Mapping and Investigating Permafrost along the Proposed Kivalliq Hydro-Fibre Link, Manitoba to Nunavut

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ABSTRACT
The proposed Kivalliq Hydro-Fibre Link (KHFL) extends from Gillam, Manitoba to Baker Lake, Nunavut. The route crosses sporadic discontinuous to continuous permafrost. The surficial geology of the of the 1,200 km-long corridor was mapped and field-checked and ground-penetrating radar surveys and ground temperature sensor installations were completed. Coarse-grained glaciomarine and reworked till deposits predominate. Glaciofluvial deposits consisting mostly of sand commonly form large eskers covered with beach ridges. Permafrost was generally >0.8 m deep in these three types of deposits. Ice content was low in till and glaciofluvial deposits, but variable in bedded glaciomarine sediments. All are acceptable substrates for transmission tower footings, with local limitations. Permafrost was ice-rich and shallow (0.4-0.5 m deep) in organics and rare deep-water glaciomarine sediments. Widespread ice-wedge polygons and thermokarst in these deposits will complicate tower placement. Permafrost along the Manitoba section of the corridor is generally "warm" (>-2°C) and thaw-sensitive where ice-rich.

RÉSUMÉ
Le projet de liaison hydroélectrique de Kivalliq (KHFL) s'étend de Gillam, au Manitoba, à Baker Lake, au Nunavut. La route traverse du pergélisol sporadique, discontinu et continu. La géologie de surface du corridor de 1 200 km de long a été cartographiée et vérifiée sur le terrain. Des relevés de géoradar et l'installation de câbles à thermistances ont été complétés. Les sédiments glaciomarins d'eau peu profonde et le till remanié prédominent. Les dépôts glaciofluviaux sableux forment de grands eskers couverts par des crêtes de plage. Le pergélisol était généralement > 0,8 m de profondeur dans ces trois types de dépôts. La teneur en glace était faible dans les dépôts de till et fluvioglaciaires, mais variable dans les sédiments glaciomarins stratifiés. Ces dépôts sont des substrats acceptables pour les socles de tour de transmission, avec des limitations locales. Le pergélisol était riche en glace et près de la surface (0,4 à 0,5 m de profondeur) dans les milieux organiques et dans les rares dépôts de sédiments glaciomarins d'eau profonde. Les polygones à coin de glace et le thermokarst dans ces dépôts compliqueront l'emplacement des tours. Le pergélisol le long de la section manitobaine du corridor est généralement « chaud » (> -2°C) et sensible au dégel lorsque la teneur en glace est élevée.

1 INTRODUCTION

The Kivalliq Hydro-Fibre Link (KHFL) project has the ambitious goal of providing several Arctic communities and mine sites in Nunavut with hydroelectricity and high-speed Internet. The project spans 1,200 km, extending from Gillam, Manitoba, to Baker Lake, Nunavut. Led by the Inuit through the formation of Nukik Corporation, the KHFL will be Nunavut's first major infrastructure link to southern Canada.

The Project area encompasses a 1.2 km-wide corridor with offshoots to various communities and mine sites (Figure 1). The current corridor was proposed by our team based on the relative suitability of ground conditions for tower installation, interpreted from a review of the prior all-weather road route selection study (SNC-Lavalin, 2007), available satellite imagery, and regional surficial geology and permafrost mapping.

In Nunavut and northern Manitoba, bedrock comprises Archean and Paleoproterozoic granitoid, metavolcanic and metasedimentary rocks of the Canadian Shield (de Kemp et al, 2006; Manitoba Geological Services, 1979). In the southern two thirds of Manitoba, Upper Ordovician limestone, with minor shale and sandstone is present (Manitoba Geological Services, 1979).

During deglaciation of the region, isostatic depression of the ground under the weight of glacial ice led to the late glacial Tyrell Sea extending much farther inland than the current Hudson Bay shoreline. As a result, almost the entire KHFL corridor was once beneath the ocean. The marine limit is shown on Figure 1.

2 METHODS

A number of different techniques were used to investigate the construction favourability of surficial deposits along the corridor. Together, the various methods allow us to characterize surficial deposits and permafrost conditions in representative terrain units along the corridor, which are imperative to understand for tower design and construction purposes.

2.1 Desktop Studies

A literature review was undertaken to summarize existing information and regional surficial geology.

Palmer mapped surficial geology at 1:20,000 scale, using DAT/EM's Summit Lite and Esri's ArcGIS software. Mapping was based on interpretation of 1.5 m-resolution colour SPOT pseudo-stereo satellite images, 25-cm resolution LiDAR stereo pair air photos and LiDAR-derived hillshade images. Freely available Esri ArcGIS Online 2D World Imagery was referred to as needed.

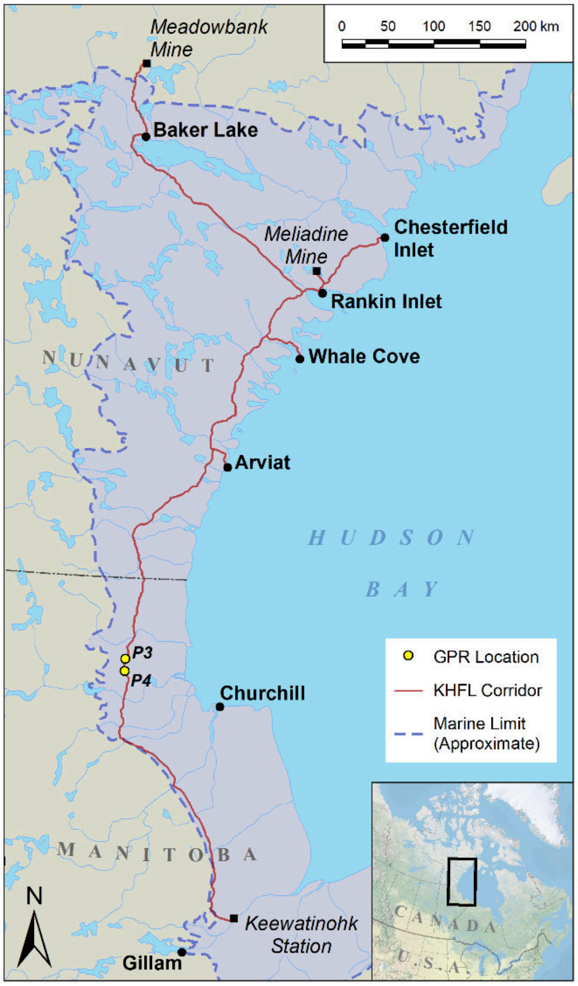

Figure 1. KHFL route corridor, Manitoba and Nunavut. Marine limit adapted from Gauthier et al. (2020) and McMartin et al. (2020). The two GPR data locations discussed in the text are shown.

2.2 Ground-Penetrating Radar Surveys

Ground-penetrating radar (GPR) surveys were completed in March, 2021, along nine transects within the Manitoba portion of the corridor. A number of areas with particularly challenging ground conditions for transmission towers were targeted, such as large wetland complexes with thermokarst depressions.

The field sites were accessed by helicopter from Churchill, giving site selection priority to windswept areas with minimal or compact snow cover wherever possible. The GPR equipment was carried in a backpack with the transmitter and receiver units being dragged across the ground in a plastic toboggan.

The surveys were carried out with an UltraGPR system, having an approximate centre frequency of 80 MHz and a trace interval of 50 cm. *Geolitix* software was used for the GPR survey interpretation and a mean velocity of 0.06 m/ns was added to the profiles. This velocity is typical for fine-grained or water-rich sediments (Cassidy, 2009). Two of the surveys are discussed herein; these are shown on Figure 1.

GPR profiles were interpreted using mainly satellite images and the new surficial geology mapping. Borehole logs and field photographs were used to help validate interpretations in the upper portion of the GPR sections.

2.3 Ground Temperature Sensor Installation

Ground temperature sensors were installed at ten locations in Manitoba in November, 2020, and at two locations in Nunavut in August, 2021. Deposit type and ecological setting were important considerations for the selection of sensor installation sites, to help capture the range of variation in ground temperatures and the depth to permafrost along the length of the corridor. In August, 2021, ground and air temperature data were downloaded from sensors installed at three locations in Manitoba in November 2020.

2.4 Field Reconnaissance

Field investigations were conducted from August 28 to September 2, 2021. Access was provided by helicopter and ground conditions were investigated on foot at numerous locations along the route. Detailed fieldwork involved acquisition of field photographs, permafrost probing, surficial geology descriptions of material visible in hand-dug testpits, and the drilling and logging of frozen ground to depths of up to 3.3 m using a portable Talon drill.

Such shallow boreholes were drilled at selected locations where GPR data were acquired, and at other locations deemed representative or otherwise useful for mapping purposes. Core tubes and drill rods were approximately 3 cm in diameter. A side-smear sampler was used to acquire core segments in 10 cm sections at selected depths. Core tubes were left to partially thaw for a few minutes to allow the sample to be retrieved from the tube if frozen in place. A hatchet was used to split frozen cores open for examination, and each core section was logged and photographed prior to complete thawing (Figures 2 and 3).

Selected samples acquired from the boreholes were analyzed for moisture content, pH, grain size distribution and selected geochemistry (including sodium content) by ALS Laboratories in Calgary, AB.

Thaw depth was recorded for both the soil pits and the boreholes, and was assumed to be a reasonable estimate of active layer thickness since data collection took place in August. Volumetric ice content in the core samples was estimated visually and later complemented by moisture content analyses. Ice structure, percentage and clarity were recorded.

3 RESULTS

3.1 Surficial Deposits

Surficial geology mapping was completed for the entire corridor (Figure 4). Mapping, and data acquired during fieldwork, including from boreholes, indicate that surficial deposits in both Manitoba and Nunavut are dominated by sand-rich deposits. These include till, glaciomarine and glaciofluvial sediments. Till and glaciofluvial deposits have been reworked by wave action and raised beaches commonly overlie eskers. Most of these deposits are ice-poor, with relatively thick active layers. Extensive boulder fields of angular to subround rocks commonly overlie bedrock or other deposits. Boulders are also common in the uppermost 25 cm of most deposits, which either reflects wave reworking as the Tyrell Sea receded during deglaciation or

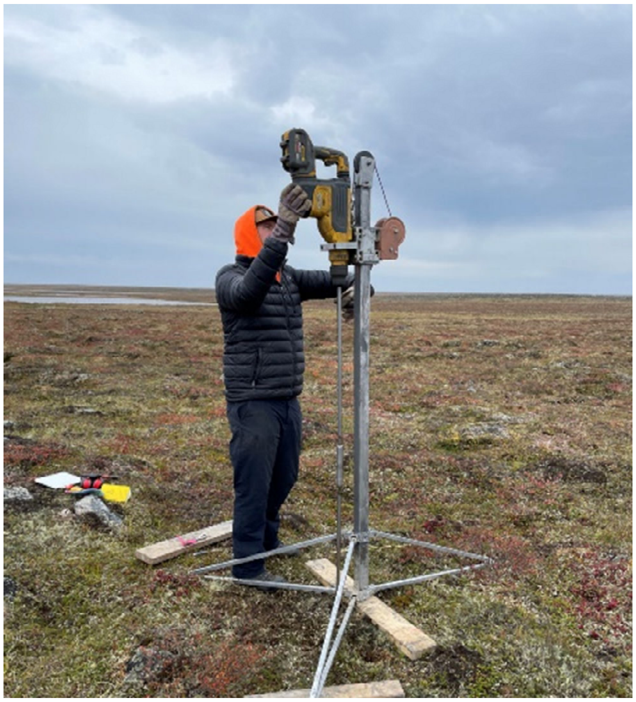

Figure 2. Drilling frozen ground with a portable Talon drill.

Figure 3. Logging frozen core obtained with the Talon drill.

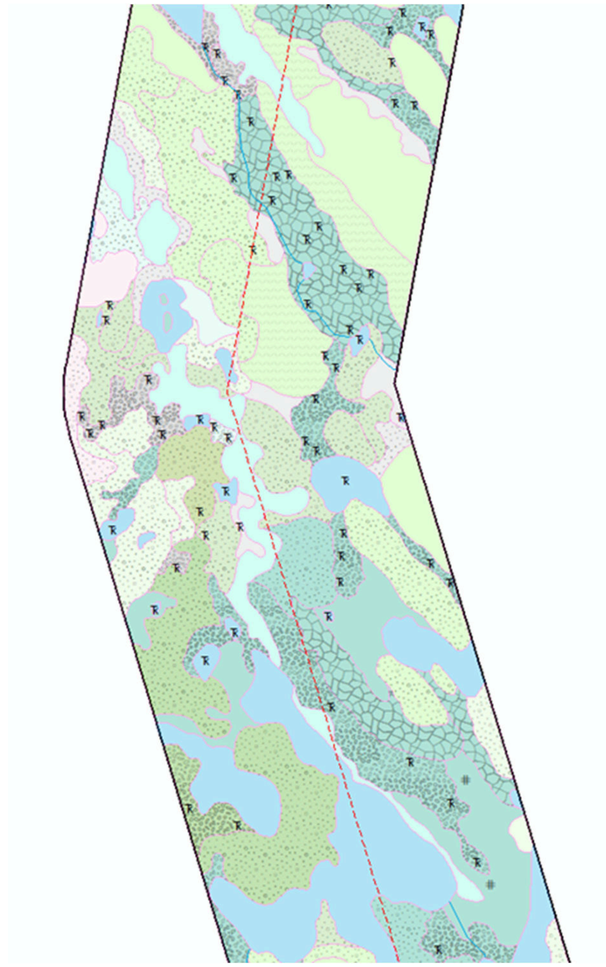

Figure 4. Example of surficial geology and geomorphology mapping along the corridor. Green represents different types of till, blue-green shows glaciomarine units, grey shows organic deposits and blue represents lakes. Patterns indicate the presence of reworked material and boulder concentrations (light and dark stipple) and patterned ground (polygonal). Point features indicate localized areas of thermokarst activity.

frost jacking, or possibly a combination of the two. Many boulder fields appear to have a felsenmeer origin, based on their locations down-ice of the oldest bedrock types.

Sample analyses confirmed the sediment grain size descriptions, and provided background geochemical, salinity and pH data for several sites along the corridor.

3.1.1 Till

The till within the corridor is a sandy diamicton with 40-50% pebbles, cobbles and boulders. It forms undulating to hummocky topography, and streamlined landforms. The till is generally moderately well drained and ice poor. In low-lying areas where the till is associated with organic deposits, or in areas downslope of organic deposits, till deposits may be locally ice-rich and have thinner active layers.

Much of the till is likely reworked by wave action, which may in part explain why the upper 25 cm of till is commonly very bouldery (to the extent that it is commonly clast-supported).

3.1.2 Glaciofluvial Deposits

Glaciofluvial deposits are relatively common, usually forming hummocky areas, large eskers, or terraces flanking modern rivers. Eskers can be more than 30 m in height and are generally covered with beach ridges. Glaciofluvial deposits consist of sand, pebbles, cobbles, and boulders as a rule, but some deposits are entirely composed of sand. Clast content ranges from 50 to 70% and boulders may litter the surface. Eolian blowouts are common on the surface of sand deposits and ice-wedge polygons are common on all glaciofluvial sediments.

Layers of fine-grained glaciofluvial deposits were detected in some of the GPR surveys. These likely comprise interbedded fine sand and minor gravel with thin clay and silt interbeds (Figure 5). These deposits could be tens of meters thick, according to GPR survey analysis.

3.1.3 Glaciomarine Deposits

Glaciomarine deposits are commonly extensive and range from <1 m to over 10 m thick.

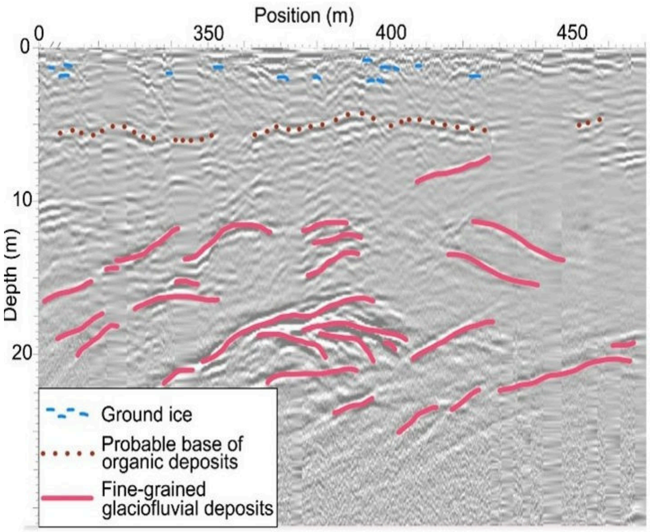

Figure 5. Part of a GPR survey interpretation (Line P4) showing fine-grained glaciofluvial or glaciomarine sediments (laminated sand and silt) underlying organic deposits. Depth and distance measurements are in metres.

Sandy shallow-water glaciomarine sediments formed in littoral settings are common and are generally moderately well to well drained. Ice-wedge polygons are widespread in these deposits. Shallow water deposits have clast contents of 20-40% and are usually very bouldery at surface or have boulder or pebble/cobble pavements. These areas and some beach ridges can have clast contents of up to 80%. Shallow glaciomarine deposits generally overlie other glaciomarine deposits, till or glaciofluvial deposits. In low-lying areas where they are associated with organic deposits, or in areas downslope of organic deposits, coarse-grained shallow-water glaciomarine sediments may be locally ice-rich.

Raised beach ridges are a subset of shallow glaciomarine deposits. They form curvilinear concentrations of cobbles and boulders on the surface of other deposits. Most beach ridges are thin enough that the underlying deposit (generally an esker) is identifiable.

GPR surveys showed only a few zones of signal attenuation in beach ridge deposits, which is consistent with layers of well-drained coarse sediments. Occasionally the presence of wet areas, likely associated with fine-grained offshore glaciomarine sediments, was detected at depths between 5 and 10 meters (Figures 6 and 7).

Fine-grained glaciomarine sediments deposited in deeper water are also present, but they are less abundant. Deep-water glaciomarine deposits form poorly drained plains in low-lying areas and comprise bedded silt, clay and fine sand. Permafrost is ice-rich and close to surface in these fine-grained deposits (Figure 7), which are prone to thermokarst activity and the development of ice-wedge cracks.

3.1.4 Other Deposits

Organic deposits that have accumulated in low-lying, poorly drained areas (i.e., wetlands, including bogs and fens) are common throughout the corridor. Organic deposits ranging from less than 1 m thick to 5 m thick were surveyed with GPR (e.g., Figure 5) and have shallow, ice-rich permafrost.

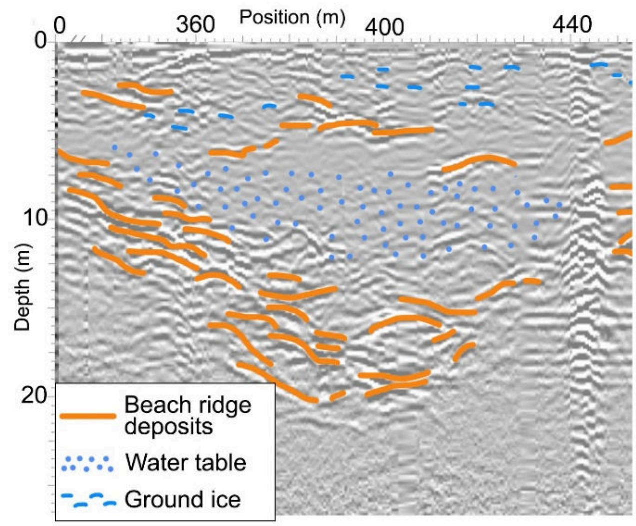

Figure 6. Part of a GPR survey interpretation (Line P3) where wet sediments 5 to 10 m below the surface are overlain and underlain by beach ridge deposits (stratified sand and gravel).

Thin fluvial deposits formed by small streams are commonly associated with organic deposits, whereas larger rivers create substantial floodplains and terraces, which may or may not contain organic accumulations. Fluvial deposits are generally composed of bedded silt and sand along small streams and stratified sand, pebbles, cobbles and boulders along larger rivers. Fine-grained fluvial sediments may have shallow, ice-rich permafrost, where no longer associated with active fluvial activity. Such environments may also be susceptible to erosion/avulsion and icings. Large rivers are likely underlain by taliks.

Colluvial deposits are rare within the low-relief landscape that typifies the corridor, but mainly comprise imperfectly to well drained deposits formed by debris slides, rotational earth slides, and active layer detachments. Toe undercutting by rivers and streams is the most common cause of slides, but permafrost thaw is responsible for some, especially in Nunavut. Colluvial sediments consist of either coarse-grained (sand to boulders) or fine-grained material (silt to sand), depending on the source area.

Lacustrine and eolian deposits are rare, but bedrock is exposed in many locations, especially in Nunavut.

Bedrock was detected at depths between 15 and 25 m in 4 out of 9 GPR surveys (e.g., Figure 7). These sites are mostly near the Manitoba-Nunavut border where bedrock is overlain by till, glaciomarine, and glaciofluvial deposits. Depth to permafrost within bedrock was not a focus of this study.

3.2 Permafrost

Permafrost has a strong influence on soil drainage conditions, rates and mechanisms of colluvial processes and the geotechnical stability of different substrates. An appreciation for permafrost characteristics and processes is important for the planning of large infrastructure projects.

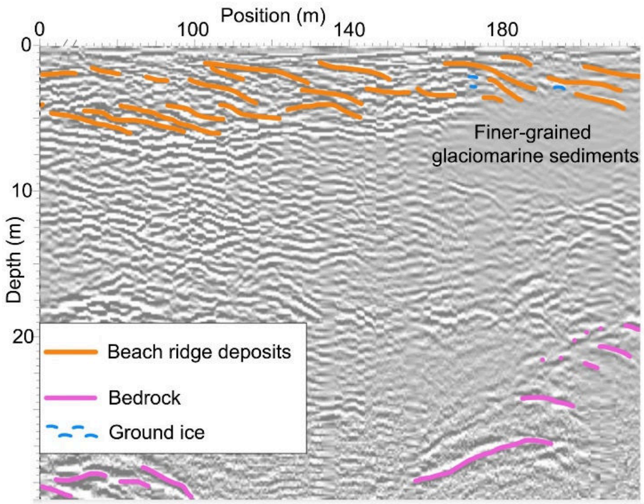

Figure 7. Part of a GPR survey interpretation (Line P3) where bedrock is detected 20 to 25 m below glaciomarine deposits (stratified sand and gravel beach ridges overlying fine-grained glaciomarine deposits).

3.2.1 Permafrost Features

Permafrost acts as a barrier to water flow; unconsolidated materials within the active layer commonly become saturated during the summer. On level ground, differential frost heave may occur in the snow-free season, resulting in frost boils, irregular micro-topography and the formation of earth hummocks; these are all common features of till deposits. Frost boils locally form stone circles and stripes. Solifluction and permafrost creep are evident on some slopes.

Patterned ground is present in the form of ice-wedge polygons in coarse-grained deposits (glaciofluvial, beach ridge and shallow-water glaciomarine sediments), fine-grained deposits (fluvial and deep-water glaciomarine sediments) and organic deposits. Ice-wedge polygons form geometric networks characterized by interconnected, linear furrows on flat to gently sloping topography and are a sign of ice-rich permafrost terrain. Wedge ice is commonly greater than 1 m thick.

Signs of thermokarst, the degradation of ice-rich permafrost, are common in low-lying, fine-grained deposits, organic deposits, and poorly drained till. Thermal erosion along ice-wedges is not common, but does occur in glaciofluvial deposits overlain by beach sediments. This leads to the formation of small drainage channels that are very angular in their upper reaches.

3.2.2 Active-layer thickness

The depth to permafrost (active layer thickness) varied spatially at regional and local scales. Well drained soils insulated by thick annual snow cover tended to have thicker active layers than wind-swept or poorly drained areas. Active layers were generally 0.9 to 1.4 m thick in till, coarse-grained shallow glaciomarine deposits and glaciofluvial deposits. Permafrost was closer to surface (0.4 m to 0.5 m below surface) in organic deposits, finer grained shallow-water glaciomarine deposits (sand and silt), fine-grained fluvial deposits and fine-grained deep-water glaciomarine sediments.

3.2.3 Ice Content

Ground ice in the project area primarily formed vein (wedge) ice, segregated ice, and pore ice. Excess ice content, the volume of frozen water that is in excess of soil pore space, was associated with a potential loss in ground volume upon thaw. Excess ice content was considered low if it made up <10% of the deposit, moderate if it formed 10-20% and high if it was >20% (Heginbottom et al., 1995).

In the Project area, wedge ice was widespread in coarse, fine, and organic deposits of the continuous permafrost zone, and constitutes an important component of the excess ice content.

Visual assessments of segregated excess ice content ranged from 5 to 60% and varied with grain size and moisture content. GPR surveys suggest that segregated ground ice content was highest in the upper 5 m of the ground (e.g., Figures 5, 6 and 7). Excluding wedge ice, excess ice content was moderate to high (10 to 60% by volume) in organic deposits, where segregated ice formed lenses and layers or ice crystals. Well bonded nonvisible ice was present as well. Massive ice was present locally in the form of thick segregated ice layers (Figure 8). Moderate to high ice contents (10-50%) were also evident in glaciomarine silt, sand and silty sand, as ice crystals, layers, reticulate structure or veins.

Figure 8. Massive ice present in a core sample.

Ice content was moderate in fluvial sand and silt (15-20%), where ice formed layers, reticulate structure and veins. It commonly ranged from 10 to 20% in silt or sand glaciomarine samples as well (ice crystals, layers and nonvisible ice).

Till samples had a low ice content (5-10%), although few deposits were investigated and refusal was reached before permafrost at one site. More drilling in till deposits is planned to confirm this finding. Low ice contents were also identified in some sandy glaciomarine sediments (5%), and sandy glaciofluvial deposits are expected to be similar.

Glaciomarine deposits generally had higher ice contents in silt and lower ice contents in sand, but many of these deposits contained mixtures of sand and silt with varying ice contents. As a result, geotechnical drilling that preserves frozen soil will be required for design purposes.

3.4 Ground and Air Temperatures

Ground temperature readings were collected in late August, 2021, from three of the ten instrument stations installed in Manitoba; ground temperatures for Nunavut have not yet been collected. Data were recorded every two hours. The preliminary data collected indicates the importance of local snow and vegetation conditions on the duration of active layer freeze back and permafrost temperatures. Even in the most northerly portions of Manitoba, permafrost temperatures were warm (> -2°C), with latent heat dominating heat exchanges at the surface through the winter and temperatures at the top of permafrost staying near zero. Slightly cooler ground conditions were found where a substantial organic layer overlies permafrost, which was associated with frost-susceptible and poorly drained fine-grained deposits. The sustainability of warm permafrost, therefore, is in part controlled by the presence of organic deposits and vegetation cover.

Once a full year of data has been collected, surface offsets (the difference between air and ground surface temperature due to vegetation and snow cover), and thermal offsets (the difference between ground surface and near top of permafrost temperature) can be assessed to support permafrost distribution and sustainability mapping along the corridor. Mitigations to protect permafrost, especially given the ongoing effects of climate change, will be important considerations for design and construction of the KHFL.

3.5 Sensitivity to Disturbance

The sensitivity of permafrost to disturbance depends on a variety of factors, including its temperature, ice content, insulating ground cover (e.g., organics) and substrate texture. Relatively warm permafrost (i.e., warmer than -2˚C) is more susceptible to thaw due to localized and even minor disturbances to the ground surface, whereas cooler permafrost is able to withstand minor disturbances without appreciable effect. Ice-rich permafrost in areas of thick organic cover is more sensitive to ground disturbance (e.g., stripping or compaction of organics). Ice-rich permafrost within fine-grained materials is more likely to contain discrete bodies of ice and, thus, is more sensitive than areas of bedrock or sandy till, for example.

In areas of ice-rich permafrost, even minor ground disturbances may trigger thermokarst activity. When this occurs, the ground subsides or, if on a slope, fails in response to the melting of buried ice bodies. Thermokarst commonly continues for years to decades once initiated, through a positive feedback cycle between increased thaw and water ponding. Along the corridor, thermokarst was expressed as small wet areas in lowlands and as thermokarst ponds that enlarge and coalesce over time. Under warm permafrost conditions, as detected in the Manitoba portion of the corridor, permafrost sustainability is partially controlled by the presence of organic deposits. The vegetation cover yields increased vulnerability to both climatic and anthropogenic disturbance, such as construction activities (e.g., stripping or compaction of organics), fires, and the warming of air temperatures. Poorly drained, frost-susceptible deposits are also likely to have a high excess ice content, implying the possibility of surface collapse, thermokarst, and positive feedbacks to continued permafrost degradation once thaw has initiated.

4 SUMMARY AND CONCLUSIONS

The study was completed for the purposes of informing tower siting, design and construction. Each surficial deposit type has unique features that affect tower constructability and long-term stability. Surficial geology and permafrost features were mapped along a 1,200-km long, 1.2-km wide preferred route corridor at 1:20,000 scale. Additional data collected by employing GPR, shallow borehole drilling and installation of ground temperature sensors were used to improve understanding of permafrost conditions.

Preliminary results indicate that the best substrates for tower construction, apart from bedrock, are till, glaciofluvial, beach ridge and shallow-water glaciomarine sediments, which are all abundant along the route. These deposits are generally sand and gravel-rich, well drained, ice-poor and have thick active layers.

More challenging deposits found along the corridor include deep-water glaciomarine sediments, fine-grained fluvial deposits and organic deposits. These deposits were poorly drained and ice-rich, with widespread polygonal ice-wedge terrain. Active layers were thin and thermokarst activity was common. Areas of patterned ground and thermokarst activity (more common in Nunavut and northern Manitoba) should be avoided or addressed through engineering design to avoid potential instability of the tower foundations. Tower installations should also avoid, or be set back from, colluvial deposits where retrogression could pose a risk to an adjacent tower.

Our work has identified sections of the corridor with permafrost that is vulnerable to thaw, but more work needs to be done to assess the extent and sensitivities of these areas. Monitoring of existing ground temperature sensors and installation of additional sensors is planned for 2022. Addition of semi-permanent temperature sensors that penetrate deeper into the deposits in key terrain units is also planned for the future, but will likely be implemented during the geotechnical engineering phase of the project. Together, these additional data will support modelling of expected changes in permafrost sustainability and design of resilient infrastructure.

5 REFERENCES

Cassidy, N.J. 2009. Chapter 2 - Electrical and Magnetic Properties of Rocks, Soils and Fluids. In *Ground Penetrating Radar Theory and Applications*. H. M. Jol, ed., Elsevier, Amsterdam, 41–72.

de Kemp, E.A., Gilbert, C. and James, D.T. 2006. Geology of Nunavut. Geological Survey of Canada and Canada-Nunavut Geoscience Office, 1: 3,500,000 scale.

Gauthier, M.S., Kelley, S.E. and Hodder, T.J. 2020. Lake Agassiz drainage bracketed Holocene Hudson Bay Ice Saddle collapse. *Earth and Planetary Science Letters* 544: 1-11.

Heginbottom, J.A., Dubreuil, M.A., and Harker, P.T. 1995. Permafrost Map of Canada. *In: The National Atlas of Canada*. Natural Resources Canada, Geomatics Canada, MCR Series No. 4177, (ed. 5), 1995, 1 sheet, scale: 1:7,500,000.

Manitoba Geological Services. 1979. Geology of Manitoba, Map 79-2, 1:1,000,000 scale.

McMartin, I., Godbout, P.-M., Campbell, J. E., Tremblay, T. and Behnia, P. 2020. A new map of glacigenic features and glacial landsystems in central mainland Nunavut, Canada. *Boreas* https://doi.org/10.1111/bor.12479. ISSN 0300-9483.

SNC-Lavalin, 2007. *Nunavut-Manitoba Route Selection Study: Final Report*. Report prepared for the Kivalliq Inuit Association