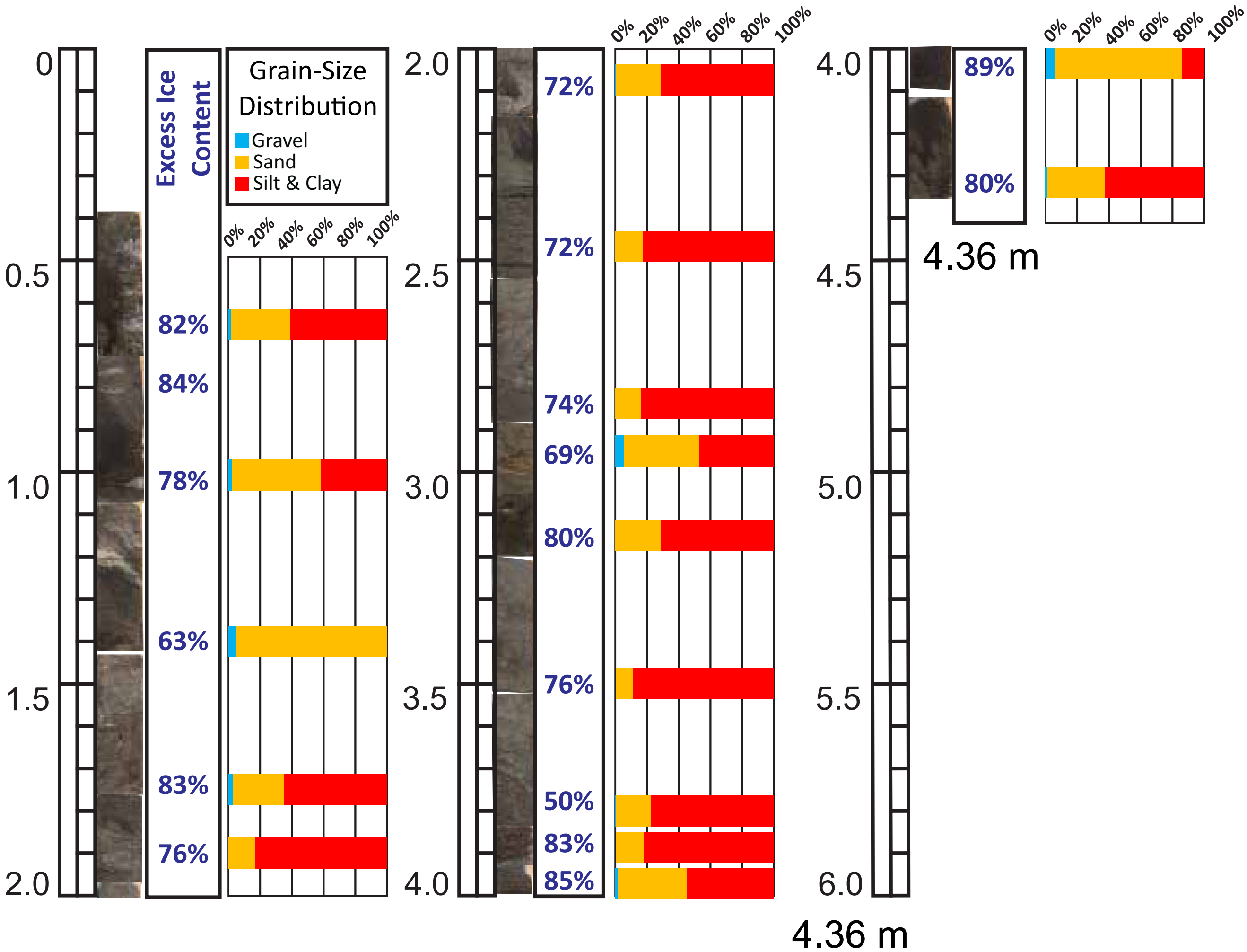
Section 13 (continued)

BH12S, km 1894.2, south slope site



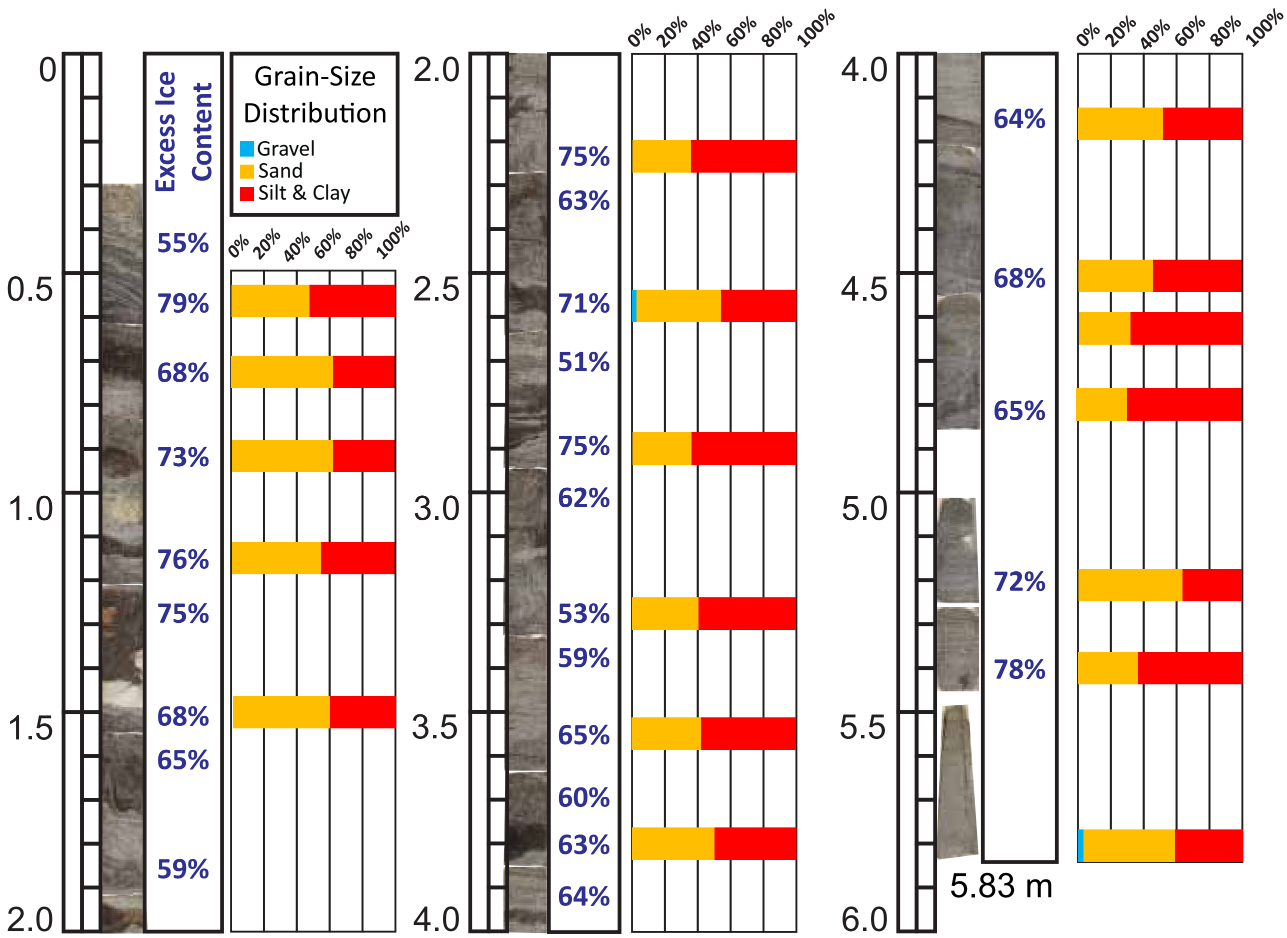
Section 13 (continued)

BH12, km 1894.4, valley bottom close to Campbell Station



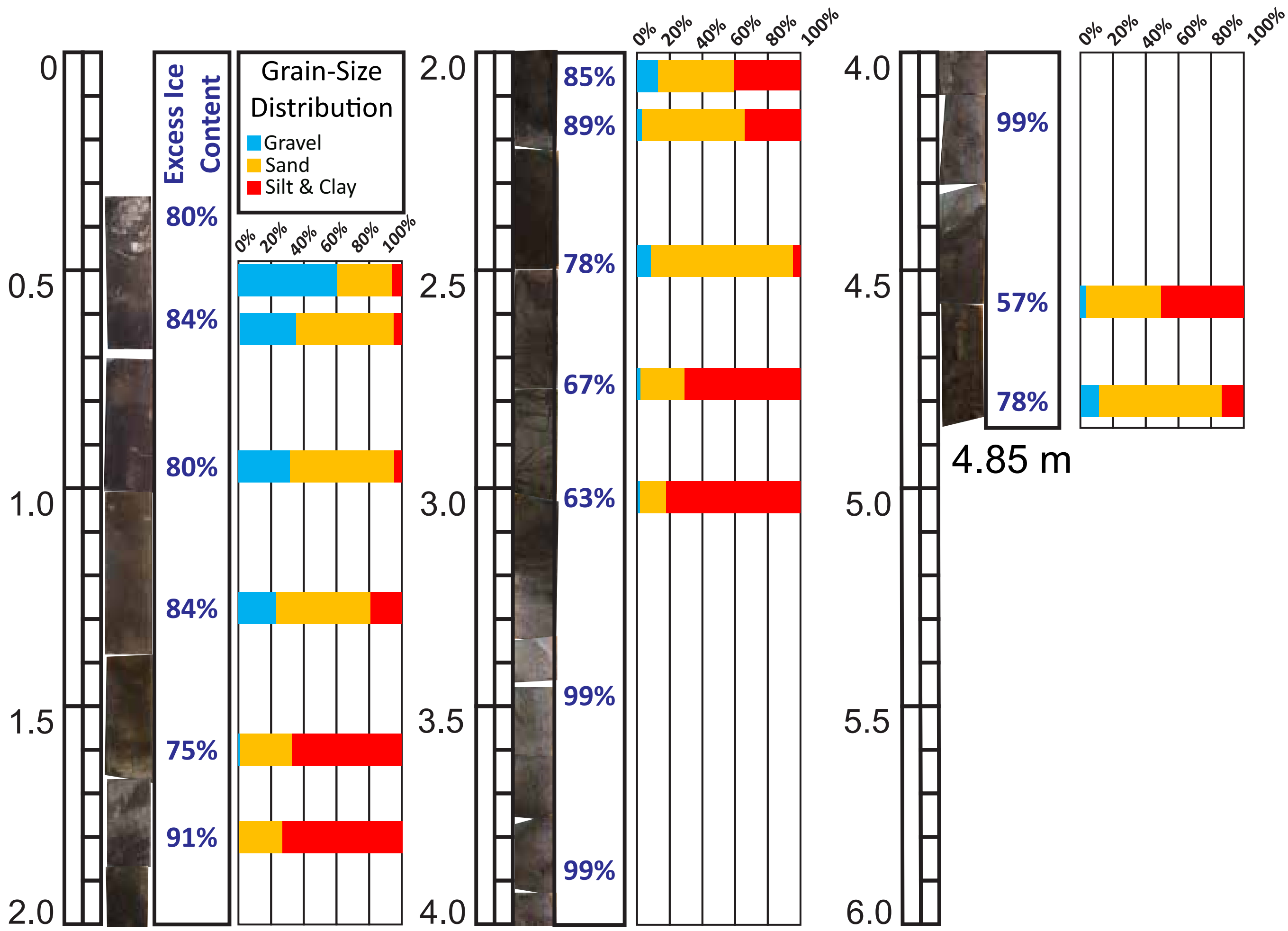
Section 13 (continued)

BH12N, km 1894.8, north slope site



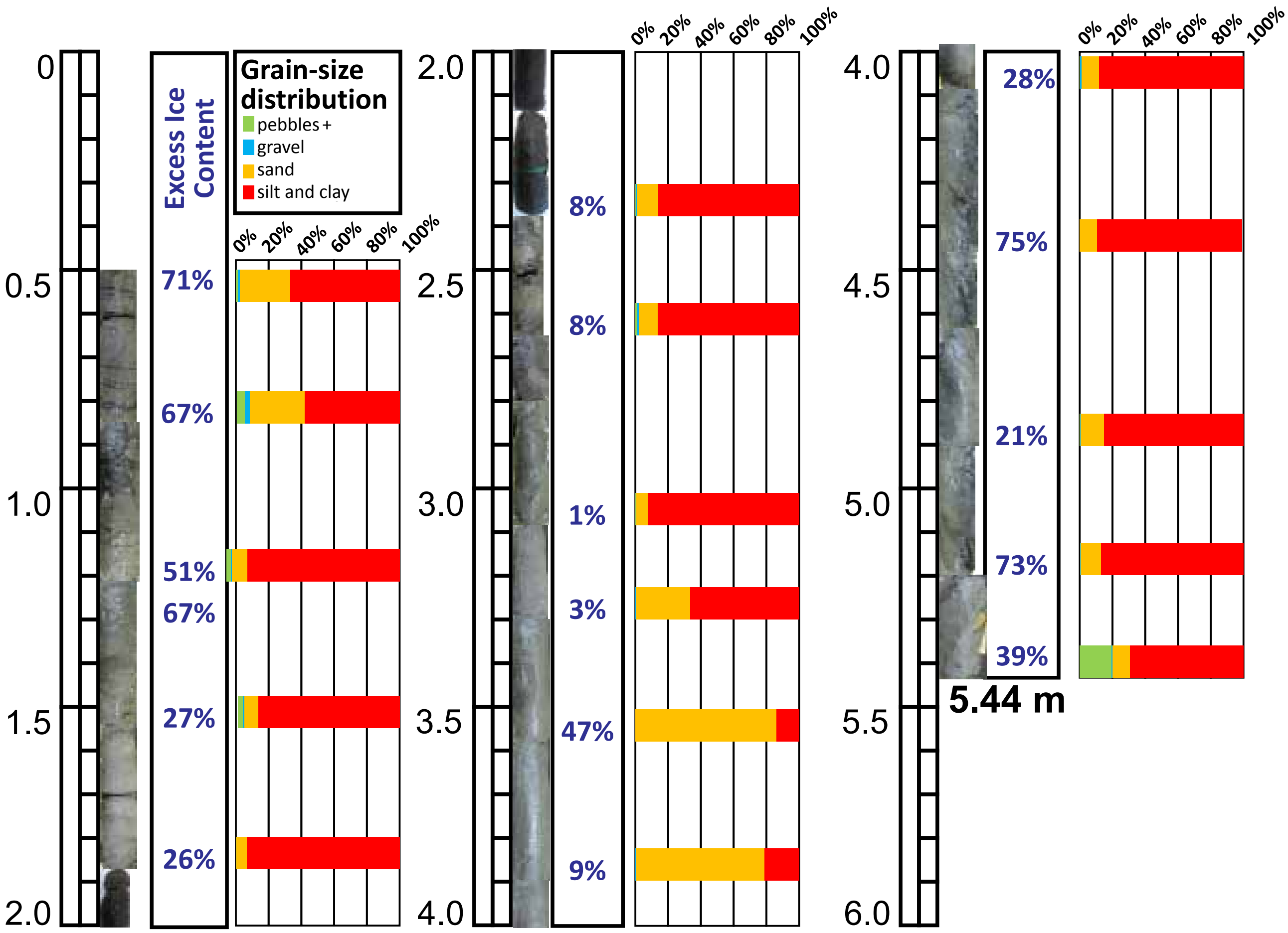
Section 13 (continued)

BH13, km 1896.3, valley bottom site



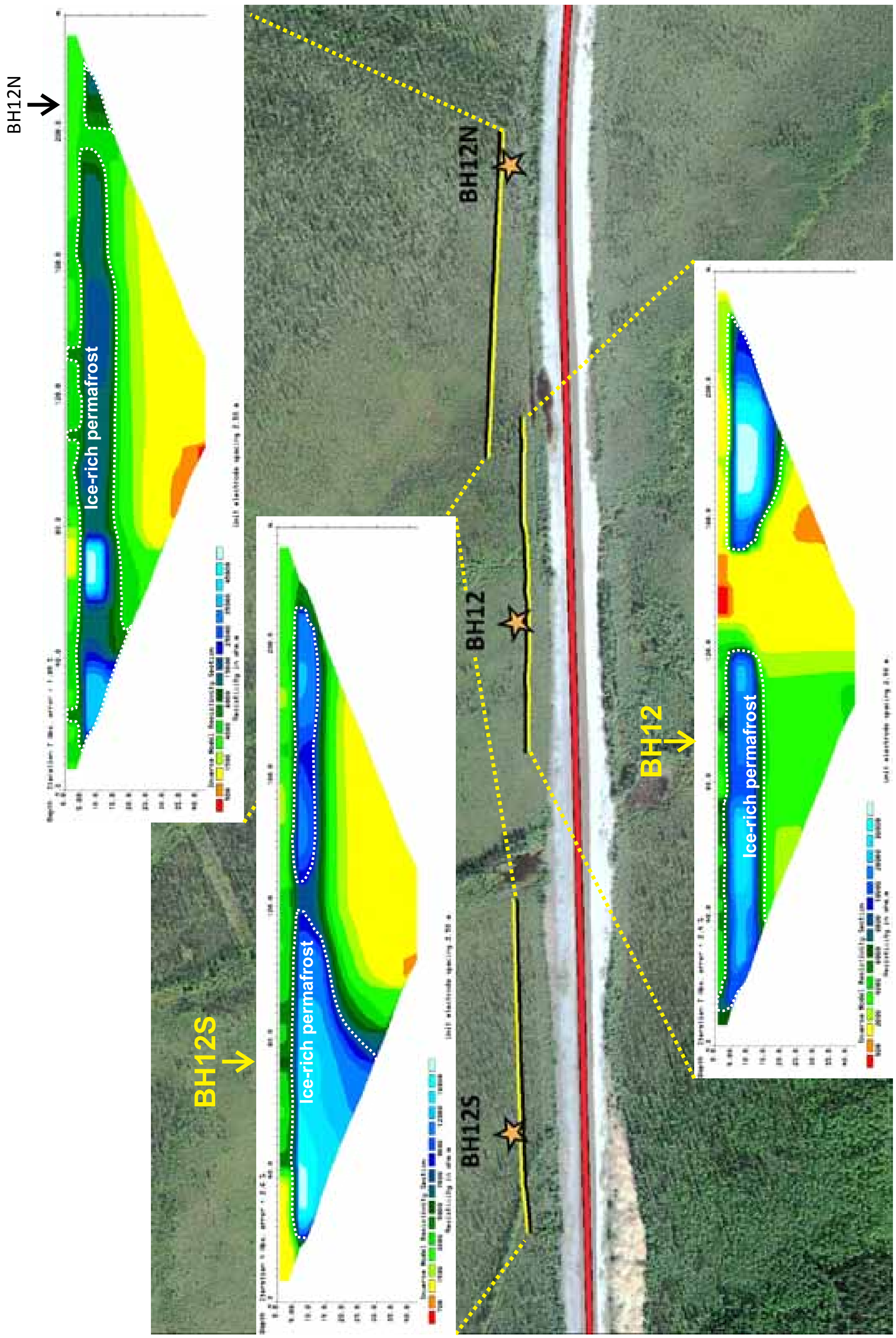
Section 13 (continued)

BH09, km 1897.8, bone cut



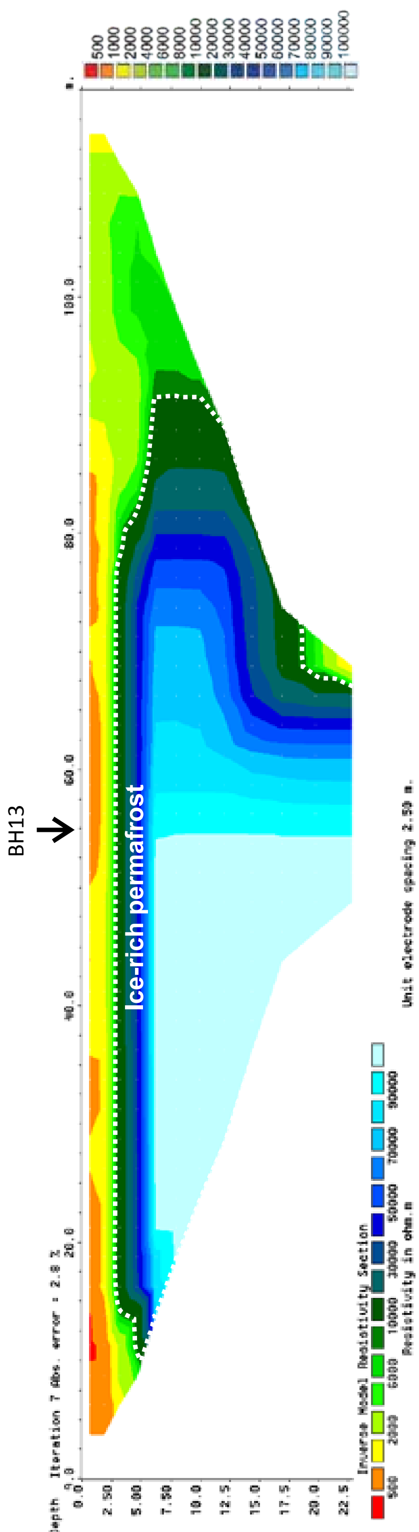
Section 13 (continued)

BH12, BH12S and BH12N, between km 1894.2 and 1894.8



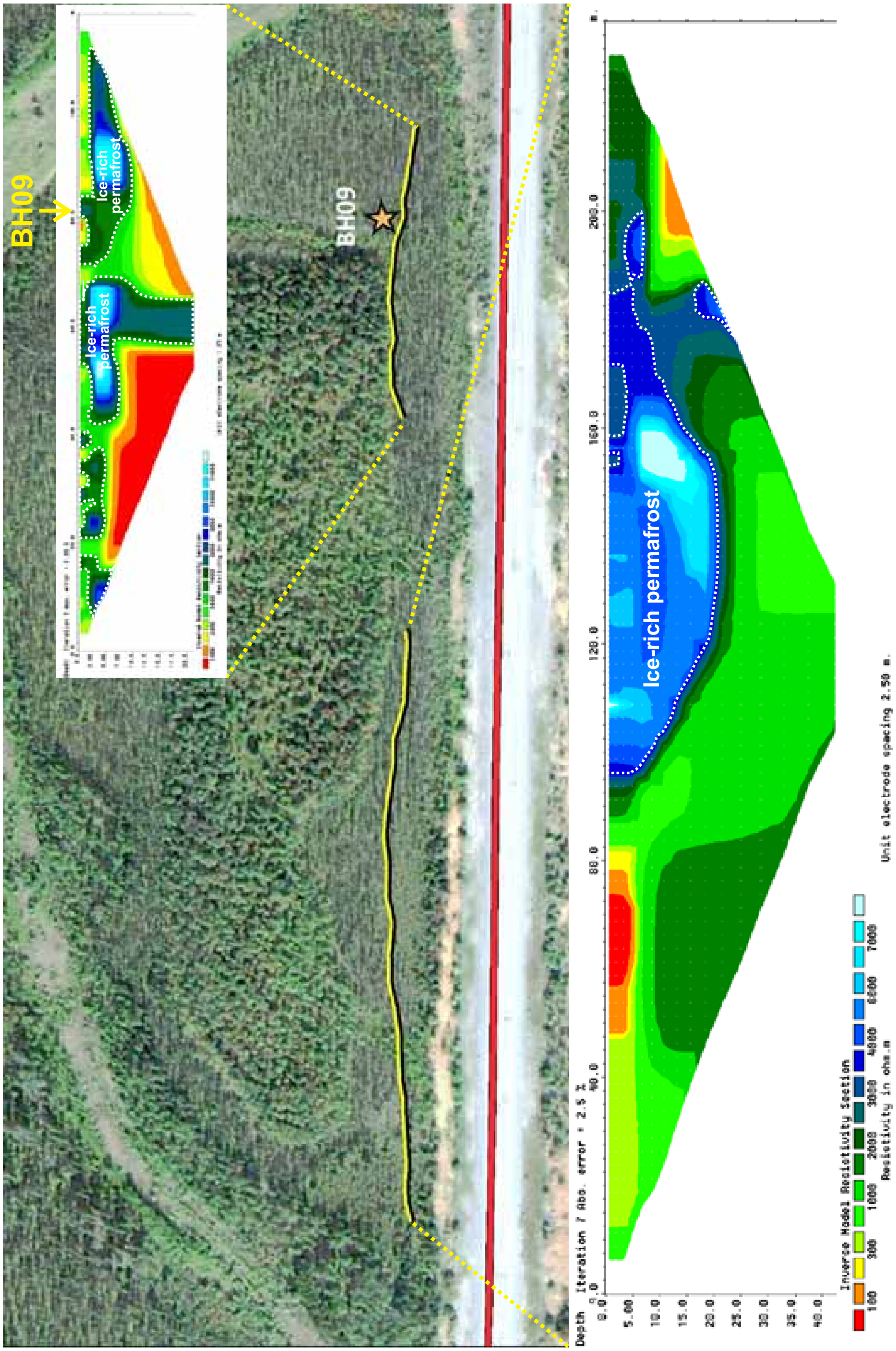
Section 13 (continued)

BH13, km 1896.3



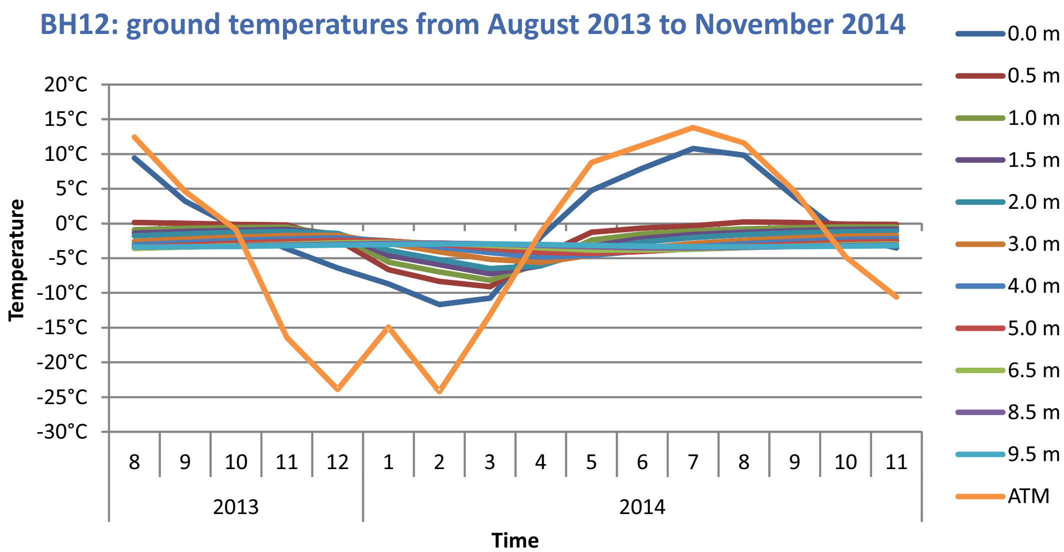
Section 13 (continued)

BH09, km 1897.8

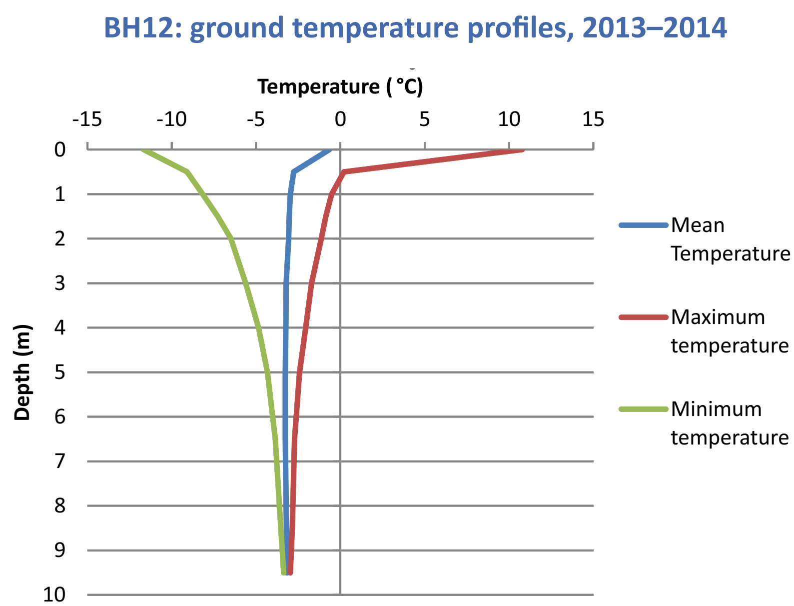


Section 13 (continued)

BH12, km 1894.4

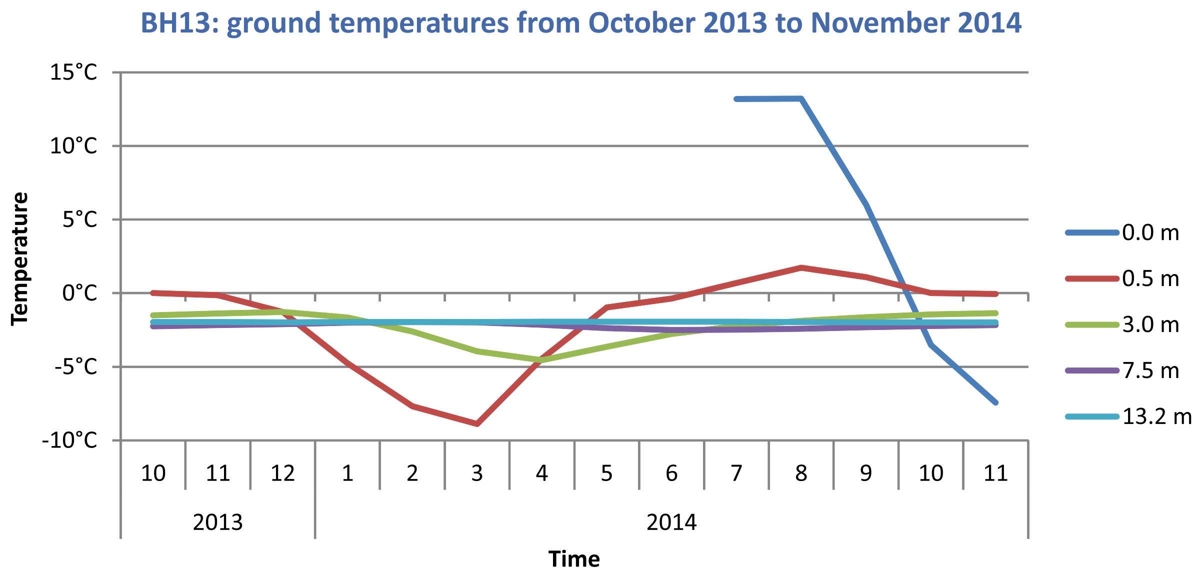


Depth (m)	0	0.5	1	1.5	2	3	4	5	6.5	8.5	9.5	Air
Mean Monthly Temperature	-0.7°C	-2.8°C	-3.0°C	-3.0°C	-3.1°C	-3.2°C	-3.2°C	-3.3°C	-3.3°C	-3.2°C	-3.2°C	-4.0°C
Maximun Monthly Temperature	10.8°C	0.2°C	-0.5°C	-0.9°C	-1.1°C	-1.7°C	-2.1°C	-2.4°C	-2.7°C	-2.8°C	-3.0°C	13.8°C
Minimum Monthly Temperature	-11.7°C	-9.1°C	-8.2°C	-7.3°C	-6.5°C	-5.6°C	-4.8°C	-4.3°C	-3.9°C	-3.5°C	-3.4°C	-24.2°C

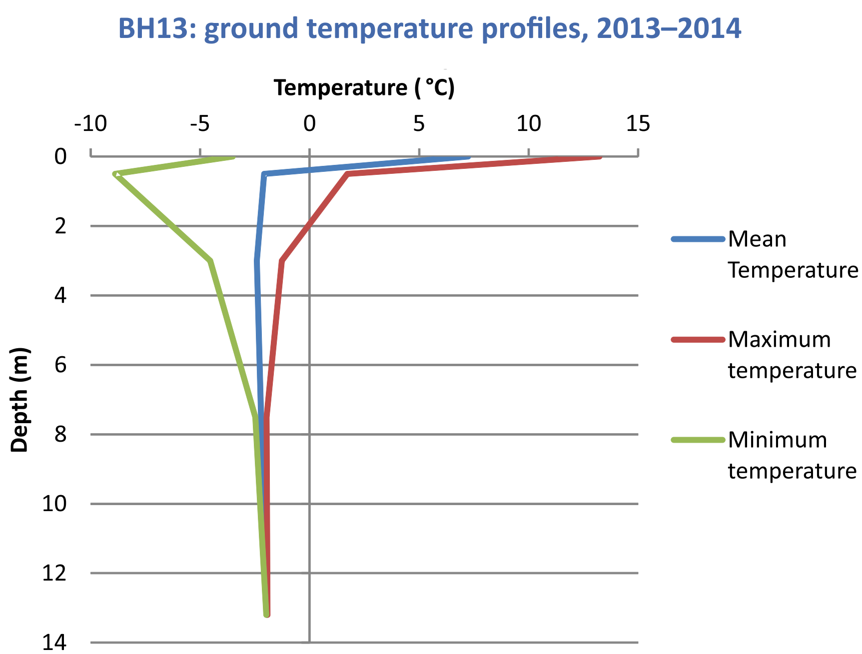


Section 13 (continued)

BH13, km 1896.3

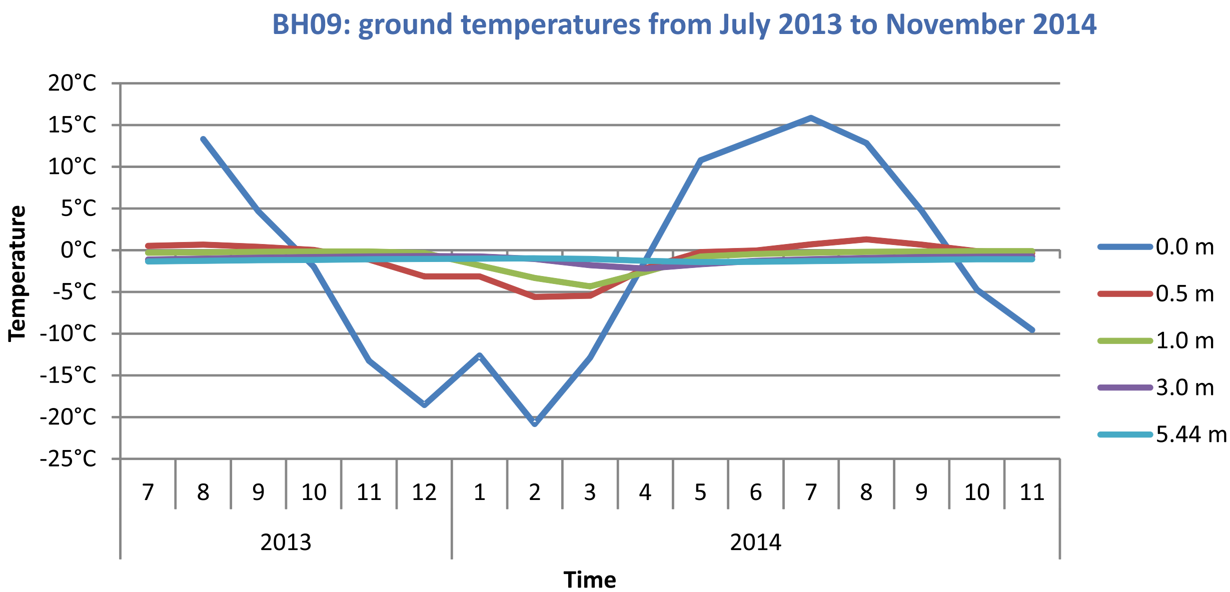


Depth (m)	0	0.5	3	7.5	13.2
Mean Monthly Temperature	7.2°C	-2.1°C	-2.4°C	-2.2°C	-2.0°C
Maximun Monthly Temperature	13.2°C	1.7°C	-1.3°C	-2.0°C	-1.9°C
Minimum Monthly Temperature	-3.5°C	-8.9°C	-4.5°C	-2.5°C	-2.0°C

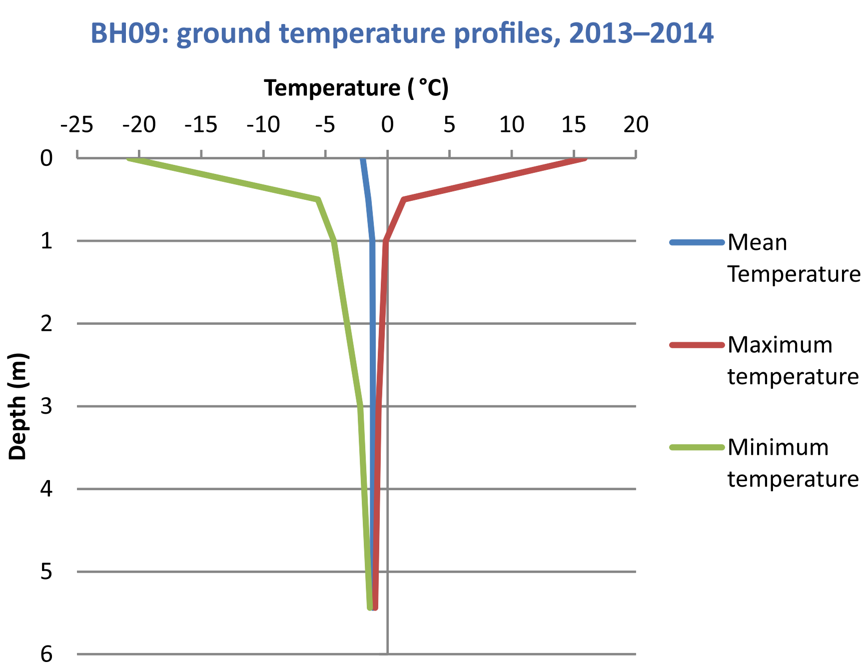


Section 13 (continued)

BH09, km 1897.8



Depth (m)	0	0.5	1	3	5.44
Mean Monthly Temperature	-2.0°C	-1.5°C	-1.2°C	-1.2°C	-1.2°C
Maximun Monthly Temperature	15.9°C	1.3°C	-0.1°C	-0.7°C	-1.0°C
Minimum Monthly Temperature	-20.8°C	-5.6°C	-4.3°C	-2.2°C	-1.4°C



Annex 2. Glossary

Please note: an asterisk (*) indicates that a term is listed in the glossary.

A2.1 Surficial geology deposits

Alluvial: This pertains to material or processes associated with transportation and/or subaerial deposition by concentrated running water.

Colluvium: Unsorted, rock fragments and soil materials produced by gravity or mass wasting are called colluvium. Landslides, mudslides and talus are all colluvial deposits. These heterogeneous deposits are generally identifiable in the field and typically lie in a slump at the base of a hill or rock outcrop.

Drift: Drift is a general word for glacial deposits and is used when the origin of the deposit is uncertain. When surficial geology is indicated as morainal (till), it means that the glacial origin was identified and supported by field analysis or observation. Drift refers to materials that are deposited by glacial action, whether directly from the ice or indirectly from meltwater. Drift includes all the material ever handled by the ice even if it has subsequently been affected by wind or water. Drift deposited indirectly from meltwater includes glaciofluvial and glaciolacustral deposits.

Eolian: This means connected with or caused by the action of the wind. Eolian deposits are the result of the accumulation of wind-driven products of the weathering of solid bedrock or unconsolidated alluvial, lacustrine, marine or other deposits.

Fluvial: These are very unsorted sediments. Fine-grained sediments are found at the bottom of the stream channel; very coarse sediments, including cobbles and pebbles, can be found along or in the stream. The particle size varies according to the force of the water flow.

Glaciofluvial: These materials are deposited by waters associated with glacial ice that are deposited by a stream or river originating from glacial meltwater.

Glaciolacustral: Materials that are deposited by waters associated with glacial ice include sediments deposited in lakes that border and/or are supplied by the glacier. Deposits from meltwater exhibit some degree of sorting and are often stratified.

Kettle hole: This is a depression in glacial drift caused by the melting of a detached block of stagnant ice that was buried in the drift. Kettle holes often contain a lake or swamp.

Lacustrine: These are fine-grained sediments that are deposited in freshwater lakes. Wave action in lakes carries the finer suspended grained silt and clay sized particles towards deeper water. As the water calms, these particles settle out and accumulate at the bottom of the lake to form what is known as lacustrine soil. The lake may no longer exist.

Morainal (till): This is unstratified and unsorted debris deposited directly from glacial ice without subsequent movement by wind or water. It consists mainly of mechanically broken fragments of bedrock, as well as any soils or earlier glacial deposits that were overridden by the glacier. It commonly includes a mixture of a few large rock fragments within a matrix of fine sand, silt and clay.

Organic: Organic soils contain well-decomposed organic matter with or without plant fibres at various stages of decomposition.

Sandur: This is a broad outwash plain.

Talik: A talik is a layer of year-round unfrozen ground that lies below permafrost.

Tephra: Solid matter, such as ash, dust and cinders, that is ejected into the air by an erupting volcano. Tephra is a general term for all pyroclastic materials ejected from a volcano.

Till: Drift deposited directly by glacial ice with no sorting action is called till.

A2.2 Permafrost and related ground ice features

Active layer: This is the layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

In the continuous permafrost zone the active layer generally reaches the permafrost table; in the zone of discontinuous permafrost it often does not. The active layer includes the uppermost part of the permafrost wherever either the salinity or clay content of the permafrost allows it to thaw and refreeze annually, even though the material remains below 0°C. The active layer is sometimes referred to as the “active zone”; the term “zone,” however, should be reserved for the areas of discontinuous and continuous permafrost.

Aggradation: A process that builds up the level of a land surface by the deposit of sediment.

Aggradational ice: This is the additional ground ice that formed as a direct result of permafrost aggradation.

Buried ice: This is ice that was formed or deposited on the ground surface and later covered by sediments. Buried ice likely represents buried glacier ice or snowbanks, or less likely, lake, river or sea ice.

Discontinuous permafrost: This occurs between the continuous permafrost zone and the southern latitudinal limit of permafrost in lowlands. Depending on the scale of mapping, several subzones can often be distinguished, based on the percentage of the land surface underlain by permafrost.

Epigenetic permafrost: This is permafrost that formed through the lowering of the permafrost base in previously deposited sediment or other earth material.

Excess ice: This the volume of ice in the ground that exceeds the total pore volume that the ground would have under natural unfrozen conditions.

In standard geotechnical terminology, a soil is considered normally consolidated when its total pore volume or its total water content is in equilibrium with the acting gravity stresses. Due to the presence of ground ice, the total water content of a frozen soil may exceed that corresponding to its normally consolidated state when unfrozen. As a result, upon thawing, a soil containing excess ice will settle under its own weight until it attains its consolidated state.

Frost heave: This is the upward or outward movement of the ground surface (or objects on or in the ground) caused by the formation of ice in the soil.

Frost action in fine-grained soils increases the volume of the soil not only by freezing of in situ pore water (≈ 9% expansion), but also by drawing water to the freezing front where ice lenses form. Soils that have undergone substantial heaving may consist of alternate layers of ice-saturated soil and relatively clear ice lenses.

The lenses are formed normal to the direction of heat flow and when freezing penetrates from the ground surface (which may be horizontal, sloping or vertical), they form parallel to that surface. When unrestrained, the amount of surface heave may be almost as much as the total thickness of the ice lenses. Frost heave can occur seasonally or continuously if the ground freezes without interruption over a period of years.

Differential, or non-uniform, frost heaving is one of the main detrimental aspects of the frost action process and reflects the heterogeneous nature of most soils, or variations in the heat removal rate and groundwater supply over short distances.

Depending on the degree of restraint, large freezing pressures (up to 1 megapascal) can develop as the ground freezes. These can be transmitted to a foundation, structure or other object placed on the ground surface, or embedded or buried in the ground, as basal (i.e., vertical) forces acting on their underside, or through freezing of the soil to the sides of the foundation, structure or object.

Frost mound: This is any mound-shaped landform produced by the ground freezing, combined with the accumulation of ground ice due to groundwater movement or the migration of soil moisture. Various types of frost mounds, (e.g., frost blisters, icing blisters, palsas and pingos) can be distinguished on the basis of their structure and duration and the character of the ice contained in them.

Frost-susceptible ground: This is ground (soil or rock) in which segregated ice will form (causing frost heave) under certain conditions of moisture supply and temperature.

Frost-susceptible ground will eventually become ice-rich, regardless of its initial total water content, if the appropriate moisture supply and temperature conditions persist. By implication, frost-susceptible ground may also be susceptible to thaw weakening effects when it thaws.

Ice-rich permafrost: Permafrost that contains excess ice is ice-rich. * Ice-rich permafrost* is thaw-sensitive.*

Ice-wedge: A massive, usually wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice.

Massive ice: This comprehensive term is used to describe large masses of ground ice, including ice wedges, pingo ice, buried ice and large ice lenses. Massive ice beds typically have an ice content of at least 250 percent (on an ice-to-dry-soil weight basis).

Permafrost: This is ground (soil or rock, along with ice and organic material) that remains at or below 0°C for at least two consecutive years.

Permafrost is defined on the basis of temperature. It is not necessarily frozen, because the freezing point of the included water may be depressed several degrees below 0°C; moisture in the form of water or ice may or may not be present. In other words, all perennially frozen ground is permafrost, but not all permafrost is perennially frozen. Permafrost should not be regarded as permanent, because natural or human-made changes in the climate or terrain may cause the temperature of the ground to rise above 0°C. Permafrost includes perennial ground ice, but not glacier ice or icings or bodies of surface water with temperatures perennially below 0°C. It also includes human-made perennially frozen ground around or below chilled pipelines, hockey arenas, etc.

Permafrost aggradation: A naturally or artificially caused increase in the thickness and/or area of permafrost.

Permafrost aggradation may be caused by climatic cooling or by changes in terrain conditions, including vegetation succession, infilling of lake basins and a decrease in snow cover. It can also occur under ice arenas, road and airfield embankments, etc. It may be expressed as a thinning of the active layer and a thickening of the permafrost, or by an increase in the areal extent of permafrost.

Permafrost base: The lower boundary surface of permafrost, above which temperatures are perennially below 0°C and below which temperatures are perennially above 0°C.

Permafrost table: This the upper boundary surface of permafrost. The depth of this boundary below the land surface, whether exposed or covered by a water body or glacier ice, varies according to such local factors as topography, exposure to the sun, insulating cover of vegetation and snow, drainage, grain size and degree of sorting of the soil, and thermal properties of the soil and rock.

Permafrost thickness: This the vertical distance between the permafrost table and the permafrost base.

Relict ice: This is ice that formed in and remains from the geologically recent past.

Segregated ice: This is ice in discrete layers or ice lenses. Segregated ice can range in thickness from a hairline to more than 10 m. It commonly occurs in alternating layers of ice and soil.

Syngenetic permafrost: This is permafrost that formed through a rise in the permafrost table during the deposition of additional sediment or other earth material on the ground surface.

Thaw-sensitive permafrost: This is perennially frozen ground which, when it thaws, will experience significant thaw settlement and lose strength to a value significantly lower than that of similar material in an unfrozen condition. Ice-rich permafrost* is thaw-sensitive.

Thawing front: This is the advancing boundary between thawed ground and frozen ground. The thawing front may be advancing into either seasonally or perennially frozen ground during progressive thawing. In non-permafrost areas there will be two thawing fronts during the annual thawing period: one moving downward from the surface, the other moving upward from the bottom of the seasonally frozen ground. The thawing front usually coincides more closely with the position of the 0°C isotherm than the freezing front, except in saline permafrost.

Thermal erosion: This is a dynamic process involving the wearing away by thermal means (i.e., the melting of ice) and mechanical means (i.e., moving water). Thermal erosion is distinct from the development of thermokarst* terrain, which results from thermal melting followed by subsidence of the ground but without earth materials being worn away by moving water.

Thermokarst: This is the process by which characteristic landforms result from the thawing of ice-rich permafrost* or the melting of massive ice.* Landforms include alasses, thermokarst lakes and thermokarst mounds.

Thermokarst lake: This is a lake that occupies a depression formed by the ground settling following the thawing of ice-rich permafrost* or the melting of massive ice.* Thermokarst lakes are generally shallow. The depressions may expand by the failure of the active layer; the lakes may expand by thermokarst processes. In glaciated terrain they may be similar in appearance to kettle lakes.

Annex 3. References

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