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Enhancement of permafrost monitoring network and collection of baseline environmental data between Fort Good Hope and Norman Wells, Northwest Territories

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Abstract: A major field program was undertaken in March 2007 by the Geological Survey of Canada in order to address gaps in baseline environmental information in the Mackenzie Valley between Norman Wells and Fort Good Hope, Northwest Territories. Sites were selected to represent a range of thermal, terrain, and vegetation conditions. Drilling of boreholes to depths of 20 m yielded data to characterize subsurface materials at nine locations, including physical properties of soils and ground-ice conditions. Eleven boreholes were preserved and instrumented with temperature cables to provide information on 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 collection of data from the thermal monitoring sites will facilitate improved characterization of current permafrost conditions and change detection.

Résumé : En 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 dans la vallée du Mackenzie, entre Norman Wells et Fort Good Hope (Territoires du Nord-Ouest). Le choix des sites visait à représenter une gamme de conditions thermiques et topographiques ainsi que l'état de la végétation. Les données recueillies à la suite du forage de puits atteignant 20 m de profondeur ont permis de caractériser les matériaux du sous-sol à neuf emplacements, notamment en ce qui a trait aux propriétés physiques des sols et à l'état de la glace dans le sol. Onze puits de forage ont été retenus et instrumentés à l'aide de câbles indicateurs de la température, afin d'obtenir de l'information sur le 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 et de l'évaluation des incidences environnementales dans le Nord. La collecte continue de données aux sites de surveillance du régime 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 that has impacts on both the natural and socio-economic environments of the region. Permafrost and its associated ground ice can influence entire ecosystems through its influence on 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 due to clearance of vegetation associated with development. Any warming and subsequent thawing of permafrost can lead to changes in the landscape such as slope movements, thermokarst development, and ground subsidence, and this can have important implications for northern infrastructure as well as 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 critical for rational planning of development in northern Canada and for understanding the impact of environmental disturbance and climate change on the permafrost environment. Increased activity is anticipated in the Mackenzie Valley associated with proposed hydrocarbon development, which includes construction of a pipeline to carry natural gas from the Mackenzie Delta to northern Alberta. A knowledge of ground thermal conditions and physical properties of the soils including ground-ice content is essential for both engineering design and assessment of environmental impacts associated with these developments. In addition, ongoing monitoring of permafrost conditions is essential to understand how these conditions may change over time, to assess impacts on northern development, and to develop strategies to mitigate these changes.

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 sites along the Norman Wells to Zama pipeline corridor (*see* for example Smith et al., 2004, 2005b). There are, however, significant gaps in the network, including the region between Norman Wells and Inuvik, sensitive peatland areas in the southern discontinuous zone, and dynamic shoreline and coastal environments. 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 obtained through a Northern Energy Development Memorandum to Cabinet. Fieldwork conducted between 2005 and 2007 was directed toward addressing these gaps through the drilling of several boreholes, the collection of samples to determine geotechnical properties, and the preservation of boreholes and the installation of instrumentation for long-term ground-temperature monitoring. This paper summarizes fieldwork conducted to fill an important gap between Norman Wells and Fort Good Hope and presents preliminary information on surficial materials and thermal condition.

REGIONAL SETTING AND SITE SELECTION

The physical landscape of the study area 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. Thick (up to 30 m), extensive deposits of glaciolacustrine and lacustrine silt and clay, which are commonly ice-rich, are found in the region that are associated with the large temporary lake basins that formed during deglaciation (Aylsworth et al., 2000; Duk Rodkin and Lemmen, 2000). 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. Where drainage is impeded, accumulations of peat (Aylsworth and Kettles, 2000) cover the mineral soils.

The regional climate is characterized by long winters with a normal mean January air temperature of -26.5°C and a normal mean July temperature of 17°C at Environment Canada's Norman Wells weather station (based on 1971–2000 normals). Normal annual total precipitation is about 290 mm at Norman Wells of which about half falls as snow that stays on the ground from October to April.

The study area lies within the zones of intermediate and extensive discontinuous permafrost defined by Heginbottom (2000) with permafrost underlying 35 to 90% of the land surface (Fig. 1). An analysis of the geotechnical borehole database of Smith et al. (2005a) provides preliminary information on the distribution of frozen ground within the Mackenzie corridor and indicates that unfrozen ground may underlie up to 30% of the ground surface between Fort Good Hope and Norman Wells (Fig. 2). 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" (*see* for example Taylor et al., 1982) and a compilation of measurements by Judge (1973). Permafrost where present is generally less than 50 m thick, and mean annual near-surface ground temperatures are generally -2°C or higher.

Sites were chosen along the winter road (Fig. 1) in order to have easy access during the winter drilling program and also for helicopter access during summer visits to retrieve data. The goal was to select 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; Nixon et al., 1995) and the thermal monitoring program along the Norman Wells pipeline

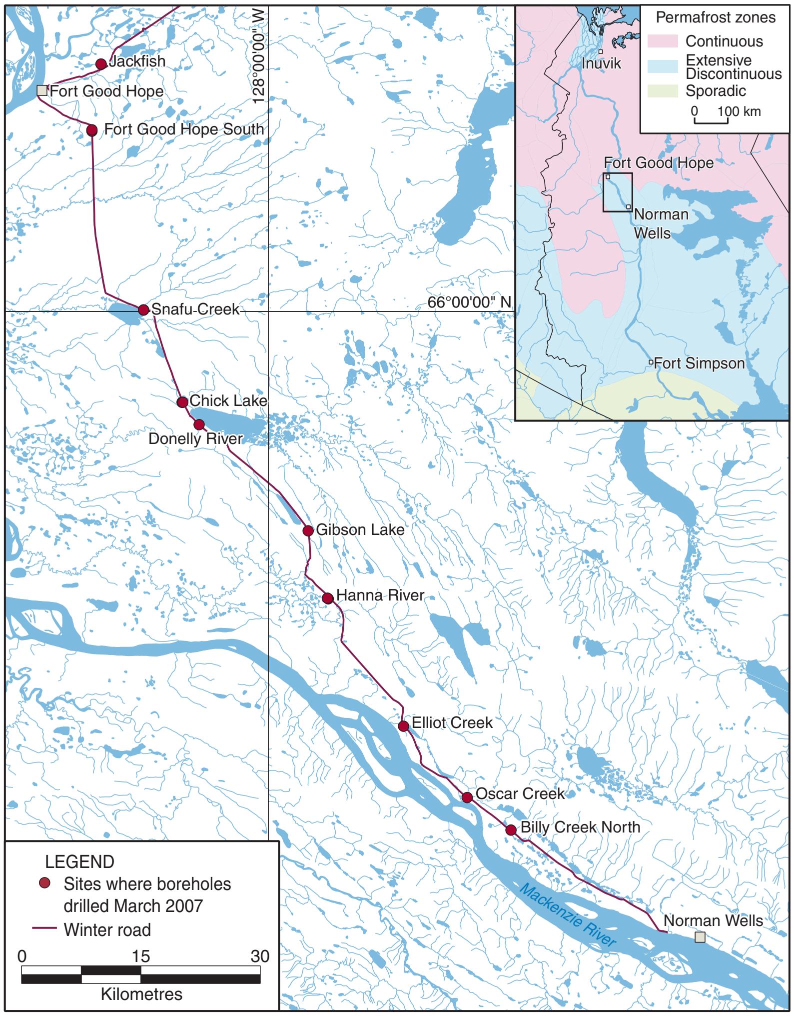

Figure 1. Permafrost distribution in the Mackenzie Valley and location of study sites between Norman Wells and Fort Good Hope where drilling was conducted in March 2007.

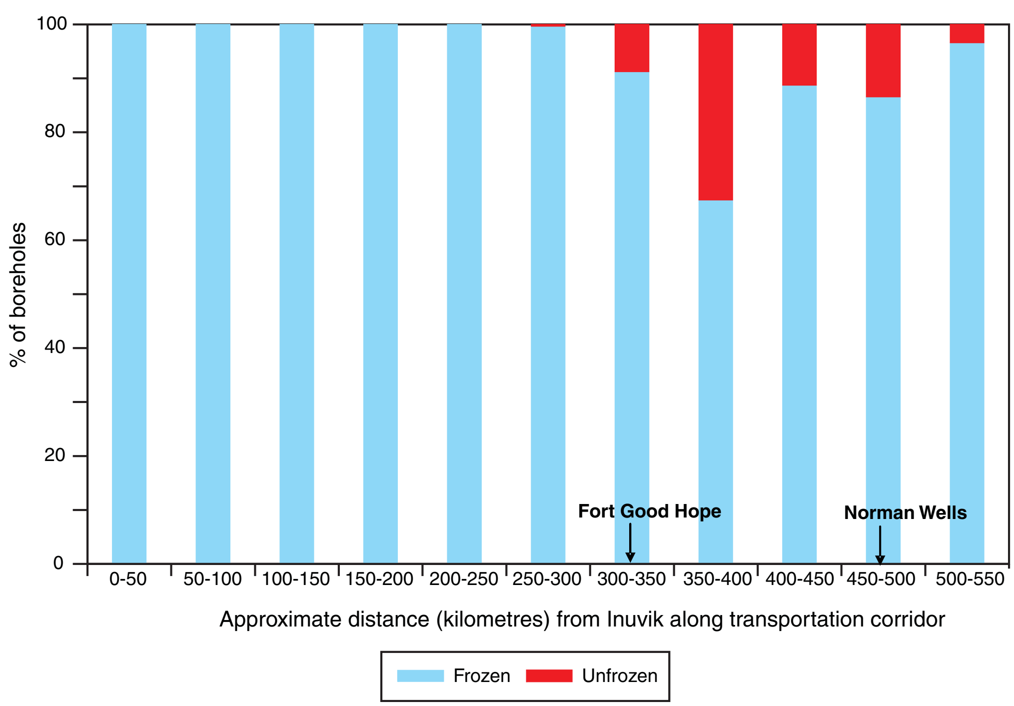

Figure 2. Proportion of boreholes previously drilled within the Mackenzie Valley corridor between Inuvik and Norman Wells, indicating the presence of permafrost from an analysis of data in Smith et al. (2005a).

corridor (Pilon et al., 1989). In addition, efforts were made at some sites to establish two boreholes a few tens of metres to 100 m 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 the transportation or transmission infrastructure. For example, two boreholes were drilled at Jackfish Creek to capture the transition between frozen, well drained sand on a dune crest and the adjacent low-lying, poorly drained, unfrozen terrain. The two boreholes drilled at Elliot Creek represent different tree types and forest-cover densities. Recent natural disturbances were also considered and sites that have been recently burned were selected.

Surficial geology maps, airphotos, and existing borehole databases (e.g. Smith et al., 2005a) and site reconnaissance 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. The consultation with communities within the Sahtu region (Tulita, Norman Wells, and Fort Good Hope) was also undertaken prior to finalizing the 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 10 sites chosen between Fort Good Hope and 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, as shown in Figure 3. Examples of the sites include a well drained, forested dune crest adjacent to a lower lying, poorly drained site (Fig. 3a), organic terrain (Fig. 3b), a recovering burn area (Fig. 3c), and a forested site on an approach to a stream crossing (Fig. 3d).

FIELD PROGRAM

Site reconnaissance was conducted on August 20, 2006, in order to finalize site selection and collect preliminary information on site characteristics. Where possible, 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. Thaw depth was determined for some of the sites (Table 1); however, since warming of the ground may continue into the fall, the summer thaw penetration may not have reached its maximum depth.

Geotechnical drilling and borehole preservation was conducted in March 2007. A rubber track-mounted M5T drill rig operated by Geotech Drilling Services Ltd. was engaged by EBA Engineering Consultants to conduct this work. The rig was equipped with 150 mm diameter solid-stem augers and 160 mm hollow-stem loggers as well as CRREL 75 mm core barrels. The goal was to drill boreholes to depths of 15 to 20 m, extract disturbed and undisturbed samples for later testing, and preserve boreholes for thermal monitoring through the installation of PVC casing. A total of 16 boreholes were planned between Norman Wells and Fort Good Hope (Fig. 1, Table 1).

All sites were accessed from the winter road and were located at distances of 20 to 30 m from the road. Prior to drilling, each site was cleared of snow and brush (by local contractors) 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 ground-surface material (mineral and organic) and vegetation. An environmental monitor from the appropriate community (Norman Wells or Fort Good Hope) 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 to 20 m, but due to limitations of the drill rig and the difficult subsurface conditions encountered at some sites, boreholes were drilled to shallower depths. In some cases, refusal was met at shallow depths (less than 4–5 m) or borehole collapse made it impractical to install thermistor strings and only limited information on materials was collected. Table 1 provides the depth of drilling and identifies boreholes preserved for temperature measurement.

A total of 11 boreholes were preserved for temperature measurement. Polyvinyl chloride (PVC) casing 50 mm in diameter was installed in each hole 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 one of the cased holes, multi-sensor temperature cables were installed. 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. A temperature cable will be installed in one of the shallower boreholes during a later site visit.

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 selected sites (*see* Table 1). These sensors were installed in a six-plate radiation shield mounted 1.5 m above the ground surface. The temperature sensor is attached 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. Where possible, several disturbed and undisturbed soil samples were collected from each borehole and preserved for laboratory testing to provide further detail on the physical properties of the surficial materials. The following information was determined during laboratory testing: grain size, moisture content (gravimetric), bulk density (undisturbed samples), Atterberg limits, and salinity.

Figure 3. Photos of selected sites illustrating the range of terrain and vegetation conditions: **a)** Jackfish Creek (Photograph by M. Burgess, August 2006); **b)** Fort Good Hope South (photo: M. Burgess, August 2006); **c)** Hanna River (Photograph by S. Smith, August 2006); **d)** Elliot Creek (Photograph by S. Smith, August 2006).

Table 1. Boreholes drilled in March 2007, site description, and instrumentation installed. Approximate site elevation was obtained from GPS or from a topographic map.

ite name	General situation	Borehole name	UTM co-ord. (Zone 9W)	approx. elev. (m asl)	Borehole-specific description, vegetation	Thaw depth (cm)	Borehole depth (m)	Instrumentation[1]
Jackfish Creek	Eolian landforms (dune) on moraine plain	JF-01	7351808 N 523779 W	75 (GPS)	Low-lying, open, shrubs	Likely unfrozen	4.9	None
		JF-02	7351772 N 523814 E	80 (GPS)	Dune crest, black spruce forest and moss cover	65-70	21.3	GT to 20 m
Fort Good Hope South	Hummocky peatland	FGHS-01	7343386 N 522694 E	134 (GPS)	Hummocky, dense shrub, open, black spruce	46-47	10.2	GT to 8 m
		FGHS-02	7343323 N 522699 E	134 (GPS)	Peat plateau, lichen, open black spruce	48-57	5.1	AT, GT to be installed to 5 m
Snafu Creek	Moraine plain	SC-01	7320273 N 529474 E	100 (GPS)	Peat bog, open black spruce and lichen	43-55	19.8	GT to 16.8 m
Chick Lake	Moraine plain	CL-01	7308478 N 534634 E	122 (GPS)	Open black spruce, shrubs	45-46	21.3	GT to 20 m
Donelly River	Moraine and fluvial plain	DR-01	7305468 N 537222 E	121 (map)	Mixed shrub, deciduous and conifers		<1.5	None
		DR-01	7305806 N 536618 E	128 (map)	Similar to DR2		<1.5	None
Gibson Lake	Hummocky, moraine plain	GL-01	7292195 N 550960 E	228 (map)	Recovering burn, shrubs	55-60	21.3	AT, GT to 20 m
Hanna River	Lacustrine plain	HR-01	7283597 N 553624	104 (map)	Recovering burn, shrubs		21.3	GT to 20 m
Elliot Creek	Lacustrine plain Undulating terrain	EC-01	7267146 N 563736 E	54 (map)	Edge of mature black spruce forest		21.3	GT to 20 m
		EC-02	7267404 N 563714 E	54 (map)	Similar to EC1		12.2	GT to 9.7 m
Oscar Creek	Undulating glacio-lacustrine terrain overlain by alluvial sediments	OC-01	7258009 N 572437 E	64 (map)	Dense forested birch and black spruce forest		18.9	GT to 16 m
		OC-02	7258968 N 572068 E	50 (map)	Old flood plain, open birch and black spruce forest		<1.5	None
Billy Creek	Alluvial and eolian sediments overlying lacustrine plain	BCN-01	7254396 N 578107 E	80 (map)	Dense forested, black spruce, mixed shrub		19.8	GT to 15 m
		BCN-02	7254364 N 578111E	80 (map)	Open forested, smaller black spruce, mixed shrub		2.3	None

[1] AT, air-temperature sensor; GT, ground-temperature cable

PRELIMINARY DESCRIPTION OF THERMAL CONDITION AND MATERIALS

Sufficient information was obtained from 12 boreholes to provide a description of surficial materials along with preliminary information on the thermal condition of the ground and ground-ice conditions. The information obtained from the field observations is provided in the simplified borehole logs shown in Figure 4. Difficult subsurface conditions prevented boreholes from being advanced at the Donelly River site so that Figure 4 only presents information for nine of the ten proposed sites. Field observations and manual probing to determine summer thaw depth provide some information on whether permafrost may be present at a particular site, but preliminary information on ground temperatures will only be obtained during the fall of 2007.

Observations indicate that permafrost may be absent or marginal (less than 5 m thick) at three sites. These sites are the low-lying, poorly drained sand at JF-01 and the organic terrain at FGHS-01 and FGHS-02. While unfrozen conditions were expected at JF-01, probing in August 2006 indicated that the permafrost table at the Fort Good Hope South sites was located at a depth of about 0.5 m (Table 1). While it is possible that seasonal frost had not thawed by late August in the organic terrain, it is also possible that permafrost is at temperatures close to 0°C and contains a high amount of unfrozen water and was thawed due to the drilling disturbance. Data to be obtained from the temperature cable will provide improved information on the thermal condition at the Fort Good Hope South sites.

Field observations also indicate the presence of unfrozen zones within the permafrost (possible talik) at three sites, SC-01, EC-02, and BCN-01. Probing in August 2006 at SC-01 (Table 1) indicates that the depth of summer thaw is approximately 0.5 m, so the unfrozen zone indicated on the borehole log would not represent the lower portion of the active layer that had not refrozen by March 2007. No information on summer thaw depth is available for EC-02 and BCN-01, but other information in the region indicates that thaw depths would likely be less than 1 m, so that the presence of unfrozen zones is not due to incomplete freeze-back of the active layer. As was mentioned above, the presence of unfrozen zones may be related to thawing of the warm frozen soil during drilling. Analysis of future ground temperature data obtained from the temperature cables will provide confirmation of the thermal condition of the ground at these sites.

Ice-rich soils were found at a number of sites (Fig. 4) and, in some cases, visible ice contents were greater than 50%. These ice-rich zones were largely associated with the lacustrine clays. This ice-rich material may be subject to thaw settlement and ponding if permafrost thaws in response to surface disturbance or climate change. Low ice contents are largely observed in the coarser granular material such as sand and gravel. While thawing of these coarser grained materials

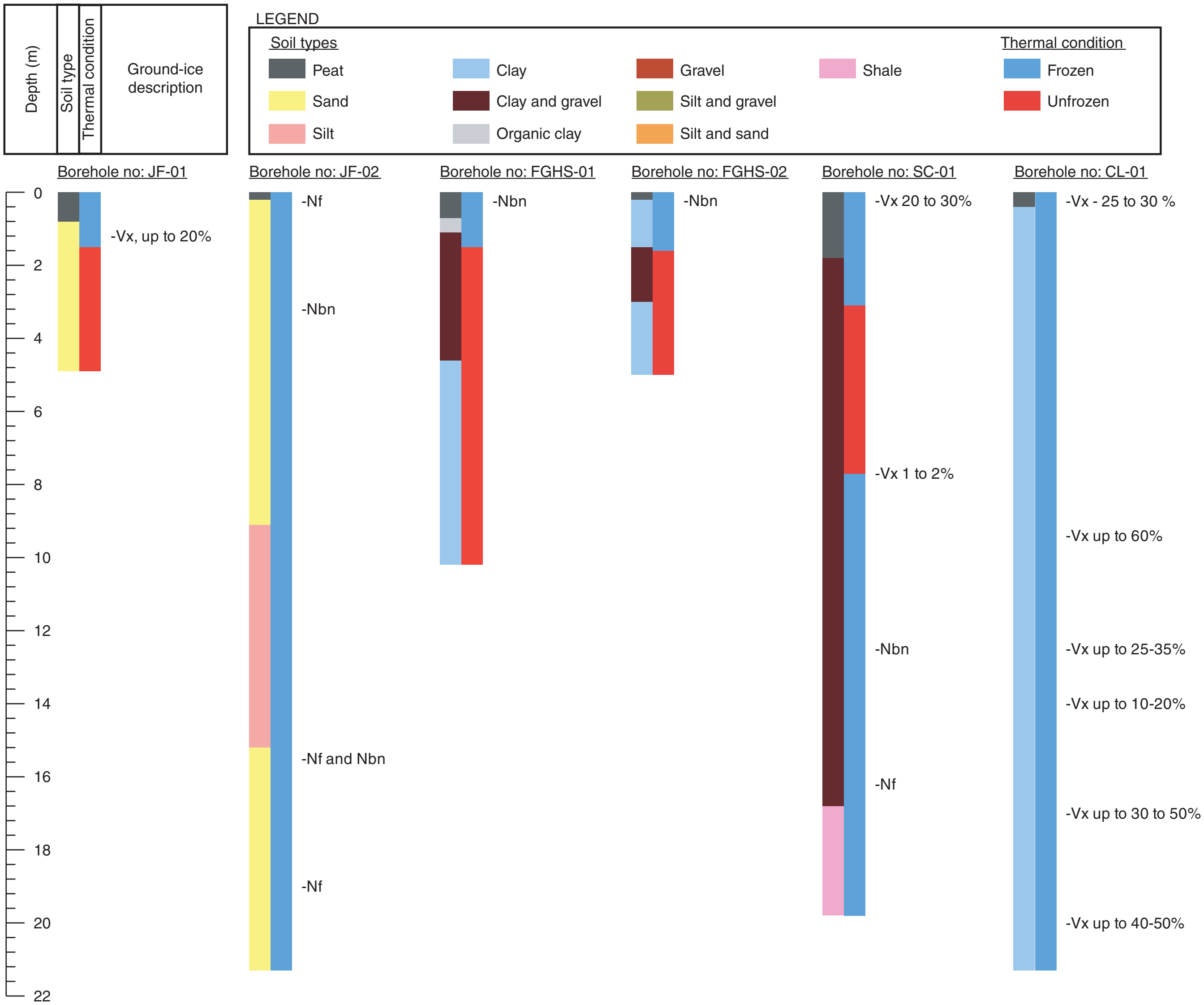

Figure 4. Simplified logs for boreholes drilled in March 2007. The description of ground ice is based on National Research Council codes provided in Table 2.

will not result in significant settlement, it may result in changes in drainage and moisture conditions, which may, for example, have implications for vegetation and ecosystems.

Unfrozen and marginal permafrost conditions were found in both granular and fine-grained sediments. If operation of infrastructure such as a gas pipeline results in freezing of fine-grained frost-susceptible sediments such as those present at the Fort Good Hope South site, development of a frost bulb may result in changes in drainage conditions in addition to frost heave, which may have implications for the infrastructure. Coarser grained sediment such as that present at JF-01 is generally not frost susceptible and therefore not subject to frost heave. However, freezing of these sediments can result in impedance of water flow and drainage diversion, which may lead to increased erosion, changes in moisture conditions, and impacts on ecosystems.

FUTURE PLANS

The information on soil properties from both field observations and laboratory testing was utilized to produce detailed geotechnical logs for each borehole. All information describing the soil physical properties will be compiled into a digital relational database to be published along with the detailed borehole logs as a GSC Open File, which will include information from all new boreholes drilled throughout the Mackenzie Valley. This will supplement the geotechnical borehole database of Smith et al. (2005a) that contains information from boreholes drilled between the 1970s and 1990s. All information will be publicly available and may be used

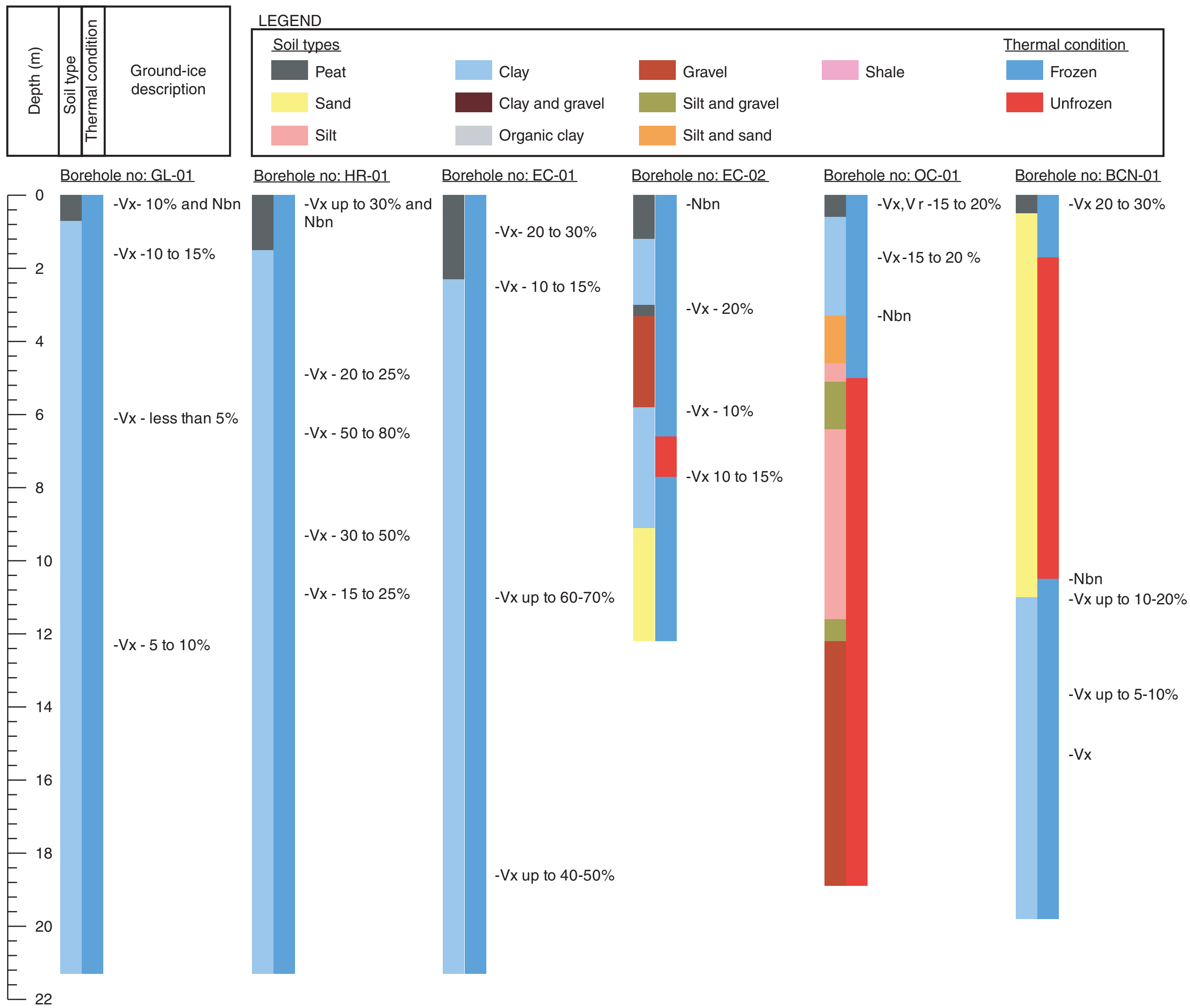

Figure 4. (cont.)

Table 2. National Research Council ground-ice description (Pihlainen and Johnston, 1963).

Category	Group symbol	Subgroup symbol	Description
Non-visible	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 +	ICE +"Soil Type"	Ice greater than 25 mm thick with soil inclusions
	or ICE	ICE	ICE greater than 25 mm thick without soil inclusions

for infrastructure design, land-use planning, and environmental impact assessments by a number of users including industry, governments, and communities.

The new thermal monitoring sites will be visited in the fall of 2007 to collect the initial temperature data and also to determine maximum thaw depths through manual probing. Further instrumentation such as ground-surface temperature sensors may be installed at this time at selected sites to better characterize the microclimate conditions. Although the data loggers connected to the cables may collect and store data for a number of years, the project aims to visit sites annually or every second year to retrieve data from the loggers, perform maintenance on equipment, and record other observations relevant to interpretation of the data.

The collection of thermal data will allow a better characterization of the ground thermal regime for representative terrain types in the Mackenzie corridor between Norman Wells and Fort Good Hope, and provide baseline information essential for infrastructure (such as pipelines) design and associated environmental impact assessment, and for future land-use planning. Ongoing operation of these monitoring sites will build up a time series of ground-temperature data that will be utilized to document recent trends in permafrost conditions, improve our understanding of permafrost-climate interaction, and improve predictions of future conditions. Since this monitoring network provides a baseline against which change can be measured, it can also contribute to monitoring programs that may be associated with development projects such as the proposed Mackenzie gas pipeline, and to an improved understanding of environmental effects and the development of mitigation strategies.

Thermal data will be compiled into digital databases and summary data will be publicly available through the Canadian Permafrost Monitoring Network website (canpfnetwork.com). This information will also contribute to international programs such as the Global Terrestrial Network for Permafrost and to Canada's contribution to the International Polar Year.

SUMMARY

To address gaps in permafrost and geotechnical baseline knowledge in the Mackenzie corridor, the GSC has undertaken since 2004 to collect information on soil physical properties and to establish permafrost thermal monitoring sites. During March 2007, a key gap in the discontinuous permafrost zone between Norman Wells and Fort Good Hope was addressed through the drilling of 16 boreholes in representative terrain types to acquire information on soil conditions, and the preservation of 11 boreholes for ground thermal monitoring. These study sites cover the range of thermal, terrain type, vegetation cover, and peat thickness conditions found within the region.

Thermal conditions at the sites range from unfrozen and marginally frozen to those underlain by permafrost greater than 20 m thick. Sites were chosen that were underlain by coarser grained granular materials of low ice content, such as the sands found associated with the eolian landforms near Fort Good Hope, which are not thaw sensitive. A number of sites are underlain by thaw-sensitive, ice-rich lacustrine silts and clays. Unfrozen or marginally frozen sites were also selected. These sites include those underlain by non-frost-susceptible, coarse-grained material such as sands and also those underlain by finer grained, frost-susceptible material.

Information on soil physical properties and the ground thermal regime generated through the project will enhance existing databases and provide key baseline information essential for infrastructure design, the assessment of environmental impacts, and land-use planning. In addition, the ongoing operation of the monitoring network and collection of thermal data will facilitate improved characterization of permafrost-climate interaction and predictions of climate change impacts. The monitoring network can also be an important component of future monitoring programs associated with hydrocarbon and other development in the Mackenzie corridor.

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