Assessing permafrost conditions in support of climate change adaptation in Pangnirtung, Nunavut

Anne-Marie LeBlanc, Greg Oldenborger, Wendy Sladen & David Mate
Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario, Canada
Andrée-Sylvie Carbonneau, Pascale Gosselin, Emmanuel L'Hérault & Michel Allard
Centre d'études nordiques, Université Laval, Québec, Québec, Canada

ABSTRACT
To reduce the negative impacts of climate change on permafrost and Infrastructure, an adaptation strategy must be undertaken to support land use planning decisions. The case of Pangnirtung, Nunavut, is taken as an example. The paper outlines the principal steps undertaken by a multidisciplinary team to assess the current permafrost conditions and presents preliminary data in regards to three main terrain units subjected to development opportunities. Results show the high variability in the distribution of the sediment types, ground ice, and ground thermal regime.

RÉSUMÉ
Afin de réduire les impacts des changements climatiques sur le pergélisol et les Infrastructures, une stratégie d'adaptation doit être établie pour améliorer les décisions en regard à l'aménagement du territoire. Le cas de la communauté de Pangnirtung est cité en exemple. Cet article décrit les principales étapes réalisées par une équipe multidisciplinaire afin d'évaluer les conditions actuelles du pergélisol et présente les données préliminaires en ce qui concerne trois principales unités de terrain sujets à des opportunités de développement. Les résultats montrent une grande variabilité dans la distribution des types de sédiments, de la glace de sol et du régime thermique des sols.

1 INTRODUCTION

Increased infrastructure in northern Canada associated with development of natural resources and population growth requires the incorporation of permafrost sensitivity into engineering design and land use planning. At a community level, land use planners have to deal with a broad range of terrain instability which may be amplified by climate change and extreme climatic events, and that may threaten the integrity of current and future infrastructure. This paper describes the research work in progress and the preliminary results that will conclude with the creation of a community hazard risk-assessment map as a support tool for land management and decision making in a climate change adaptation perspective. This case study is located in Pangnirtung, Nunavut, as it was seriously affected by an extreme rain event in June 2008, which has lead to severe permafrost degradation due to thermal-erosion along the river banks located inside the municipality boundaries.

In the past, the area of Pangnirtung was the focus of several studies mainly in regards to glacial and sea-level history (Dyke 1979; Aitken and Gilbert 1989), delineation of the bedrock surface beneath the intertidal flats (Pullan et al. 1983), geotechnical aspects associated with the construction of the water reservoir (Isherwood and Smith 1983, Smith et al. 1989) and nearby ground thermal regime (Hyatt 1998), reconstruction of Holocene environments based on ice wedge characteristics (Hyatt 1990) and the characterisation of ice-rich permafrost in the core of a moraine upstream of the Duval River (Hyatt 1992, Hyatt et al. 2003). Essential information from these studies is useful to understand the past and current permafrost conditions. However, more work is necessary to fill the scientific gaps in order to provide baseline information for economic development and to enhance the planning capacity of Pangnirtung.

2 STUDY AREA

Pangnirtung is located on the west side of Cumberland Peninsula and on the southeast side of the Pangnirtung fjord, at approximately 66º5' N latitude and 65º45' W longitude (Figure 1). The fjord is a classical U-shaped valley and the Duval River valley is characterized by the presence of terminal moraines. In most areas, bedrock is overlain by glacial till while a raised delta was formed by the Duval River when sea level where higher than present (Smith et al. 1989).

Based on published data, the mean annual air temperature (MAAT) and the annual precipitation for the period 1925 to 1950 were -8 ºC and 336 mm, respectively (Dyke 1977). During the period from 1950 to early '90, the high Arctic is characterized by a cooling climate and at the latest stage of this period, the MAAT was about -10 ºC (Maxwell 1980) and -8.9 ºC (Hyatt 2003). During this period, the area received an average of 395 mm of precipitation annually, of which 44% occurs as rain between June and September (Masterton and Findlay, 1976). Recent data from Environment Canada (Environment Canada. 2009) for the period of 1996 to 2009 indicates a warmer climate with a MAAT of -7.6 ºC and an increase of rain precipitation. The MAAT at Pangnirutng is warmer than the more southern community of Iqaluit. This may be linked with the complexity of the atmospheric-ocean currents and the ice-open water dynamics of water bodies located near the two communities. Between 1996 and 2007, Pangnirtung

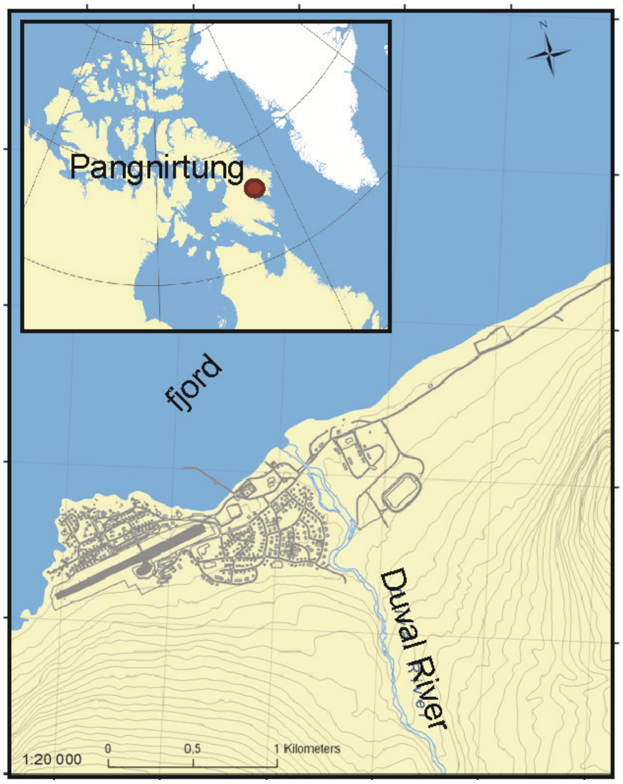

Figure 1. Location of the study site, Pangnitung, Nunavut.

received nearly 200 mm of precipitation during summer months, which it is about 54% of the annual precipitation.

The community of Pangnirtung lies within the continuous permafrost zone (Hegginbottom et al. 1995). In previous studies, permafrost temperatures were recorded between 1988 and 1991 at depths of 15 m ranging from -6.5 to -7.5 ºC (Hyatt 1998). Thermistor cables were installed near the current water reservoir in a till deposit. Ground temperatures were also monitored in sand and boulders deposit and in finer sediments close to the fjord; data range from -3 to -8 ºC at depths of 8 m (Isherwood and Smith 1983; Smith et al. 1989), but precise location of these measurements are not known. In most areas, the maximum active layer varies from 0.5 to 1.5 m, except in coarser deposit where depth of thaw of 3 m can be reached (Smith et al. 1989).

3 FIELD WORK

None of the thermistor cables installed in previous studies are currently functioning. Therefore, until recently, no ground temperature data were available to reflect the warmer climate of the last decade. With funding from the Federal Government's International Polar Year (IPY) Program, the Geological Survey of Canada (GSC) has established a Nunavut permafrost monitoring network (see Ednie and Smith 2010). In 2008, one thermistor cable was installed in collaboration with the Pangnirtung hamlet. Ground temperature data from this cable are integrated in the present study. However, results from previous studies have shown that the spatial variability in ground temperature conditions is high within the municipal boundary. Therefore, there is a need to document this variability.

During the summer 2009, fieldwork was conducted in the community of Pangnirtung by a multidisciplinary scientific team in order to assess the permafrost conditions both within the current infrastructure area and the new developing sector. The methodology integrates results from surficial geology, surface hydrology, permafrost geomorphology, ground thermal conditions, geotechnical properties, geophysical surveys, and snow thickness cover (Figure 2).

Terrain reconnaissance was first carried out to validate the interpretation of surficial geology, surface hydrology, and periglacial processes from stereo-viewing of areal photographs.

A total of 20 shallow bore holes (SBH) were drilled with a portable earth-drill and core samples were extracted to measure ice and water content, grain size, salinity, and Atterberg limits. Maximum depths reached are between 1 and 3.2 m. In addition, two deep bore holes (DBH) were completed with an air track drill to maximum depth of 13.9 and 14.9 m. Thermistor cables were installed in the deep bore holes and in two additional shallow drillings to monitor the permafrost temperatures in different terrain units. The third thermistor cable that belongs to the Nunavut permafrost monitoring network is also shown in Figure 2. This thermistor cable is near the airport and close to the weather stations of Environment Canada. The maximum depth of the thermistor cable is 15 m. Mini-dataloggers were buried in the near surface at various sites across the village to monitor the soil surface temperatures, and therefore, to infer the ground temperatures in deeper layers. Among them, four are located at sites SBH-06, SBH-14, DBH-01 and DBH-02, and five are located at sites with different ground surface conditions (road, wet zone, snow bank, etc.). One mini-datalogger was also used to measure the air temperature at the airport.

Electrical and ground penetrating radar surveys (GPR) were used to characterize the spatial stratigraphy and the ground ice distribution. Electrical and electromagnetic properties are highly sensitive to the transition from unfrozen to frozen state. GPR surveys were carried out with a pulseEkko 1000 from Sensors and Software inc. using antennas of 50, 100 and 200 MHz. The bulk of the electrical experiments were carried out using a capacitively-coupled resistivity (CCR) meter (Geometrics OhmMapper) and complimentary data were collected at select sites using a multi-electrode galvanic resistivity (GR) meter (IRIS Syscal R1+ Switch 48). Initial survey areas were targeted based on hazard identification (the Duval River) and community planning, but also along many segments over roads to provide a wide geographic coverage and additional information near of the shallow and the deep the bore holes.

Characterization of the snow cover was conducted during winter 2010 in order to correlate the snow properties and the soil surface temperatures. Snow depth and densities profiles were measured at every shallow and deep bore holes sites. Snow transects were also carried out along the east side of the Duval River and

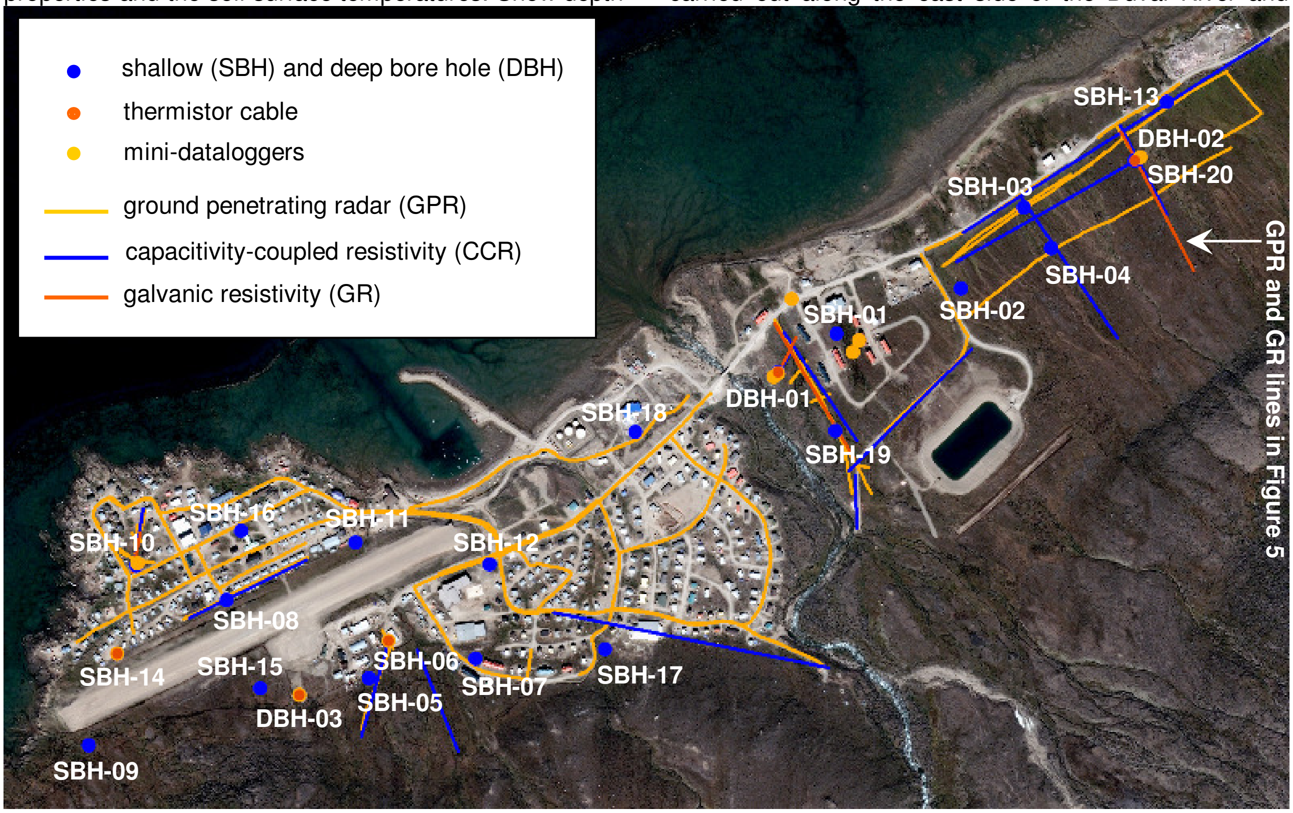

Figure 2. Map showing the location of the field work conducted in Pangnirtung. Background image (Quickbird), Includes copyrighted material DigitalGlobe, Inc., All rights Reserved.

along the road parallel to the fjord on the east side of the water reservoir to capture the snow thickness variability.

4 COMMUNITY HAZARD RISK-ASSESSMENT MAP

A state of the art database for archiving permafrost and climate data was developed. Field data are then used to create different layers of map such as surficial geology and vertical cross-section, ground ice, distribution of pore water salinity, surface hydrology, periglacial processes, surface and ground thermal conditions and snow cover. Furthermore, all the field-acquired information is currently compiled over a digital elevation model (DEM) to facilitate the analysis of dynamic processes. Integration of the different layers of information will conclude to the creation of a community hazard risk-assessment map as a support tool for land management and decision making.

5 SUMMARY OF THE TERRAIN UNITS AND THE PERMAFROST CONDITIONS

5.1 Mapping and drilling data

The mapping of Quaternary deposits was carried out at a scale of 1:2000 with aerial photographs (Figure 3). The infrastructure of Pangnirtung is build on four major units: 1) the sloping terrace covered by colluvial material to the east of the Duval River, 2) the alluvial terrace with boulders and eroded channels along the banks of the Duval river, 3) the Holocene debris fan of the Duval river, and 4) a rocky promontory covered with marine silts and sands. Delineation of surficial deposits is slightly different and more detailed from the one presented by Smith and al. (1989). Preliminary results of drillings from units 1, 3 and 4 are presented in this paper.

According to the most recent Pangnirtung Community Plan & Zoning By-law (FoTenn and Trow 2007), most of the current and future development areas are located to the east of the Duval River, and therefore, in unit 1. Shallow drillings in this area reveal that the thaw depth in mid-August ranges from 0.2 m up to 0.75 m according to soil moisture and peat layer. The visual description of the core samples down to 3 m depth indicate a sequence of coarse brown sand, gravel and pebbles with fine sand and grey silt (Figure 4a). The shape of the grains is angular. Below the active layer, ice lenses, ranging from millimetres to centimetres in thickness, are present mostly within the fine sand and the grey silt layers. This sequence of sediments is interpreted as a colluvial blanket. The area is also characterized by the presence of parallel drainage gullies from which eroded sediments are transported and by areas of poor

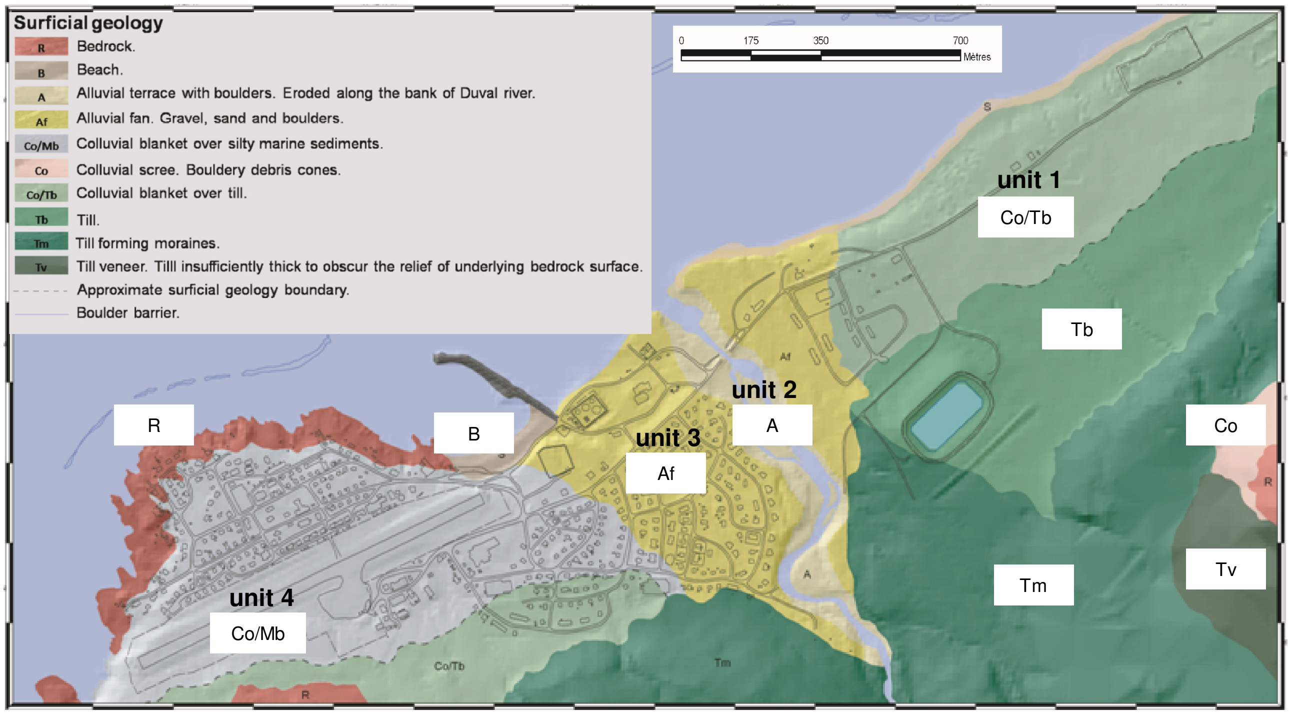

Figure 3. Surficial geology (A.-S. Carbonneau).

drainage. Upslope, towards the moraines, the colluvial blanket vanishes.

The Holocene debris fan unit is the natural foundation for old and recent infrastructures, respectively on the west and the east sides of the Duval River. The only redevelopment opportunities have been identified on the west side of the Duval River within the debris fan limits (FoTenn and Trow 2007). However, the permafrost degradation that occurred in 2008 along the river banks spreads towards the Inuit owned lands, close to the east side of the Duval River. Three shallow drillings were performed in this unit. In two cases, the drilling was stopped at 1 and 1.4 m depth when the drill was rejected by a boulder. At the site SBH-18, the soil was completely thawed to 1.4 m depth. However, the soil was perturbed and likely considered as infill. At the two remaining sites, the visual description of the core samples within the first metre or so of soil indicates a sequence of coarse oxidised sand with fine silty-sand and some organic content (Figure 4b). The active layer thickness in mid-August was 0.72 m in both sites. No ice lenses were found below the active layer, but the investigation depths remain superficial.

Most of the community infrastructures, including the airport, are located over the rocky promontory covered with the marine silts and sands unit. Options for future development in unit 4 were pointed out in the case of relocation of the airport (FoTenn and Trow 2007). The majority of the shallow drillings were performed in this unit. The thaw depth in mid-August ranges from 0.41 to 1.05 m. Massive clay sediments are encounter at sites SBH-14, SBH-08 and SBH-10 at depths of 1 to 2 m below the surface (Figure 4c), which are overlain by medium to coarse sand. At other sites, ice-rich sand and gravel were observed in the stratigraphic profiles. Site SBH-06 is particularly ice-rich (Figure 4d) potentially a result of being located in an area where surface water accumulates from drainage gullies.

5.2 Geophysical investigation

GPR and the electrical resistivity results provide deeper subsurface information than the mapping and drilling data. All the three units described above show distinctive geophysical signatures. Contact to bedrock was not observed in any of the results, even in unit 4 where the bedrock outcrops near the fjord. It is expected that the bedrock topography overlain by the marine sediments changes rapidly given the sudden variability in topography of the exposed bedrock surfaces.

Only the results from terrain unit 1 are presented in this paper. Cross-section of the ground interpreted from the major reflectors identified on the GPR profile is shown in Figure 5a. The travel time profile was converted into a depth profile using the velocity of the radar signal into the ground estimated from a CMP survey (Common

Mid Point). An average velocity of about 0.9 m/ns was then used at all depths. The cross-section shows two different layers: the colluvial blanket deposit of about 2 m thick underlain by a till deposit. The strongest reflection more or less parallel to the surface was interpreted as the stratigraphic contact between the two layers since the thawing front was observed to range from 0.2 to 0.75 m. Hyperbolic reflections more or less equally spaced within

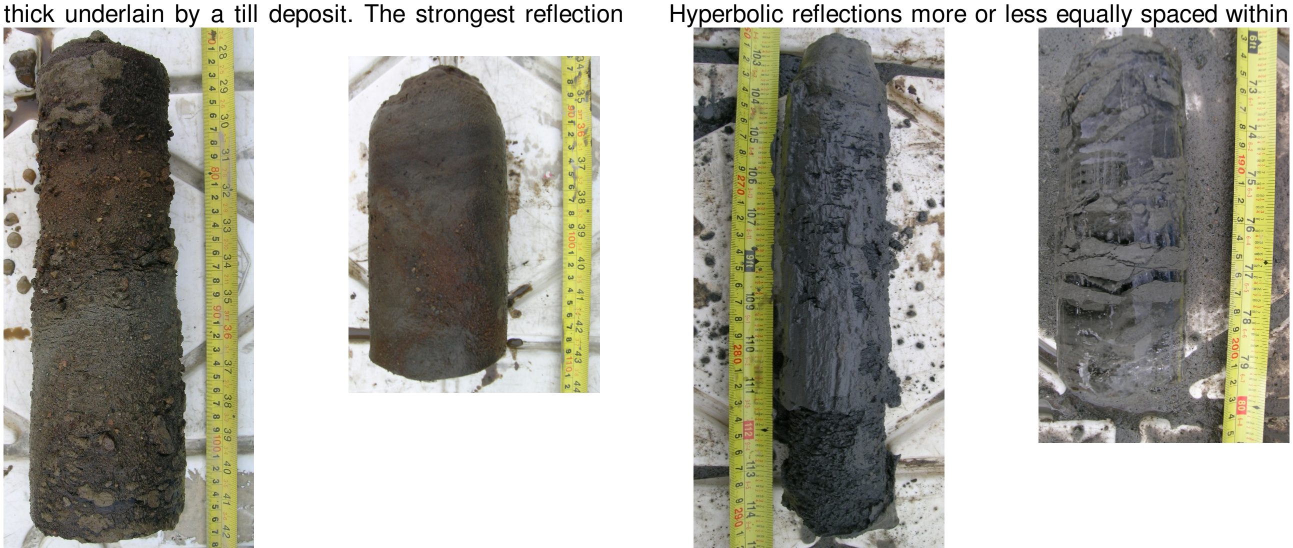

Figure 4. Permafrost core samples. a) coarse brown sand, gravel and pebbles with fine sand and grey silt (SBH-20, unit 1), b) coarse oxidised sand with fine silty-sand and some organic content (SBH-19, unit 3), c) massive clay (SBH-10, unit 4), d) ice-rich silty-sand (SBH-06, unit 4). See Figure 2 for site locations.

the colluvial layer or slightly below the stratigraphic contact were interpreted as possible ice wedges. Ice wedges tend to produce refraction of the electromagnetic (EM) signal inside the ice wedges while oblique reflection of the EM signal is produced by the ice-wedge walls due to the range of emitting antenna (Fortier and Allard 2004). Hyperbolic reflections produced by individual boulders are rather characterized by multiple hyperbolic reflections without any refraction of the EM signal. Many ice wedges were observed during the construction of the current water reservoir located in the same terrain unit, but further west (Smith et al. 1989). The thick colluvial deposit tends to mask the presence of those ice wedges, which otherwise can be normally seen on aerial photographs.

Both CCR and GR were performed along the same GPR survey lines. Each set of apparent electrical resistivity data were inverted to produce a model of electrical resistivity. The inversion methodology is a smoothness-constrained least-squares. Both CCR and GR data were inverted using the software packages Res2Dinv (Loke and Baker 1996; Loke et al. 2003). Only the model from GR is presented. Just as the GPR data, the GR model clearly shows two different layers (Figure 5b). The resistive surface layer is interpreted as frozen sand and silt about 3 m thick. This layer appears thicker than the value interpreted from the GPR, however, resistive layers tend to look thicker than in actuality. Resolution of GR (or CCR) is too low to allow any ice wedge identification. On the other hand, the presence of several ice wedges can explain the resistive surface layer. The lower layer, interpreted as the till deposit, is conductive. The low values of resistivity indicate that the till should be rich in fine sediments (silt or clay). Smith et al. (1989) reported that the glacial till consists of occasional cobbles and boulders in a dense matrix of silty sand.

5.3 Ground thermal regime

Ground temperature monitoring is essential for engineering design and community planning since the behaviour of soils is highly influenced by its temperature. Since different soils will behave differently for the same change in temperature, thermistor cables were installed in various terrain units.

Among the five thermistor cables, three of them are located in the terrain unit 4 (DBH-03, SBH-06, and SBH-14). Presently, ground temperature data for more than one year (June 2008 to March 2010) is only available at the site DBH-03. For the sites SBH-06 and SBH-14, and also for terrain units 1 (DBH-02) and 3 (DBH-01), an eight month record is available (August 2008 to March 2010).

Monthly temperatures were calculated for each measurement depth and are shown in Figure 6. At 12 m depth, the ground temperatures are -2.8, -5.2, and -7.1 ºC, respectively for the sites DBH-01, DBH-03, and DBH-02. The debris fan of the Duval River may explain the warmer ground temperature measured since the thermal conductivity of the gravelly and bouldery sand is probably higher, and thus, respond faster to recent increases of air temperature. The thermistor cable is located in an old channel of the Duval River where snow accumulation is slightly higher compared to wind exposed surface at sites DBH-02 and DBH-03. This may lead over time to an increase of the ground temperature compared to the two other sites. In March 2010, the snow cover was 0.37, 0.16, and 0.20 m, respectively at sites DBH-01, DBH-02, and DBH-03. However, the thicker snow cover at site SBH-01 is not enough to explain a difference of more than 4 ºC at 12 m depth. The proximity of the Duval River and the groundwater movement in the upper thawed layer may also have induced additional heat and is probably the primary reason for the warmer ground temperature.

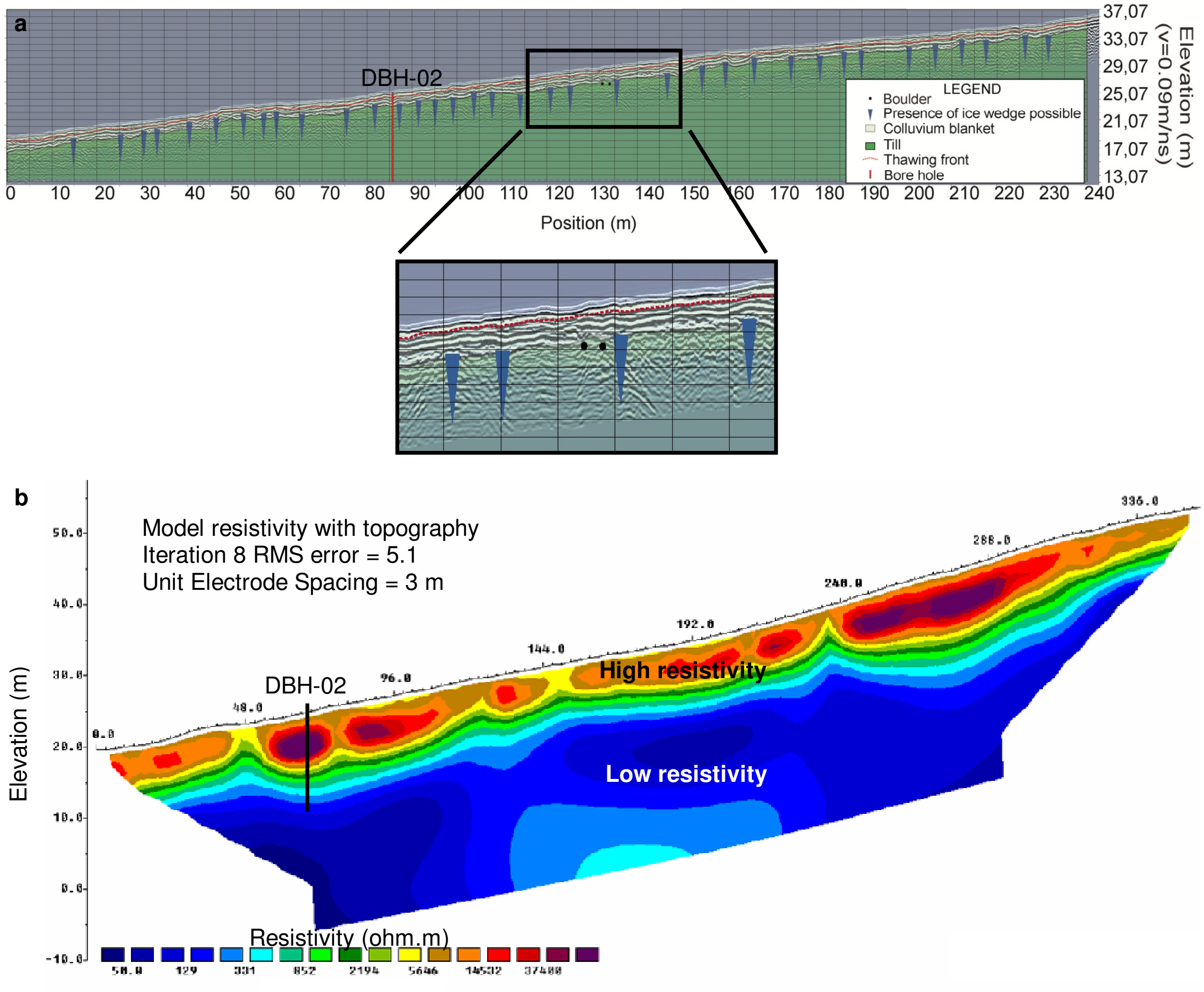

Figure 5. a) Ground penetrating radar (GPR), b) Galvanic resistivity (GR). See Figure 2 for site location.

The depth of the level of zero annual amplitude below which seasonal variation is negligible is 12.3 m at site DBH-03 and more than, but close to 14 m at sites DBH-01 and DBH-02. The range in temperature over an eight month period at site SBH-14 indicates a smaller amplitude at the near surface and a rapid decrease of the thermal amplitude with depth compared to other sites. Hypothesis of a high unfrozen water content of the massive cryostructure of the silty-clay sediments from almost the surface down to 2.7 m probably explain the narrow thermal amplitude and the shallow depth of the level of zero annual amplitude. The thicker snow cover of about 1.23 m could also be responsible to maintain warmer ground temperature profiles, and thus, reducing the thermal amplitude.

The maximum summer thaw depth (maximum active layer) given by the intersection between the maximum temperature profile and the 0 ºC is also shown in Figure 6. In terrain unit 4, the maximum thaw depth in 2009 varies from 0.75 m to 1.8 m at three different locations. Unlike sites SBH-06 and SBH-14, site DBH-03 was installed on a gravel pad, where the general surface area is mostly bare. These differences may explain the thicker active layer measured because the heat wave from the air is transferred to the surface of the soil with less interference. Even if summer air temperature is one of the primary factors to explain active layer depth, snow cover from previous winter may also contribute to the increase of the thawing depth (L'Hérault 2009). If a similar thick snow cover of 1.23 m at the site SBH-14 likely occurred during the previous winter, this may have lead to an increase in the 2009 summer thaw compared to site SBH-06 where the snow cover was only 0.20 m. Greater peat content was also observed near the surface at site SBH-06. In terrain units 1 (DBH-02) and 3 (DBH-01), the active layer thickness of about 1 and 2.5 m respectively, are mostly related to sediment type, surface conditions and water content. However, in the case of site DBH-01,

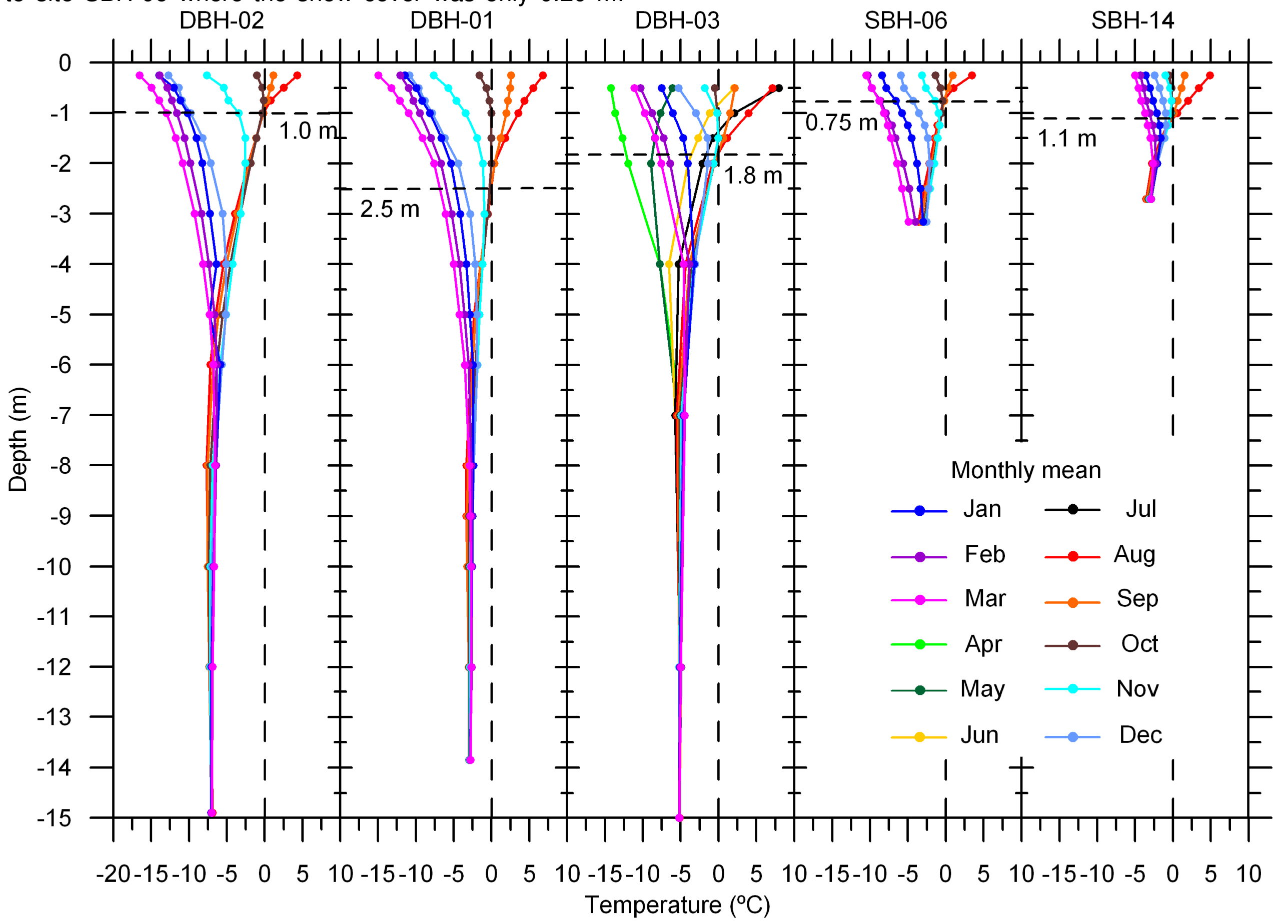

Figure 6. Ground temperatures from first year of data collection (April 2009 to March 2010). Maximum active layer thickness is shown for each site. See Figure 2 for site locations.

the active layer thickness is probably also influenced by the warmer mean annual ground temperature since the thawing depth in mid-August was only 0.72 m in the two shallow bore holes that are located in the debris fan, but away from the river.

6 CONCLUSION AND NEXT STEPS

To reduce the negative impacts of climate change on permafrost and infrastructure, an adaptation strategy must be undertaken to support land use planning decisions. Assessing the permafrost conditions is one of the first steps to develop this adaptation strategy. Preliminary results presented in this paper provide baseline information on the geological units and the current permafrost conditions in the study area. A surficial map was created, shallow and deep soil characterization including ground ice features were described and ground temperatures were analyzed for three main terrain units subjected to development opportunities. More data analysis, integration and interpretation will be needed to fully answer the research goals and to create a terrain hazard map at a scale reliable for community planning. Measurements of ice and water content, grain size, salinity, and Atterberg limits are in progress. Snow cover measurements will be linked to the soil surface temperatures to infer the ground temperatures in deeper layers at various locations. Observations on active geomorphic and surface hydrology will be linked with the permafrost conditions. The research will also include a more detailed study of the thermo-erosion along the Duval River. With the integration of all the results, it will be possible to interpret the field data in terms of the permafrost sensitivity to climate change. Finally, the methodology of this study will be applicable to similar projects.

ACKNOWLEDGEMENTS

Support for this project was provided by Natural Resources Canada (NRCan) and the Canada-Nunavut Geoscience Office (CNGO). The DEM and the Quickbird satellite imagery were supplied by the Government of Nunavut, special thanks go to R. Chapple. M. Ednie (NRCan) provided helpful comments on the manuscript. Thanks go also to A. Dyke (NRCan) for his initial work on surficial geology. Finally, the authors wish to thank the members of the community of Pangnirtung for their interest in the project and their knowledge on the landscape, the Hamlet office and the SAO, R. Mongeau, for the logistical support, and Jimmy Uniushagak and Noah Maniapik for their helpful assistance making the fieldwork a success. ESS Contribution Number 20100074.

REFERENCES

Aitken, A.E. and Gilbert, R. 1989. Holocene nearshore environments and sea-level history in Pangnirtung fjord, Baffin Island, N.W.T., Canada. *Arctic and Alpine Research* 21(1):34-44.

Dyke, A. 1979. Glacial and sea-level history of southwestern Cumberland peninsula, Baffin Island, N.W.T., Canada. *Arctic and Alpine Research*, 11(2):179-202.

Dyke, A. 1977. Quaternary geomorphology, glacial chronology, and climatic and sea-level history of southwestern Cumberland Peninsula, Baffin Island, Northwest Territories, Canada. Ph.D. thesis, University of Colorado, Boulder, 182 pp.

Ednie, M. and Smith, S.L. 2010. Establishment of Community-based Permafrost Monitoring Sites, Baffin Region, Nunavut. *6th Canadian Permafrost Conference*. This issue.

Environment Canada. 2009. The climate normals of Canada. http://www.climate.weatheroffice.gc.ca/climate_normals/stnselect_e.html. Accessed March 15, 2010.

Fortier, D. and Allard, M. 2004. Late Holocene syngenetic ice-wedge polygons development, Bylot Island, Canadian Arctic, Archipelago. *Canadian Journal of Earth Sciences*, 41: 997–1012.

Fotenn and Trow, 2007. Final Background Report Pangnirtung Community Plan and Zoning By-law Update. Community and Government Services, Government of Nunavut and Hamlet of Pangnirtung, 48 pp.

Hegginbottom, J.A., Dubreuil, M.A. and Harker, P.T. 1995. Canada, Permafrost. *National Atlas of Canada*. 5th ed., Natural Resources Canada, MCR 4177.

Hyatt, J.A. 1998. Ground thermal regimes at a large earthwork reservoir on Baffin Island, Nunavut, Canada. *Seventh International Conference on Permafrost*. Edited by A.G. Lewkowicz and M. Allard. Yellowknife NWT. Collection Nordicana 57: 479-486.

Hyatt, J.A. 1993. Permafrost conditions near two water storage facilities on Baffin Island, Northwest Territories. Unpublished Ph.D. Thesis, Department of Geography, Queen's University, Kingston, Ontario, 264 pp.

Hyatt, J.A. 1992. Cavity Development in ice-rich permafrost, Pangnirtung, Baffin Island, Northwest Territories. *Permafrost and Periglacial Processes*, 3: 293-313.

Hyatt, J.A. 1990. Reconstruction of Holocene periglacial environments in the Pangnirtung area based on ice wedge characteristics. *Proceedings of the Fifth Canadian Permafrost Conference.* Edited by M.M. Burgess, D.G. Harry and D.C. Sego. Quebec City. Collection Nordicana, 54: 17-21.

Hyatt, J.A., Michel, F.A. and Gilbert, R. 2003. Recognition of subglacial regelation ice near Pangnirtung, Baffin Island, Canada. *Proceedings of 8th International Conference on Permafrost*. Edited by M. Phillips, S.M. Springman, and L.U. Arenson. Zurich Switzerland. A.A. Balkema, 1: 443-448.

L'Hérault, E. 2009. Contexte climatique critique favorable au déclenchement de ruptures de mollisol dans la vallée de Salluit, Nunavik. M.Sc. thesis. Department of Geography, Laval University, Quebec, Quebec, 161 pp.

Isherwood, A.E. and Smith, L.B. 1983. New Pangnirtung water reservoir, detailed geotechnical investigation. Government of the Northwest Territories, Department of Public Works.

Loke, M.H., Acworth I. and Dahlin, T. 2003. A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. *Exploration Geophysics*, 34: 182-187.

Loke, M.H. and Barker, R.D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophysical Prospecting*, 44: 131-152.

Masterton, J.M. and Findlay, B.F. 1976. The climate of Auyuittuq National Park, Baffin Island, Northwest Territories. Atmospheric Environment Service Canada, 104 pp.

Maxwell, J.B. 1980. The Climate of the Canadian Arctic Islands and Adjacent waters. Atmospheric Environment Service Canada, 1, 532 pp.

Pullen, S.E., Hunter, J.A. and Gilbert, R. 1983. A shallow seismic survey on the interdidal flats at Pangnirtung, Baffin Island, Northwest Territories. *Current Research, Part B,* Geologiocal Survey of Canada, Paper 83-1B: 273-277.

Smith, L.B., Notenboom, W.G., Campbell, M., Cheema, S. and Smyth, T. 1989. Pangnirtung water reservoir: geotechnical aspects. Canadian Geotechnical Journal, 26: 335-347. Williams, P.J., and M.W. Smith. 1989. The frozen earth: fundamentals of geocryology. Cambridge, UK: Cambridge University Press.