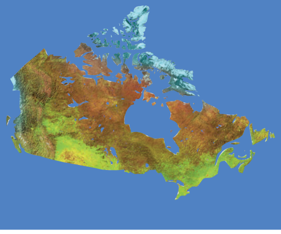
Natural Resources Canada
Ressources naturelles Canada



Baseline geotechnical and permafrost data from new field sites established in the Mackenzie corridor south of Norman Wells, Northwest Territories

S.L. Smith, T.-N. Nguyen, D.W. Riseborough, M. Ednie, S. Ye, and J. Chartrand

Geological Survey of Canada

Current Research 2010-2

2010

Canada

Geological Survey of Canada
Current Research 2010-2

Baseline geotechnical and permafrost data from new field sites established in the Mackenzie corridor south of Norman Wells, Northwest Territories

S.L. Smith, T.-N. Nguyen, D.W. Riseborough, M. Ednie, S. Ye, and J. Chartrand

2010

ISSN 1701-4387
Catalogue No. M44-2010/2E-PDF
ISBN 978-1-100-14563-1
DOI 10.4095/261487

Toll-free (Canada and U.S.A.): 1-888-252-4301

Recommended citation

Smith, S.L., Nguyen, T.-N., Riseborough, D.W., Ednie, M., Ye, S., and Chartrand, J., 2010. Baseline geotechnical and permafrost data from new field sites established in the Mackenzie corridor south of Norman Wells, Northwest Territories; Geological Survey of Canada, Current Research 2010-2, 15 p.

Critical reviewer

B. Wang

Authors

***S.L. Smith** (ssmith@nrcan.gc.ca)*
D.W. Riseborough (drisebor@nrcan.gc.ca)
M. Ednie (mednie@nrcan.gc.ca)
J. Chartrand (jachartr@nrcna.gc.ca)
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

T.-N. Nguyen (Nicholas.Nguyen@eg.gc.ca)
Canadian Ice Service
Environment Canada
373 Sussex Drive, E-3
Ottawa, Ontario K1A 0H3

S. Ye (Shiqiang.Ye@bchydro.com)
BC Hydro
6911 Southpoint Drive
Burnaby, British Columbia V3N 4X8

Correction date:

Baseline geotechnical and permafrost data from new field sites established in the Mackenzie corridor south of Norman Wells, Northwest Territories

S.L. Smith, T.-N. Nguyen, D.W. Riseborough, M. Ednie, S. Ye,
and J. Chartrand

Smith, S.L., Nguyen, T.-N., Riseborough, D.W., Ednie, M., Ye, S., and Chartrand, J., 2010. Baseline geotechnical and permafrost data from new field sites established in the Mackenzie corridor south of Norman Wells, Northwest Territories; Geological Survey of Canada, Current Research 2010-2, 15 p.

Abstract: A major field program was undertaken in February and March 2007 by the Geological Survey of Canada in order to address gaps in baseline environmental information in the Mackenzie Valley, south of Norman Wells, Northwest Territories. Sites were selected to represent a range of ground-thermal, terrain, and vegetation conditions. Drilling of boreholes to depths of 20 m yielded data for characterization of subsurface materials at 16 locations, including physical properties of soil and ground-ice conditions. Twenty boreholes were preserved and instrumented with temperature cables and the data acquired has enabled a preliminary characterization of the ground-thermal regime. Key baseline information was generated for a suite of representative terrain types that may be utilized in planning northern development and environmental impact assessment. Ongoing data collection from thermal monitoring sites will facilitate improved characterization of current permafrost conditions and change detection.

Résumé : En février et mars 2007, la Commission géologique du Canada a entrepris un important programme de travaux sur le terrain afin de combler des lacunes dans l'information environnementale de base sur la vallée du Mackenzie, au sud de Norman Wells, dans les Territoires du Nord-Ouest. Le choix des sites visait à représenter toute une gamme de conditions liées au régime thermique du sol, à l'état du terrain et à la végétation. Le forage de trous d'une profondeur de 20 m a permis de recueillir des données de caractérisation des matériaux de subsurface à 16 endroits, dont des données sur les propriétés physiques des sols et l'état de la glace de sol. Vingt trous ont été maintenus en état et instrumentés à l'aide de câbles de mesure de la température, et les données qui y ont été recueillies ont permis une caractérisation préliminaire du régime thermique du sol. L'information de base essentielle ainsi obtenue pour une série de types de terrains représentatifs pourra être utilisée aux fins de la planification de la mise en valeur du Nord et de l'évaluation des incidences environnementales. La collecte continue de données aux sites de surveillance thermique permettra d'améliorer la caractérisation de l'état actuel du pergélisol et la détection des changements.

INTRODUCTION

Permafrost is an important feature of the Mackenzie Valley landscape and is an important influence on the biophysical and socioeconomic environments of the region. Permafrost and the ground ice it contains are important factors controlling drainage patterns and ground stability and also present challenges to northern development. Since permafrost is a thermal condition, its distribution and temperature are sensitive to changes in the surface energy balance that may result from changes in climate or disturbance of the ground surface such as that resulting from clearance of vegetation associated with development. Warming and subsequent thawing of permafrost can lead to changes in the landscape such as slope movements, thermokarst development, and ground subsidence that may have implications for infrastructure, surface and subsurface hydrology, ecosystems, and northern lifestyles.

Knowledge of permafrost conditions (temperature, active-layer thickness, and ground-ice conditions) and their spatial and temporal variations is essential for rational planning of northern development and for understanding the impact of environmental disturbance and climate change on permafrost-affected landscapes. Increased activity associated with proposed hydrocarbon development is anticipated in the Mackenzie Valley, including construction of a pipeline to carry natural gas from the Mackenzie Delta to northern Alberta. Knowledge of ground-thermal conditions and the physical properties of the soil are essential for both engineering design and assessment of environmental impacts associated with these development projects. Ongoing monitoring of permafrost conditions is essential to understand how conditions may change over time, to assess related impacts on northern infrastructure, and to develop strategies to mitigate these impacts.

Since the mid 1980s, the Geological Survey of Canada (GSC) has been developing and maintaining a permafrost monitoring network in the Mackenzie Valley, including a suite of study sites along the Norman Wells to Zama (Enbridge Pipelines (NW) Inc.) pipeline corridor (*see* for example Smith et al., 2004, 2005b). Significant gaps exist in the network including the region between Norman Wells and Inuvik and sensitive peatland areas in the southern discontinuous zone. Gaps in baseline geotechnical and permafrost information were identified in an analysis led by the Department of Indian and Northern Affairs (Gartner Lee Limited, 2003). In 2004, the GSC undertook to address this gap with funding acquired through the Northern Energy Development Initiative. Fieldwork conducted between 2005 and 2007 was directed toward addressing these gaps through drilling of several boreholes, the collection of samples to determine geotechnical properties, and the preservation of boreholes and installation of temperature cables for long-term ground-thermal monitoring. Smith et al. (2007, 2008b) reported on field studies to address a major gap between Norman Wells and Fort Good Hope. This paper summarizes the fieldwork to fill gaps south of Norman Wells and presents preliminary information on surficial materials and the ground-thermal regime.

REGIONAL SETTING AND SITE SELECTION

The physical landscape of the study area (Fig. 1) is primarily a result of the last continental glaciation that covered most of the region about 30 000 years ago, and most areas are underlain by unconsolidated glacial and postglacial deposits. Extensive deposits up to 30 m in thickness of glaciolacustrine and lacustrine silt and clay, associated with the large temporary lake basins that formed during deglaciation, are found within the region (Aylsworth et al., 2000; Duk-Rodkin and Lemmen, 2000) and are commonly ice-rich. The postglacial landscape comprises morainic and fluvial landforms of the northern Interior Plains. Boreal forest dominates the area and is characterized by spruce, shrub undergrowth, and a moss-lichen floor. Accumulations of peat cover the mineral soils in areas where drainage is impeded (Aylsworth and Kettles, 2000). Between Norman Wells and the Alberta border, lacustrine deposits dominate the northern portion of the region, whereas till units and organic terrain are prevalent in the southern portion. South of Fort Simpson, peatlands, defined as organic wetlands having 40 cm or more of peat, cover over 60% of the terrain (Burgess and Lawrence, 2000).

The regional climate is characterized by a cold and relatively dry continental climate with mean annual air temperatures (based on Environment Canada's 1971–2000 climate normals) ranging from -5.5°C at Norman Wells to -3.2°C at Fort Simpson. Normal annual total precipitation is about 290 mm at Norman Wells and 369 mm at Fort Simpson, with about half falling as snow that often stays on the ground from October until April.

The permafrost distribution within the study area ranges from sporadic in the south to extensive discontinuous permafrost in the north (Heginbottom, 2000) with permafrost underlying 10–90% of the land surface (Fig. 1). An analysis of observations of thermal conditions during excavation of the Enbridge Pipelines (NW) Inc. pipeline ditch (Burgess and Lawrence, 2000) indicates that frozen ground underlies 80–90% of the land surface near Norman Wells, declining to less than 20% about 100 km south of Fort Simpson. Frozen ground is largely confined to organic terrain south of Fort Simpson. Much of this permafrost likely formed during the Little Ice Age (e.g. Halsey et al., 1995) and has been preserved under subsequent warmer climatic conditions by a thick layer of insulating peat.

Regional information on permafrost thickness and ground temperature has been summarized in Smith and Burgess (2000, 2002) and is largely based on precise borehole temperature logs of the "Canadian Geothermal Data Collection – Northern Wells" (Taylor et al., 1982), a compilation of

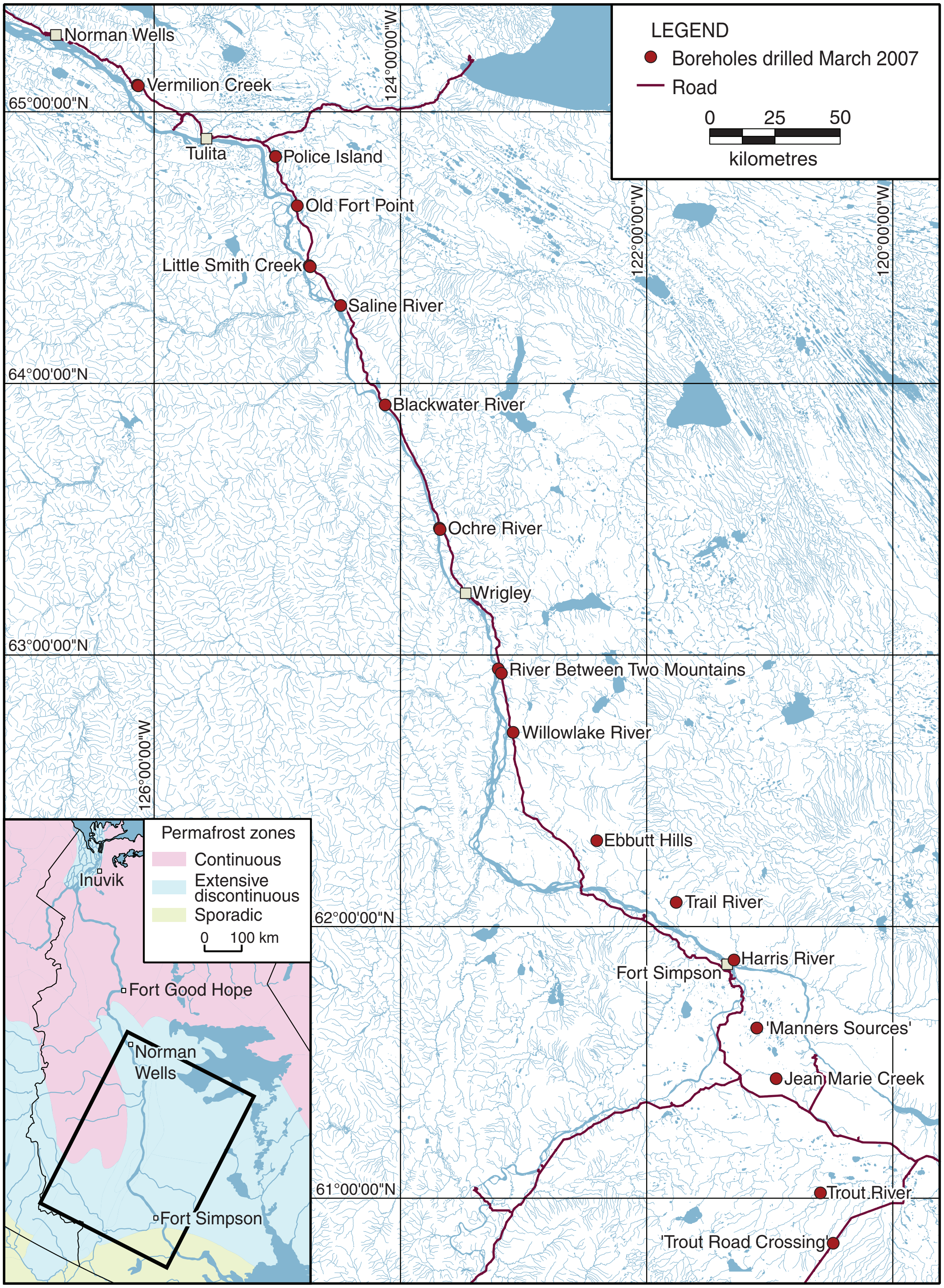


Figure 1. Location of boreholes drilled in February–March 2007 shown on permafrost distribution map (Heginbottom et al., 1995). Borehole locations in single quotation marks are informal names.

measurements by Judge (1973) and data collected as part of the Permafrost Terrain Research and Monitoring Program (*see* for example MacInnes et al., 1990; Smith et al., 2004) along the Enbridge Pipeline (NW) Inc. corridor. Where permafrost is present, its thickness ranges from a few metres to about 50 m. Mean annual near-surface ground temperatures are generally above -2°C.

Considerable information has been compiled (Smith et al., 2005a) on geotechnical properties of soils for the Mackenzie Valley south of Norman Wells primarily associated with geotechnical investigations along the Enbridge Pipeline (NW) Inc. corridor. Although the GSC maintains several permafrost monitoring sites in the Mackenzie Valley south of Norman Wells, there are both spatial and thematic gaps in the knowledge of recent ground-thermal conditions. The objective of this project was to address some of these gaps through selection of study sites representative of the terrain and vegetation conditions found throughout the region, similar to the rationale utilized for the establishment of the active-layer monitoring program in the Mackenzie Valley (*see* for example Nixon and Taylor, 1994) and the thermal monitoring program along the Norman Wells pipeline corridor (Pilon et al., 1989). Since natural gas pipeline operations may involve subzero pipe temperature leading to frost bulb development and potentially frost heave in currently unfrozen soils, an attempt was made to establish sites in unfrozen terrain to better characterize its ground-thermal regime.

Sites were chosen along the winter road, the all season Mackenzie Highway (Fig. 1), the Enbridge Pipeline (NW) Inc. right-of-way, and other cutlines in order to have easy access (by road or helicopter) during the winter drilling program and also for access during summer visits to retrieve thermal data. Surficial geology maps, airphotos, exisiting borehole databases (e.g. Smith et al., 2005a), and site reconnaissance conducted in May 2006 and September 2006 were utilized to select the sites. The 'Archeological Database' of the Prince of Wales Northern Heritage Centre in Yellowknife was also consulted to determine whether heritage resources were present at the proposed sites. Consultation with communities within the Sahtu (e.g. Norman Wells and Tulita) and Deh Cho settlement areas (e.g. Wrigley, Fort Simpson, Trout Lake, Jean Marie River, Kakisa) was undertaken prior to finalizing site selection. The traditional knowledge provided on proposed sites was essential to ensure that areas of special importance and cultural significance to the community were not disturbed and that all work was carried out in a respectful manner. Community members expressed their support for the project and provided important guidance on site selection.

The locations of the 16 sites chosen south of Norman Wells are shown in Figure 1 and a brief description is provided in Table 1. The sites represent a variety of terrain and vegetation conditions. At some sites, efforts were made to drill two boreholes up to 0.5 km apart to capture the spatial variability and transitions in surficial materials, permafrost, and ground-ice conditions that may occur over short distances and be important for design of transportation or transmission infrastructure. For example, two boreholes were drilled at Little Smith Creek (LS-01, LS-02) and Saline River (SR-01, SR-02) to capture the transition between alluvial and glaciofluvial sediments. The two boreholes drilled at 'Manners Sources' (unofficial name; MS-01, MS-02) capture a transition in terrain and vegetation types, well drained eolian sediments to poorly drained thermokarsted shrub fen. Recent natural disturbances were also considered and two boreholes were drilled at Police Island (PI-01, PI-02) to capture the transition between a recovering burnt area and an unburnt area.

FIELD PROGRAM

Site reconnaissance was conducted in May and September 2006 in order to finalize site selection and collect preliminary information on site characteristics. Where possible, at sites visited in September 2006, preliminary information on the thermal condition of the soils was obtained through inserting a metal probe into the ground to determine if frozen ground was present in the upper 1.2 m and to provide an estimate of thaw depth (Table 2).

Geotechnical drilling and borehole preservation was conducted February to March 2007. For sites between Norman Wells and Willowlake River, rubber track-mounted M5T drill rigs operated by Geotech Drilling Services Ltd. or Mobile Augers were engaged by EBA Engineering Consultants and AMEC Earth & Environmental Ltd., respectively (AMEC Earth & Environmental, unpub. report, 2007; EBA Engineering Consultants, unpub. report, 2008). The rigs were equipped with 150 mm diameter solid-stem augers and 160 mm hollow-stem loggers as well as CRREL 75 mm core barrels. For sites south of Willowlake River, the GSC engaged a heliportable drill rig operated by GeoChem Surveys Ltd. The goal was to drill boreholes to depths of 15–20 m, extract disturbed and undisturbed samples for laboratory testing, and preserve boreholes for thermal monitoring through the installation of polyvinyl choride (PVC) casing. A total of 24 boreholes were planned between Norman Wells and the Trout River winter road (Fig. 1, Table 1).

All sites north of Willowlake River were accessed from the winter or all-season road, whereas sites to the south were accessed by helicopter from either the Enbridge Pipeline (NW) Inc. right-of-way or other cutlines. Boreholes were generally located at least 10 m from existing cutlines to ensure than any thermal effects related to the prior clearing would be minimal (Smith and Riseborough, 2010). Prior to drilling, each site was cleared of snow and brush (either by GSC staff or local contractors and community members) to provide access to the site and a stable and safe platform for the drill rig. Care was taken to not cause excessive disturbance or damage to the ground-surface material

Table 1. Boreholes (BH) drilled in February and March 2007, site description, and instrumentation installed. Approximate site elevation was obtained from GPS or from a topographic map. AT = air temperature sensor, GT = ground temperature cable. Cables were installed in February or March 2007 except where September (Sept.) or August (Aug.) installation is indicated.

Site name	BH ID	UTM zone	UTM co-ordinate	Approx. elev. (m a.s.l.)	Landform	Vegetation cover	BH depth (m)	Instrumentation
Vermilion Creek	VC-01	9W	7222434N, 634464E	92 (map)	Moraine plain at approach to water crossing	NW side of creek, on top of ridge in black spruce forest	8.2	AT, GT to 8 m
	VC-02	9W	7222160N, 634972E	92 (map)	Moraine plain at approach to water crossing	SE side of creek on plateau in area of burnt black spruce	5.5	GT to 5 m (Sept.)
Police Island	PI-01	10W	7191493N, 404417E	113 (GPS)	Lacustrine plain	Recovering burn (burnt black spruce forest)	12.9	GT to 10 m
	PI-02	10W	7191398N, 404454E	113 (GPS)	Lacustrine plain	Unburnt, black spruce forest with moss and lichen ground cover	19.5	GT to 19.4 m
Old Fort Point	OFP-01	10W	7170979N, 412221E	122 (GPS)	Lacustrine plain	Open mixed spruce, pine deciduous forest adjacent to open, low-lying fen	20	GT to 15 m
Little Smith Creek	LS-01	10W	7146259N, 416233E	80 (GPS)	Alluvial flood plain	Open mature black spruce forest	20.6	GT to 14.9 m
	LS-02	10W	7145819N, 416567E	112 (GPS)	Glaciofluvial outwash plain	Tamarack, birch, poplar, and pine forest transition to spruce	20	GT to 19.4 m
Saline River	SR-01	10W	7130133N, 428109E	100 (map)	Alluvial terrace	Old burnt black spruce forest	2.3	None
	SR-02	10W	7129938N, 428106E	140 (map)	Glaciofluvial veneer over lacustrine	Burnt black spruce forest	20.4	AT, GT to 20 m
Blackwater River	BW-01	10W	7088467N, 444851E	114 (map)	Alluvial and glaciofluvial landforms	Flat forested (birch, deciduous) area	0.5	None
Ochre River	OCR-01	10W	7037588N, 465976E	146 (map)	Lacustrine and fluvial terrain	Valley bottom, dense black spruce forest	1.5	None
	OCR-02	10W	7037012N, 466239E	146 (map)	Lacustrine and fluvial terrain	Ridge on south side of river, stunted black spruce forest	2.0	None
River Between Two Mountains	RBTM-01	10W	6979706N, 489609E	120 (map)	Transition lacustrine to alluvial to moraine terrain	Dense black spruce forest	20.6	GT to 15 m
	RBTM-02	10W	6977913N, 490871E	150 (map)	Transition lacustrine to alluvial to moraine terrain	Dense black spruce forest	12.5	GT to 10 m
Willowlake River	WLR-01	10W	6953658N, 495685E	122 (map)	Alluvial fan	Open mixed forest	3.7	GT to 3.7 m (Aug.)
Ebbutt Hills	EH-01	10W	6909592N, 530836E	324 (map)	Moraine	Dense black spruce, labrador tea and cloudberry-lichen bog	16	GT to 15 m
Trail River	TR-01	10W	6884733N, 564755E	181 (map)	Lacustrine plain and eolian landforms	Black spruce and tamarack forest with understory of sphagnum and feathermoss	12.2	GT to 10 m
Harris River	HAR-01	10W	6861673N, 589929E	146 map)	Moraine	Predominately birch	16	GT to 15 m
'Manners Sources'	MS-01	10W	6834043N, 600416E	182 (map)	Eolian interdune	Thermokarsted shrub fen	16	GT to 15 m
	MS-02	10W	6834045N, 600488E	182 (map)	Eolian dune crest	Pine forest	16	GT to 15 m
Jean Marie Creek	JMC-01	10W	6813448N, 609445E	198 (map)	Transition alluvial flood plain to organic (fen) over lacustrine plain	Poorly drained shrub fen	8.5	GT to 5 m (Sept.)
	JMC-02	10W	6813530N, 609408E	198 (map)	Transition alluvial flood plain to organic (fen) over lacustrine plain	Sandy ridge with spruce, pine forest	10	GT to 5 m (Sept.)
Trout River	TroutR	10W	6767353N, 630326E	350 (map)	Organic terrain	Peatland with scattered spruce and sphagnum ground cover	7.2	GT to 5 m (Sept.)
'Trout Road Crossing'	TRC	10W	6746943N, 636730E	420 (map)	Bog-dominated moraine plain	Dry peatland vegetation consisting of black spruce, tamarack, and feathermoss	12	GT to 10 m

Table 2. Active-layer thicknesses for borehole sites preserved for temperature measurement. The depth of thaw was either determined through mechanical probing (probe) or through interpolation of maximum ground-temperature profiles (temp.). UF = ground is unfrozen, i.e. permafrost is absent. NA = it was not possible to determine the depth of thaw.

Borehole ID	Active layer probe (cm, average and range)	Active layer temp. (cm)
VC-01	NA	74
VC-02	NA	NA
PI-01	NA	284
PI-02	NA	222
OFP-01	95 (88–108)	94
LS-01	>120	421
LS-02	>120	811
SR-02	>120	538
RBTM-01	UF	UF
RBTM-02	76 (74–78)	<150
WLR-01	>110	NA
EH-01	NA	NA
TR-01	UF	UF
HAR-01	UF	UF
MS-01	UF	UF
MS-02	UF	UF
JMC-01	UF	UF
JMC-02	UF	UF
TroutR	UF	UF
TRC	UF	UF

(mineral and organic) and vegetation. An environmental monitor accompanied the field crew to ensure that all work was carried out in a respectful manner.

Attempts were made to complete all boreholes to the desired depth of 15–20 m, but due to limitations of the drill rig and the difficult subsurface conditions encountered at some sites, some boreholes were drilled to shallower depths. In cases where refusal was met at shallow depths (less than 4–5 m) or borehole collapse made it impractical to install thermistor cables, only limited information on earth materials was collected. Table 1 provides the depth of drilling and identifies boreholes preserved for temperature measurement.

A total of 20 boreholes were preserved for temperature measurement. Polyvinyl choride casing 25–50 mm in diameter was installed in each borehole and the hole was backfilled with extracted material. The PVC casing was filled with silicone oil to reduce convection within the hole. In all but five of the cased holes, multisensor temperature cables were installed during the winter field program. Shorter cables were installed in the remaining five holes in summer and autumn 2007. Thermistors utilized are YSI 46004, which have an accuracy of ±0.1°C. Eight-channel data loggers manufactured by RBR Ltd. were attached to all cables to collect data at eight-hour intervals. The measurement system allows for a resolution of ±0.01°C

To provide further information on climatic conditions, and to fill in gaps in the GSC's network of air-temperature monitoring sites, an air-temperature sensor was installed at two sites (Table 1). These sensors were installed in a six-plate radiation shield mounted 1.5 m above the ground surface. The temperature sensor is connected to a single-channel mini logger (Vemco) programmed to collect data at three-hour intervals. The accuracy and resolution of the air-temperature monitoring system is ±0.5°C and ±0.3°C, respectively.

Visual observations were made in the field of material type and ice content from cores and cuttings extracted from the boreholes. Several disturbed and undisturbed soil samples were collected and preserved for laboratory testing to provide further detail on the physical properties of the surficial materials. Grain size, moisture content (gravimetric), bulk density (undisturbed samples), Atterberg limits, and salinity were determined. All information on physical properties, including results of the laboratory testing, has been compiled into a digital database by Smith et al. (2009).

Sites were visited in August or September 2007 to service equipment, retrieve temperature data from the loggers, take manual temperature readings, and conduct manual thaw-depth probing. For sites where cables were installed in February or March 2007, data for five to six months were retrieved. At some sites, however, problems with the logger connections or logger malfunction resulted in less data being collected. Although data collected over a full year is required to define the temperature envelope (annual maximum and minimum temperatures with depth), the temperature data collected as well as the manual probing does provide an indication of the thermal condition of the ground (i.e. presence or absence of permafrost) and provide confirmation of the winter field observations of thermal state of the ground. In addition these data provide an indication of the depth of zero annual amplitude (depth of seasonal variation) and the annual range in ground temperature and the thaw depth.

DESCRIPTION OF MATERIALS AND THERMAL CONDITION

Description of surficial materials

Sufficient information was obtained from 24 boreholes to provide a description of surficial materials along with preliminary information on the thermal condition (frozen versus unfrozen) of the ground and ground-ice conditions; however, for four boreholes limited information is available as auger refusal was met at depths of 2.5 m or less. The information obtained from the field observations is provided in the simplified borehole logs shown in Figure 2 and explained in Table 3. Detailed borehole logs including more detailed soil descriptions and grain size distributions can be found in Smith et al. (2009).

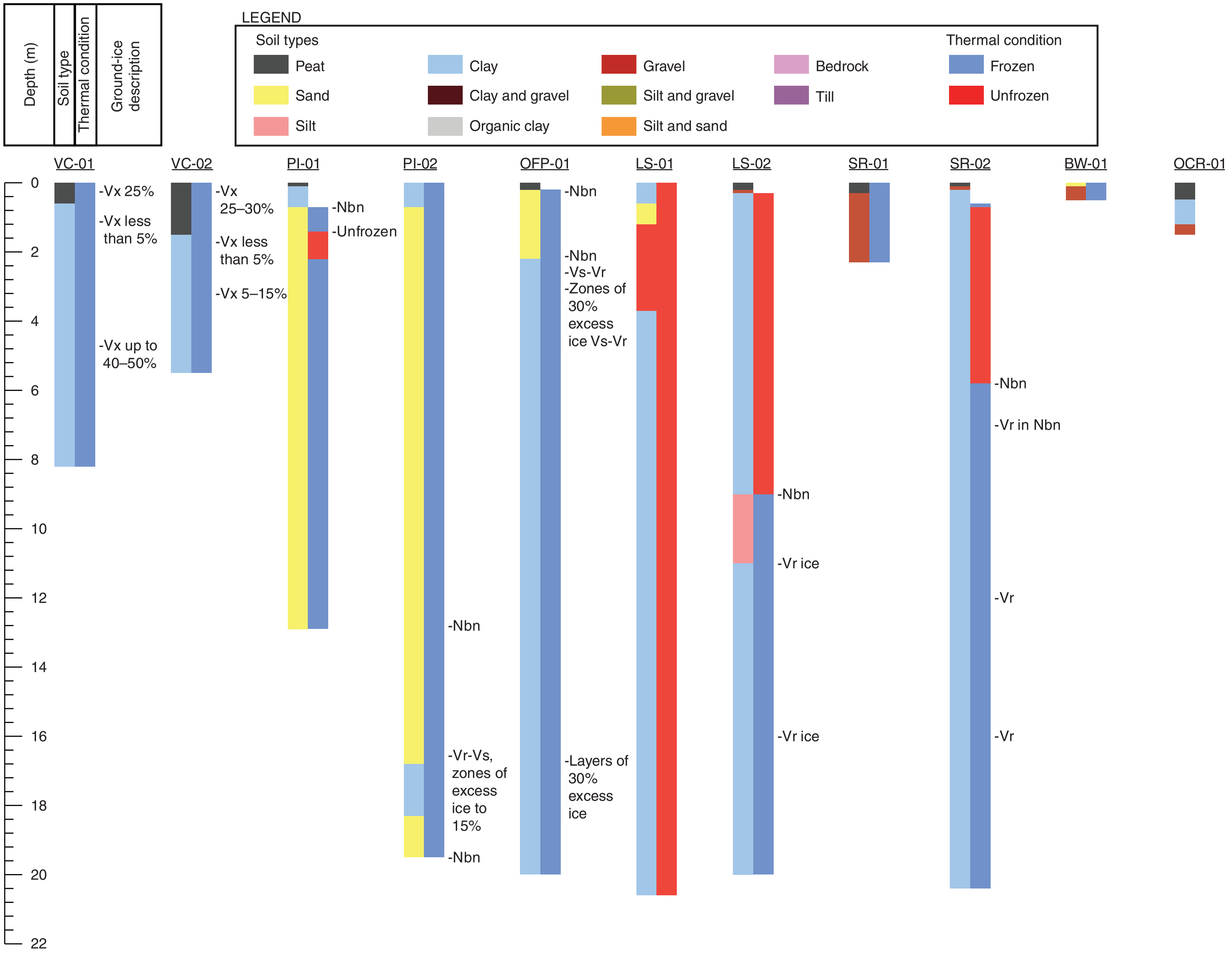


Figure 2. Simplified logs for boreholes drilled in February–March 2007. The description of ground ice is based on National Research Council codes provided in Table 3.

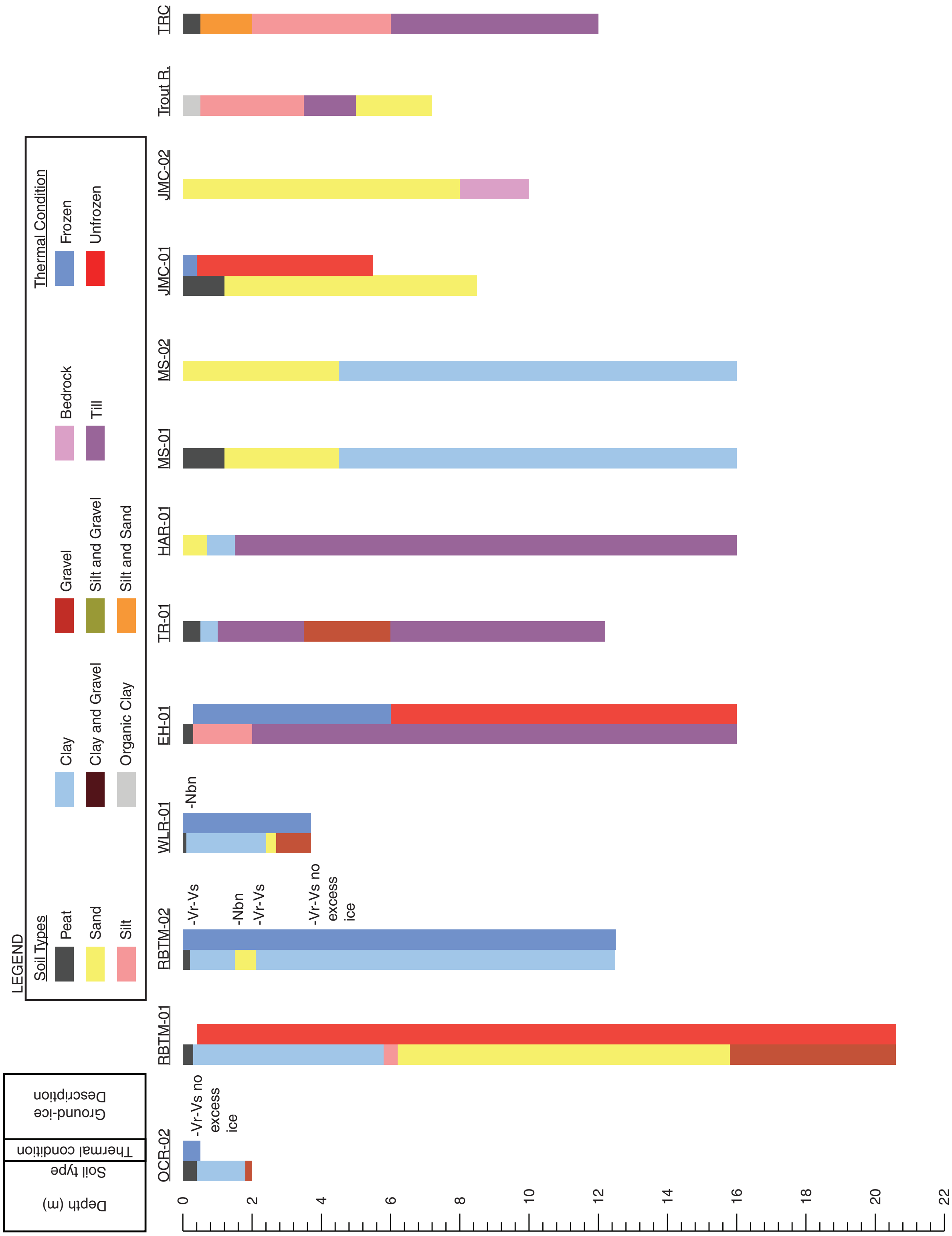


Figure 2. continued

Table 3. National Research Council ground-ice description (Pihlainen and Johnston, 1963)

Category	Group symbol	Subgroup symbol	Description
Nonvisible	N	NF	Poorly bonded or friable frozen soil
		Nbn	Well bonded frozen soil with no excess ice
		Nbe	Well bonded frozen soil with excess ice
Visible ice less than 25 mm thick	V	Vx	Individual ice crystals or inclusions
		Vc	Ice coating on particles
		Vr	Random or irregular oriented ice formations
		Vs	Stratified or distinctly oriented ice formations
Visible ice greater than 25 mm thick	ICE + or ICE	ICE +"Soil Type"	Ice greater than 25 mm thick with soil inclusions
		ICE	ICE greater than 25 mm thick without soil inclusions

The borehole logs indicate the regional trend in material type: fine-grained lacustrine sediments dominate the northern part of the study region whereas coarser grained sediments, till units, and organic terrain become more dominant in the south. Also represented are alluvial sediments consisting of coarser gravel found in valley bottoms and flood plains (e.g. sites LS-01, OR-01) and eolian sand (e.g. sites TR-01, MS-02).

The field observations of the core indicate that permafrost is absent at 14 borehole sites. Eight of these sites are located in the southern portion of the study area, south of site EH-01. The ground-temperature data, where available (discussed in further detail below) also confirm the absence of permafrost at these sites. Permafrost is generally only found in the vicinity of Fort Simpson where there is an insulating organic layer (*see* e.g. Burgess and Smith, 2000), whereas permafrost tends to be absent from sites with mineral soils. Much of the permafrost in organic terrain or peatlands likely formed under colder conditions during the Little Ice Age (Halsey et al., 1995) and has been preserved by the insulation provided by the peat. Within this region, however, degradation of permafrost in frozen peatlands has been documented (e.g. Beilman and Robinson, 2003; Smith et al., 2008a) and this may be the case at site MS-01 where a peat layer is present.

In the northern part of the region, field observations during drilling indicated that unfrozen mineral soils were present at six sites. At some sites permafrost may be present, i.e. ground temperatures are below 0°C, but it may be very warm and the material may not be ice-bonded or in the case of fine-grained soil, have a high unfrozen water content. Some thawing of warm frozen soil during drilling may also have occurred. This likely explains the observation of unfrozen conditions in the upper 9 m with frozen conditions at greater depth at site LS-02. An unfrozen zone between 2 m and 3 m depth was also recorded during drilling at site PI-01. Since this area is a recovering burn, it is possible that a talik developed as permafrost degraded following the fire. Ground-temperature data can be utilized to better characterize the thermal conditions at the sites and a more detailed discussion on the presence or absence of permafrost at each site can be found below.

Ice-rich soils were found at a number of sites and in some cases, visible ice contents were as high as 30–50% (Fig. 2). These ice-rich zones were largely associated with fine-grained lacustrine silt and clay. High ice contents (>25%) were also observed in frozen peat. This ice-rich material can have high thaw strains (Burgess and Smith, 2003) and be subject to thaw settlement and ponding if permafrost thaws in response to surface disturbance or climate change. Lower ice contents are associated with the coarser grained sand and gravel (Fig. 2). Although thawing of these coarser grained materials will not result in significant thaw settlement, changes in drainage and moisture conditions may occur that may have implications for vegetation and ecosystems.

Unfrozen conditions were found in both granular and fine-grained sediments, particularly in the southern portion of the study region. The operation of infrastructure such as a natural gas pipeline can result in freezing of the surrounding ground. In fine-grained frost-susceptible material such as the silt units found at site TroutR or TRC, development of a frost bulb may result in drainage changes in addition to frost heave, each of which may have implications for infrastructure. Coarser grained material (such the sand found at sites JMC-02 or MS-02) is not frost-susceptible, although freezing of these sediments can impede subsurface water and divert drainage that may lead to increased erosion, changes in moisture conditions, and impacts on ecosystems.

Preliminary ground-temperature data

Table 2 provides general information describing the thermal state of the ground at sites where boreholes were preserved for temperature measurement. The ground-temperature data can be utilized to determine the presence or absence of permafrost. At permafrost sites with sufficient ground-temperature data, interpolation of the late summer–early autumn temperature profile or the maximum profile for the recording period was used to determine the annual maximum thaw depth (Table 2). Active-layer thickness determined through mechanical probing during late August or late September site visits is also presented in Table 2. Mechanical probing was not possible at all sites due to the presence of coarse material. The thaw depths provided may be underestimates of the actual annual maximum thaw as the ground at depth may continue to warm late into the autumn, past the time that the measurements were made. Active-layer thickness at permafrost sites ranges from less than 1 m to greater than 5 m at sites located close to streams. It should

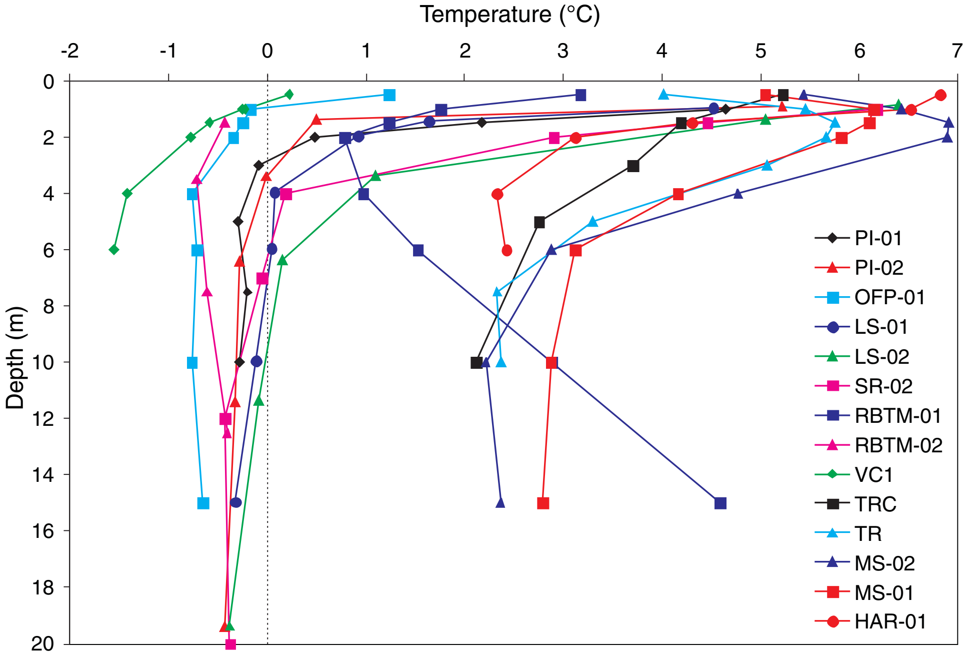


Figure 3. August–September 2007 ground temperatures for sites south of Norman Wells. The temperature recorded for the shallowest sensor is not shown for all sites in order to expand the horizontal scale.

be noted (as shown in Fig. 3 and discussed further below), ground temperatures were near isothermal with depth and close to 0°C at some sites. The deeper thaw depths that were interpolated may be an artifact of the resolution of the measurement system rather than the temperature at depth being slightly above 0°C.

Figure 4 shows the ground temperature at a depth of 6 m in August–September 2007 at sites where cables were installed in winter 2007. There is a general trend in ground temperatures with latitude. Temperatures as low as -1.5°C are found in the northern portion of the study region with temperatures generally increasing southward with generally unfrozen conditions existing at the most southerly sites. Superimposed on this latitudinal trend are local variations in ground temperatures, which in some cases occur over relatively short distances and may be related to changes in vegetation, terrain type, or topography. Figure 3 shows August–September 2007 temperature profiles to depths of 20 m for all sites for which data are available. Figure 3 provides a further illustration of range in thermal conditions from completely unfrozen to frozen ground at temperatures below -1°C. Although the mean temperature for frozen ground falls within a narrow range (close to 0°C to -1.5°C), unfrozen soils can be several degrees warmer. Where permafrost is present, it can be more than 20 m thick.

A comparison of August mean ground-temperature profiles (Fig. 5) for boreholes located within a few hundreds of metres of each other illustrates the influence of the spatial variability in surface conditions and subsurface materials that can occur over short distances. In August 2007, the ground temperatures at site MS-01 were colder than at site MS-02 in the upper 4 m. The greater water content at site MS-01 may be a factor explaining this difference since site MS-02 was well drained whereas site MS-01 was in thermokarst terrain. Proximity to the river (and therefore a heat source) and the possibility of convective heat flow may explain the warmer ground conditions at site RBTM-01 compared to site RBTM-02 (Fig. 5). There is also a difference in material with sand being present to depths of 6 m at site RBTM-01, whereas clay is dominant throughout the soil profile at site RBTM-02 (AMEC Earth & Environmental, unpub. report, 2007). Sites LS-01 and LS-02 were established to capture the transition between alluvial and glaciofluvial terrain types. From the ground surface to 1 m, temperatures at site LS-01, on alluvial terrain with clay and sand soil, were warmer than at site LS-02, with gravel and clay soil (Fig. 5). From 1 m to 6 m, site LS-02, with clay soil, had warmer ground temperatures than the gravel layer at site LS-01. Below 6 m, the two profiles were comparable and clay was dominant at both sites (AMEC Earth & Environmental, unpub. report, 2007). The effects of environmental disturbance are illustrated by comparing ground temperatures between a recovering burnt area at site PI-01 and an unburnt area at site PI-02 (Fig. 5). Both sites were underlain by clay and sand, but thawing is deeper at the recovering burnt site (P1–01). Ground temperatures in the upper 2.5 m were also warmer at site PI-01 compared to site PI-02.

Figure 6 shows the range (for sites where data were available) in ground temperature at each depth (March to August-September 2007). Sites have been classified by terrain types. These graphs also provide an indication of the depth of zero annual amplitude. Data were not sufficient to determine the range in ground temperature for sites PI-01 and OFP-01 since only August 2007 data were available for these sites. For frozen soils, the annual temperature wave propagates to shallower depths in lacustrine finer grained soil (e.g. site PI-02) compared to the coarser grained alluvial sediments that generally have lower ice/moisture content (e.g. site LS-01). Where permafrost is warm, at temperatures

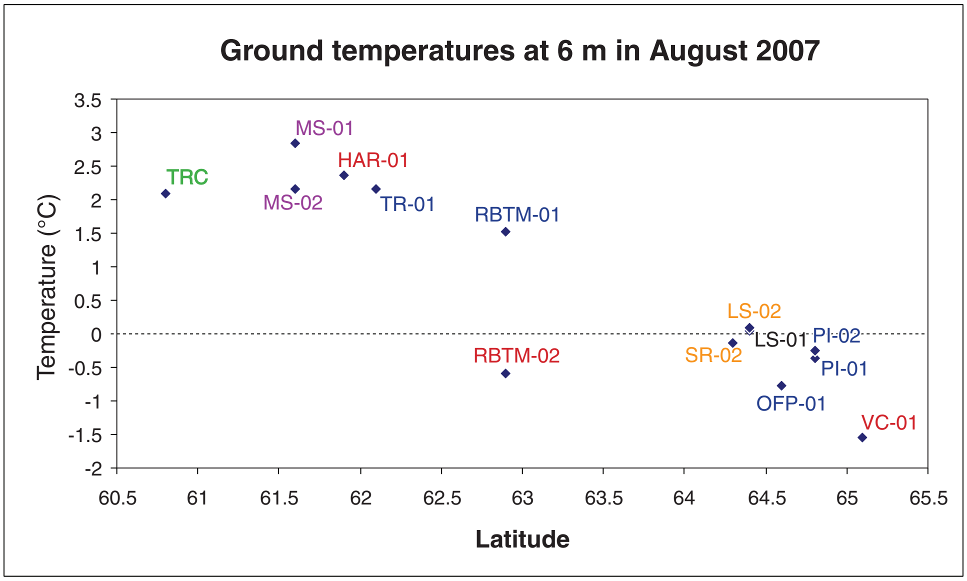


Figure 4. Mean August temperature at 6 m as a function of latitude for all sites south of Norman Wells for which data were available. Sites are categorized by terrain types: peatland (in green), eolian terrain (in purple), moraine plain (in red), lacustrine plain (in blue), glaciofluvial plain (in yellow), and alluvial plain (in black).

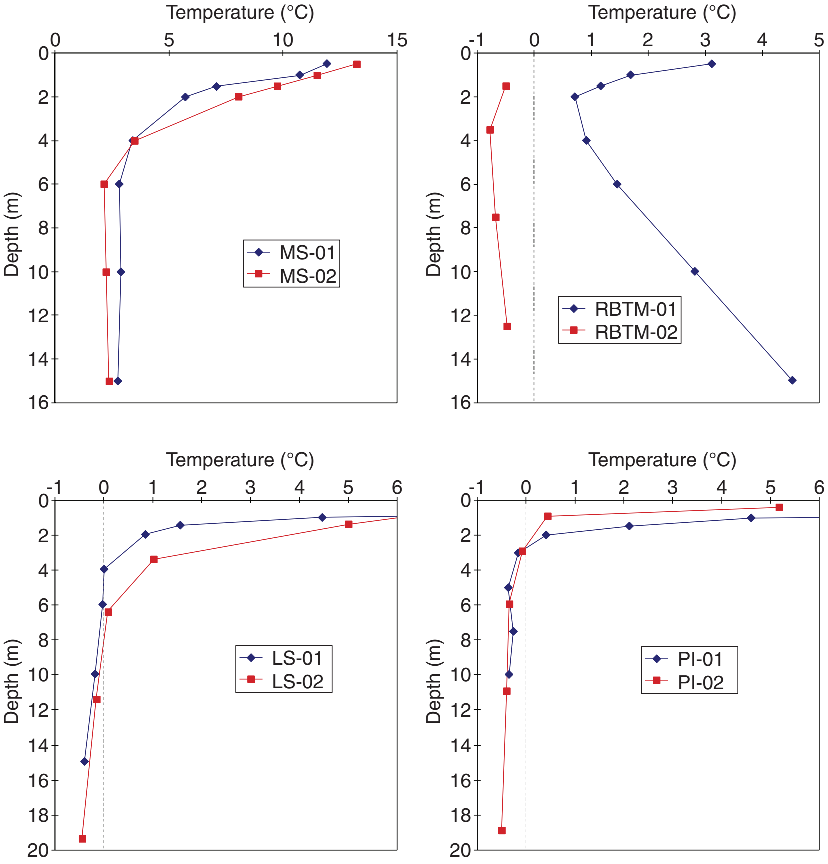


Figure 5. August ground temperatures for sites with two boreholes drilled up to 0.5 km apart to capture the spatial variability in ground cover, surficial, and subsurface materials.

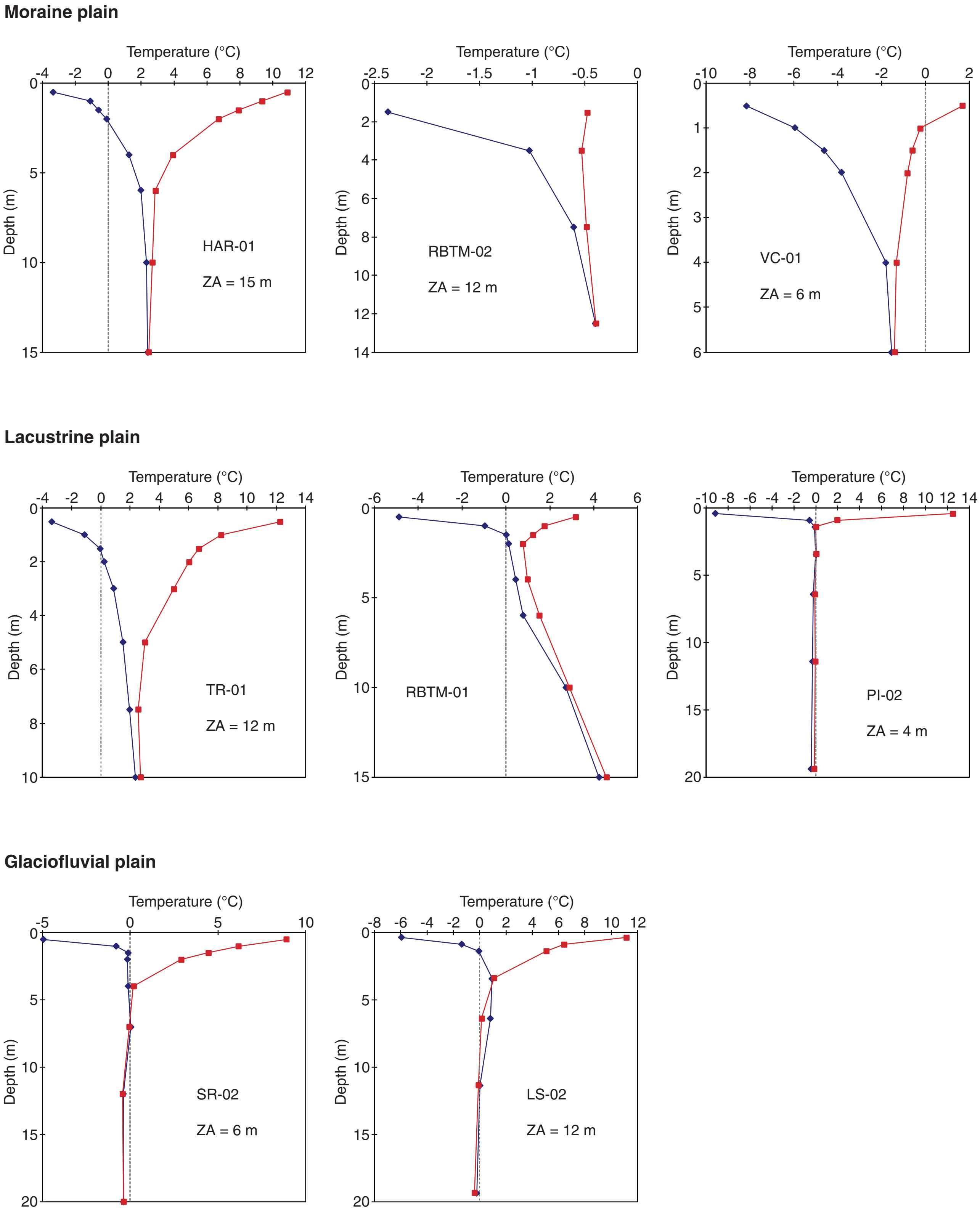
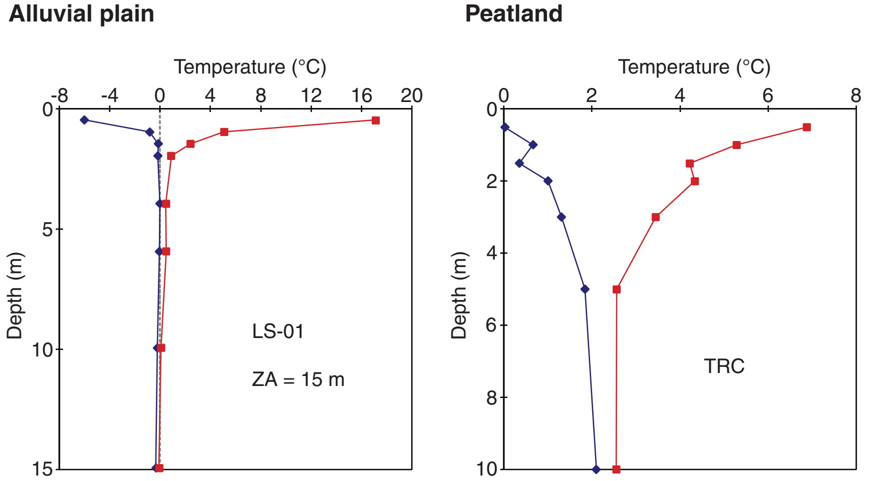


Figure 6. Ground-temperature envelopes representing the range in temperature for February-March to August-September 2007 (based on mean monthly ground temperatures determined for each depth). Sites are categorized by terrain types and along a latitudinal gradient south-north from the left to right. Zero annual amplitude (ZA) depths derived from temperature data are also provided where available. Only March and August data were available for sites RBTM-01, SR-02, and LS-02.


Alluvial plain

Peatland

Eolian plain

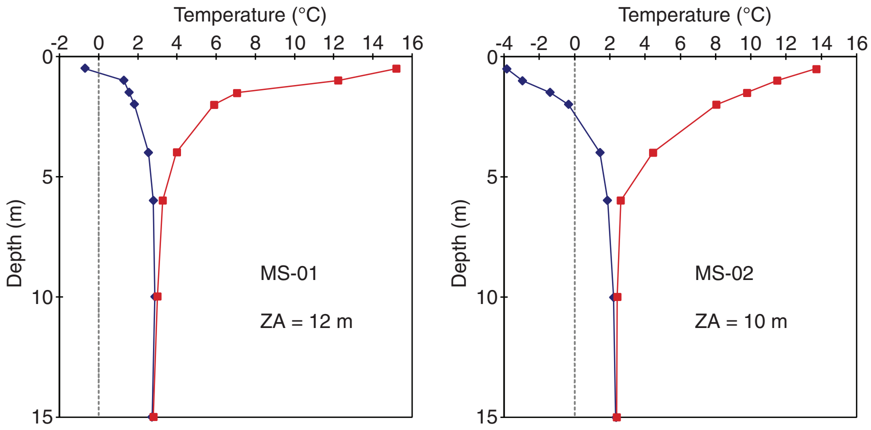


Figure 6. continued

close to 0°C, the range in temperatures is small (e.g. sites SR-02, PI-02) compared to that for sites where ground temperatures are colder (e.g. sites VC-01, RBTM-02). High unfrozen water content at temperatures close to 0°C and the latent heat exchanges associated with phase change act to dampen the fluctuations in temperature that occur at the ground surface (Smith et al., 2005b).

The effects of increasing latitude leading to ground-temperature cooling could be observed when sites were categorized by terrain type (Fig. 6) and vegetation cover along a latitudinal gradient. Sites HAR-01, RBTM-02, and VC-01 are all on moraine plains with dense forest cover; however, the zero amplitude at site HAR-01, the southernmost site of the three, was the deepest at 15 m and the range in shallow ground temperature was the greatest. No permafrost was present at site HAR-01 which is in a warmer climatic region. In contrast, the level of zero amplitude at site VC-01, the northernmost site of the three, was reached at 6 m and ground temperatures were the lowest of the three sites and also indicated permafrost was present and the thaw depth of less than 1 m (Fig. 6). This trend in ground temperatures with latitude for sites with similar terrain type can also be observed with a scatter plot of ground temperatures as a function of latitude (Fig. 4). The same tendency could be observed for the three sites on lacustrine plains (Fig. 6) where site TR-01, the southernmost site of all three, was found to have no permafrost and had a depth of zero amplitude of about 12 m; however at site PI-02, the northernmost site of the three, the level of zero amplitude was at 4 m, with permafrost at temperatures close to 0°C and a thaw depth of about 2 m.

Sites SR-02 and LS-02, both on glaciofluvial terrain, and subjected to similar air-temperature conditions, have similar ground-temperature conditions, with permafrost at temperatures close to 0°C and thick active layers. Note that, due to a malfunction of the data logger at site LS-02, only temperatures determined through manual measurements in March and August data were available. Since the March measurements were made shortly after establishment of the borehole, the above freezing temperatures at depths between 1.5 m and 12 m may still reflect the disturbance of the drilling. Eolian landforms are represented by site MS-02, located on a well drained dune crest with pine forest and site MS-01 located in poorly drained interdune thermokarst terrain with shrubs. Permafrost is absent from both sites. Winter frost penetration is greater and winter ground temperatures are lower at site MS-02 likely due to the low moisture content of the soil and therefore lower latent heat exchange during freezing (Fig. 6). Interception of snow by the coniferous forest at site MS-02 may also partially explain the colder winter ground conditions compared to site MS-01, which has lower shrub vegetation that may trap snow and result in a thicker insulating snow cover. The shallower depth of zero annual amplitude and smaller range in ground temperature over the monitoring period at depth at site MS-01 also reflects the wetter conditions and the higher apparent heat capacity of the soil.

SUMMARY

To address gaps in baseline permafrost knowledge, the GSC undertook a major field program in the Mackenzie corridor to establish new thermal monitoring sites and collect information on properties of surficial materials. During February and March 2007, 24 boreholes were drilled in the corridor south of Norman Wells, of which 20 were preserved for thermal monitoring. These monitoring sites cover the range of conditions within the region including the thermal regime (frozen and unfrozen conditions), terrain type, vegetation cover, and peat thickness.

Ground-thermal conditions at borehole sites range from unfrozen to marginally frozen, generally in the southern portion of the study region, to areas where permafrost is greater than 20 m thick. Coarser grained, granular material, associated with for example eolian and alluvial landforms underlies some of the sites and may be associated with frozen and unfrozen conditions. These sediments generally would be neither thaw sensitive nor frost susceptible. A number of sites are underlain by thaw-sensitive, ice-rich fine-grained sediments associated with lacustrine or moraine plains. Some of the southerly nonpermafrost sites are underlain by fine-grained sediments or associated with organic terrain that tends to be frost susceptible.

Initial ground-temperature data from several of the monitoring sites have been presented that allows a preliminary characterization of the shallow ground-thermal regime. Where permafrost exists, it is generally at temperatures above -1.5°C and in some cases only a few tenths of a degree below 0°C. Although there is a general decrease in ground temperature northward, there is considerable spatial variability due to local factors such as vegetation and soil conditions. The results indicate that permafrost temperatures in a large proportion of the corridor south of Norman Wells may be close to the thawing point and therefore be sensitive to vegetation clearance and surface disturbance that can accompany construction of pipelines and other infrastructure. These activities may therefore lead to degradation of permafrost and where soils are ice-rich, significant settlement and ponding may accompany thawing, having implications for infrastructure integrity, drainage, and ecosystems. Thermal monitoring sites were also established in areas where permafrost is absent and where mean annual ground temperatures can be greater than 2°C. In unfrozen terrain, knowledge of the baseline ground thermal regime is essential to understanding the impact of ground cooling and freezing, resulting from operation of infrastructure such as chilled pipelines, which can lead to frost heave and drainage diversion.

Key baseline information on the geotechnical and ground-thermal conditions has been generated through this project that is essential for infrastructure design, the assessment of environmental impacts, and land-use planning. A preliminary characterization of the ground-thermal regime is now available for areas that were not covered by the existing monitoring network. This will be refined as further data are collected leading to an updated characterization of the ground-thermal regime throughout the Mackenzie corridor. The monitoring network can also be an important component of future monitoring programs associated with hydrocarbon and other development in the Mackenzie corridor.

ACKNOWLEDGMENTS

Support for this project was provided by Natural Resources Canada, the Northern Energy Development Initiative, and the Program for Energy Research and Development. The field drilling program was conducted under contract by EBA Engineering Consultants, AMEC Earth & Environmental, and Geochem Surveys Ltd. The support provided by the communities in the Sahtu and the Deh Cho settlement areas is greatly appreciated, including the traditional knowledge that aided site selection, the provision of environmental monitors, and other logistical support. The authors are also appreciative of the support provided by Enbridge Pipelines (NW) Inc. B. Wang is thanked for his critical review of the manuscript.

REFERENCES

Aylsworth, J.M. and Kettles, I.M., 2000. Distribution of peatlands; *in* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change, (ed.) L.D. Dyke, and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 49–55.

Aylsworth, J.A., Burgess, M.M., Desrochers, D.T., Duk-Rodkin, A., and Traynor, J.A., 2000. Surficial geology, subsurface materials, and thaw sensitivity of sediments; *in* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 41–48.

Beilman, D.W. and Robinson, S.D., 2003. Peatland permafrost thaw and landform type along a climate gradient; *in* Proceedings Eighth International Conference on Permafrost, (ed.) M. Phillips, S.M. Springman, and L.U. Arenson; A.A. Balkema, Zurich, Switzerland, p. 61–65.

Burgess, M.M. and Lawrence, D.E., 2000. Permafrost and subsurface materials along a north-south transect in the Mackenzie Valley: observations from the Norman Wells pipeline; *in* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change, (ed.) L.D. Dyke, and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 127–141.

Burgess, M.M. and Smith, S.L., 2000. Shallow ground temperatures; *in* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change, (ed.) L.D. Dyke, and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 89–103.

Burgess, M.M. and Smith, S.L., 2003. 17 years of thaw penetration and surface settlement observations in permafrost terrain along the Norman Wells pipeline, Northwest Territories, Canada; *in* Proceedings Eighth International Conference on Permafrost, (ed.) M. Phillips, S.M. Springman, and L.U. Arenson; A.A. Balkema, Zurich, Switzerland, p. 107–112.

Duk-Rodkin, A. and Lemmen, D.S., 2000. Glacial history of the Mackenzie region; *in* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 11–20.

Gartner Lee Limited, 2003. Identification of the biophysical information and research gaps associated with hydrocarbon exploration development and transmission in the Mackenzie Valley, action plan; Report Prepared for the Department of Indian Affairs and Northern Development, the Government of the Northwest Territories, and the Environmental Studies Research Funds, 92 p.

Halsey, L.A., Vitt, D.H., and Zoltai, S.C., 1995. Disequilibrium response of permafrost in Boreal Continental Western Canada to climate change; Climatic Change, v. 30, p. 57–73. doi:10.1007/BF01093225

Heginbottom, J.A., 2000. Permafrost and distribution and ground ice in surficial materials; *in* The physical environment of the Mackenzie Valley, Northwest Territories: a base line for the assessment of environmental change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 31–39.

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

Judge, A.S., 1973. The thermal regime of the Mackenzie Valley: observations of the natural state; Environmental-Social Committee Northern Pipelines Task Force on Northern Oil Development, Report No. 73–38, 177 p.

MacInnes, K.L., Burgess, M.M., Harry, D.G., and Baker, T.H.W., 1990. Permafrost and terrain research and monitoring: Norman Wells Pipeline, Volume II. Research and monitoring results: 1983–1988; Environmental Studies Report, Department of Indian and Northern Affairs Canada, Northern Affairs Program, 204 p.

Nixon, F.M. and Taylor, A.E., 1994. Active layer monitoring in natural environments, Mackenzie Valley, Northwest Territories; Geological Survey of Canada, Current Research 1994-B, p. 27–34.

Pihlainen, J.A. and Johnston, G.H., 1963. Guide to a field description of permafrost; National Research Council, Technical Memorandum 79, 23 p.

Pilon, J.A., Burgess, M.M., Judge, A.S., Allen, V.S., MacInnes, K.L., Harry, D.G., Tarnocai, C., and Baker, H., 1989. Norman Wells to Zama pipeline permafrost and terrain research and monitoring program: site establishment report; Geological Survey of Canada, Open File 2044, 332 p.

Smith, S.L. and Burgess, M.M., 2000. Ground temperature database for northern Canada; Geological Survey of Canada, Open File 3954, 28 p.

Smith, S.L. and Burgess, M.M., 2002. A digital database of permafrost thickness in Canada; Geological Survey of Canada, Open File 4173, 38 p.

Smith, S.L. and Riseborough, D.W., 2010. Modelling the thermal response of permafrost terrain to right-of-way disturbance and climate warming; Cold Regions Science and Technology v. 60, p. 92–103. doi:10.1016/j.coldregions.2009.08.009

Smith, S.L., Burgess, M.M., Chartrand, J., and Lawrence, D.E., 2005a. Digital borehole geotechnical database for the Mackenzie Valley/Delta region; Geological Survey of Canada, Open File 4924, 30 p.

Smith, S.L., Burgess, M.M., and Riseborough, D.W., 2008a. Ground temperature and thaw settlement in frozen peatlands along the Norman Wells pipeline corridor, NWT Canada: 22 years of monitoring; *in* Ninth International Conference on Permafrost, (ed.) D.L. Kane and K.M. Hinkel; Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, Alaska, v. 2, p. 1665–1670.

Smith, S.L., Burgess, M.M., Riseborough, D., Coultish, T., and Chartrand, J., 2004. Digital summary database of permafrost and thermal conditions – Norman Wells Pipeline study sites; Geological Survey of Canada, Open File 4635, 104 p.

Smith, S.L., Burgess, M.M., Riseborough, D., and Nixon, F.M., 2005b. Recent trends from Canadian permafrost thermal monitoring network sites; Permafrost and Periglacial Processes, v. 16, p. 19–30. doi:10.1002/ppp.511

Smith, S.L., Chartrand, J., Nguyen, T.N., Riseborough, D.W., Ednie, M., and Ye, S., 2009. Geotechnical database and descriptions of permafrost monitoring sites established 2006–07 in the central and southern Mackenzie Corridor; Geological Survey of Canada, Open File 6041, 183 p.

Smith, S.L., Nguyen, T.-N., Riseborough, D.W., Ednie, M., Ye, S., and Chartrand, J., 2008b. Preliminary ground-thermal data for permafrost-monitoring sites established in 2007 between Fort Good Hope and Norman Wells, Northwest Territories, Geological Survey of Canada, Current Research 2008-20, 9 p.

Smith, S.L., Ye, S., and Ednie, M., 2007. Enhancement of permafrost monitoring network and collection of baseline environmental data between Fort Good Hope and Norman Wells, Northwest Territories; Geological Survey of Canada, Current Research 2007-B7, 10 p.

Taylor, A.E., Burgess, M., Judge, A.S., and Allen, V.S., 1982. Canadian geothermal data collection-northern wells 1981; Earth Physics Branch, Energy, Mines and Resources Canada, Geothermal Series no. 13, 153 p.

Geological Survey of Canada Project Y51