Geotechnical Investigation at the Long Lake Containment Facility, Ekati Diamond Mine, NT

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ABSTRACT
The Long Lake Containment Facility (LLCF) at the Ekati Diamond Mine (Ekati) is the primary containment area for processed kimberlite generated during diamond ore processing. In the winter of 2013, a geotechnical investigation was completed in the LLCF to investigate the in situ conditions of the processed kimberlite (PK) and to evaluate permafrost growth in the facility. Continuous core samples were obtained with a sonic drill rig. Geotechnical and geochemical testing was completed to characterize the material. Investigation results indicate significant permafrost growth in the LLCF, with unfrozen material encountered at the southern limits of the investigation area where recent processed kimberlite deposition has occurred. Geochemical testing on recovered samples suggest some expulsion of solutes during the freezing process.

This paper provides an overview of the investigation and summarizes the geotechnical and geochemical test results. Comparison with previous investigation results are also made to evaluate historical permafrost growth and material variations within the LLCF.

RÉSUMÉ
L'installation de confinement de Long Lake (LLCF) à la mine de diamants Ekati (Ekati) est la zone de confinement primaire pour entreposer la kimberlite traitée, laquelle est produite pendant le traitement du minerai de diamant. À l'hiver 2013, une étude géotechnique a été réalisée dans le LLCF pour examiner les conditions in situ de la kimberlite traitée (PK) et évaluer la croissance du pergélisol dans l'installation de confinement. Des échantillons de carottes ont été prélevés de façon continue à l'aide d'une foreuse sonique. Des essais géotechniques et géochimiques out été effectués afin de caractériser la nature du matériel. Les résultats de l'étude indiquent une croissance significative du pergélisol dans le LLCF, avec du matériel non gelé rencontré à la limite sud de la zone d'étude, où se trouvent des dépôts de kimberlite traitée récemment déposés. Des études géochimiques sur les échantillons récupérés suggèrent l'expulsion de solutés pendant le processus de congélation.

Ce document présente un aperçu de l'étude et un résumé des résultats des tests géotechniques et géochimiques. Les résultats de l'étude sont aussi comparés aux études précédentes afin d'évaluer l'historique de croissance du pergélisol et les variations du matériel à l'intérieur du LLCF.

1 INTRODUCTION

The Ekati Diamond Mine (Ekati) is located in northern Canada, approximately 300 km northeast of Yellowknife, Northwest Territories (See Figure 1).

Ekati is Canada's first operating diamond mine and began production in 1998. Kimberlite ore is sourced from a combination of open pit and underground mining operations. In total, seven open pits have been developed (Fox, Panda, Koala, Koala North, Beartooth, Misery and Pigeon pits), with subsurface mining occurring below three pits (Panda, Koala and Koala North pits).

Ekati is located in the zone of continuous permafrost. The mean annual air temperature is approximately -10°C, with ground temperatures typically in the order of -3°C to -5°C (BBCI, 2011).

Ekati is located in the Canadian Shield and arctic tundra, approximately 100 km north of the tree line. The local terrain is characterized by boulder fields, tundra, wetlands and numerous lakes with interconnecting streams. There are more than 8,000 lakes within the Ekati claim block (BBCI, 2011).

Figure 1. Location of the Ekati Diamond Mine (modified from Wikimedia.org)

Ore processing consists of grinding, washing, and screening of kimberlite ore to recover diamondiferous material. Processing generates two waste materials: coarse processed kimberlite (CPK), which is hauled and stockpiled adjacent to the waste rock storage area, and fine processed kimberlite (FPK), which is pumped as a slurry to the Long Lake Containment Facility (LLCF) where it is discharged in subaerial beaches.

CPK is a relatively uniform material with a particle size ranging from 0.5 to 1.2 mm. The FPK particle size ranges from clay size to fine sand, with a maximum particle size of 0.5 mm (BHP, 2012). The FPK is pumped with an approximate solids content of 40 percent and exhibits segregating behaviour during deposition, with coarser material settling on the high beach slopes and finer material being carried down gradient.

The closure design for the LLCF includes a combination of rock and vegetative cover (BBCI, 2011). Permafrost is expected to aggrade into the deposited processed kimberlite, thereby providing a stable surface for cover construction.

A site investigation was undertaken in 2013 to sample the FPK in the LLCF and characterize the properties of FPK pore water. Boreholes were advanced into old and new FPK deposition areas as well as in locations where investigations were previously undertaken. Ground temperature cables were installed to monitor the freeze back and temperature conditions during closure.

Specific objectives of the investigation included:

- Investigating in-situ soil conditions in the processed kimberlite and foundation soils;
- Evaluating variation in processed kimberlite properties derived from different kimberlite sources. Previous investigations were limited to processed kimberlite sourced primarily from the Panda and Koala pits;
- Collection of in-situ porewater samples;
- Installation of instrumentation to monitor freeze back of the processed kimberlite; and
- Evaluating the surface foundation conditions for use in the LLCF cover design.

This paper focuses on the investigation results from the northern most cell of the LLCF (Cell B) where FPK deposition is complete.

2 KIMBERLITE PROPERTIES

Kimberlite material properties at Ekati vary with the source pit. Accordingly, FPK generated from different ore bodies exhibits different properties, consistent with the parent ore body. Of particularly interest are differences in the Panda/Koala and Fox kimberlites, as these form the bulk of the material deposited into Cell B, and are believed to most influence the in situ properties and material behaviour.

An FPK characterization study completed prior to mine development (EBA 1998) noted the Fox kimberlites have a higher portion of clay minerals when compare to Panda/Koala kimberlites. For both sources a significant portion of the clay minerals were noted to be smectitic in nature with Fox kimberlite containing a larger proportion of smectite.

Fox FPK were noted to exhibit frost heave behaviour whereas similar behaviour was not noted for Panda/Koala kimberlites. Fox FPK were also noted to have a higher proportion of unfrozen water content, and a larger thaw strain.

3 LLCF HISTORY AND DEVELOPMENT

3.1 LLCF Configuration

LLCF Development began in 1998, concurrent with commencement of mining operations. The LLCF is located in a series of former lake basins to the west of the Ekati process plant and main camp area as shown in Figure 2.

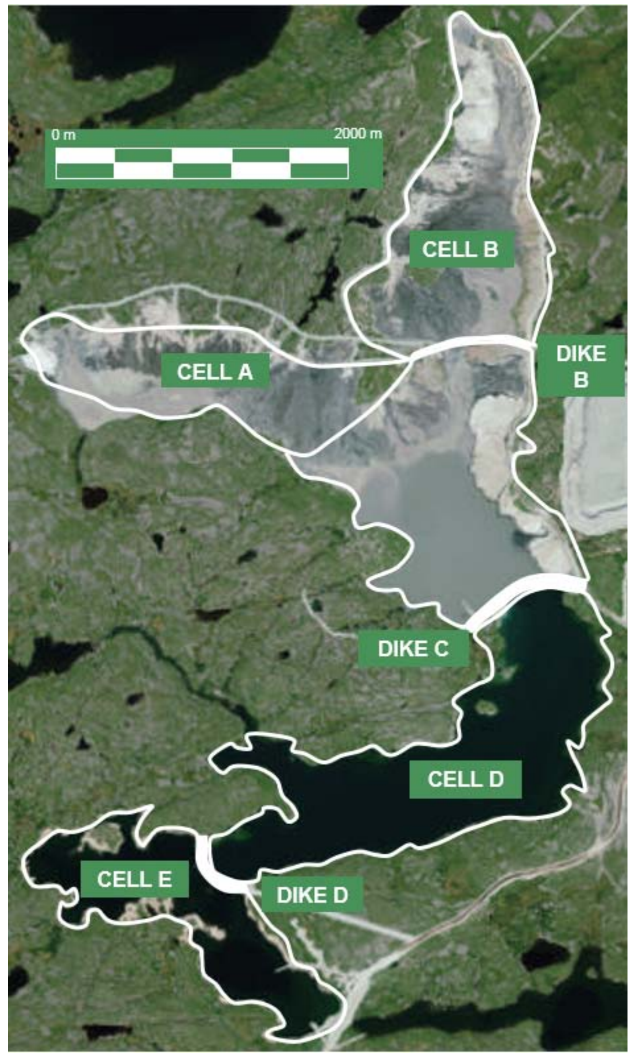

Figure 2. LLCF Overview

The LLCF is divided into five cells (referred to as Cells A, B, C, D and E) by three semi-pervious filtration dikes. FPK is presently deposited in the three northernmost cells (Cells A, B, and C) with Cells D and E serving as finishing and polishing ponds. The LLCF is bounded at its southern limits by Outlet Dam, which is an impervious frozen core dam.

The filtration dikes (Dikes B, C, and D) are designed to retain FPK and other suspended solids on the upstream side while allowing water to migrate through. The generalized design of each dike comprises a run-of-mine core supporting an upstream granular filter system.

Several roads have been constructed around the LLCF to access the facility and provide FPK discharge locations. Roads have also been constructed across the dikes.

3.2 Preconstruction Conditions

Prior to LLCF development, taliks are expected to have existed under the lakes in the areas where the water depth was greater than approximately 1.5 m. This water depth corresponds to the typical thickness of ice that formed on the original lakes during the winter (EBA, 2013). Where ice freezes to the lake bottom, heat is extracted from the underlying lakebed allowing permafrost to exist. Figure 3 shows the estimated talik extents within the Cell B perimeter, prior to FPK deposition.

Site investigations within the Cell B footprint were not completed prior to cell deposition; however, previous investigations for LLCF infrastructure and preconstruction aerial photographs suggests the soil stratigraphy consists of glacial till overlying granitic bedrock. Lacustrine deposits may also have been present in lake areas with greater water depths.

3.3 Deposition History

FPK has been discharged to the three northern cells (Cells A, B, and C) with some recent deposition to the abandoned Beartooth Pit.

Discharge within the LLCF has occurred from a number of perimeter spigot points, located on or near the cell perimeter roads. Some deposition has also occurred from jetties pushed out into the cell, in order to increase the cell storage capacity.

Deposition is rotated among spigot points to maximize cell storage and discourage ice lens development during winter placement. Since 2005, when an investigation identified ice lenses through the FPK, winter deposition has been limited to a thickness of 2 m. By maintaining a maximum 2 m thickness, a full summer thaw of the previous winter's deposition is allowed prior to subsequent winter placement.

Cell B deposition has occurred over two periods. Initial deposition in Cell B began from the east side of the cell in 1998, and continued until approximately 2003. Deposition began on the north end of the cell progressing southwards, and established a raised beach with a roughly east-west slope.

During this period, kimberlite ore was sourced from the Panda/Koala Pits, with some Misery ore included when the Misery Pit came on line in 2001. The misery ore accounted for a maximum of 16 percent of the ore blend during this time (EBA, 2013).

Cell B deposition was suspended from 2004 to 2008, while FPK was deposited in Cells A and C. Cell B deposition resumed in 2008 from the west side of the cell. FPK was spigoted in an eastward direction, the deposition covering over a portion of the previously deposited FPK. Figure 4 illustrates the two deposition periods in Cell B.

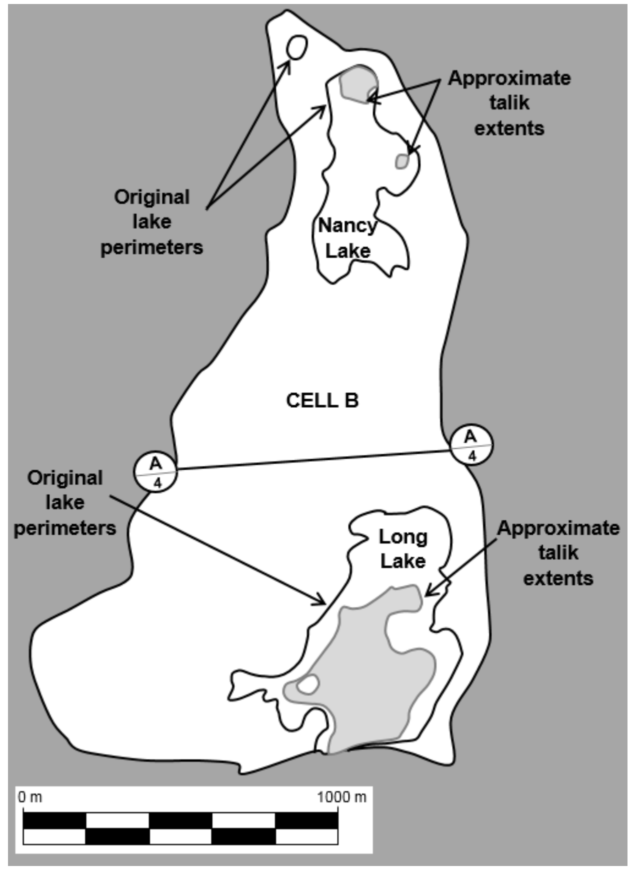

Figure 3. Cell B

The ore blend processed during the second deposition period consisted of a blend of Fox Pit ore, with smaller proportions of Panda, Beartooth, and Koala ore. The ore blend was typically composed of 50 to 60 percent Fox ore (EBA, 2013).

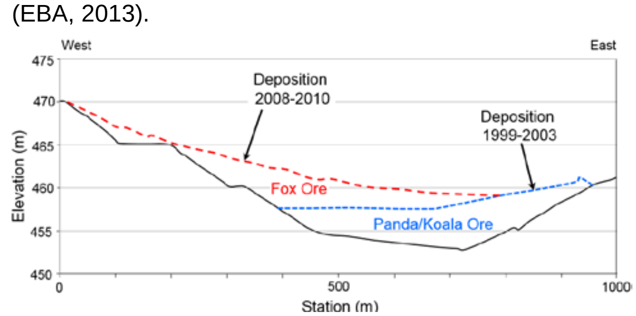

Figure 4. Cell B cross section A-A

4 CLOSURE DESIGN

The LLCF will be closed and reclaimed upon completion of mining activities. The closure design is a combination of rock and vegetation cover intersected by erosion protection along the beach slopes. Ponds will be developed at select locations, while ditches will control the flow of water through and around the LLCF. The Outlet Dam will be breached and weirs constructed in the filtration dikes to control water flow (BHP, 2011).

FPK deposition in the LLCF is expected to shift the permafrost table and talik from its original location. The conceptual permafrost table and talik location expected after mine closure is shown in Figure 5.

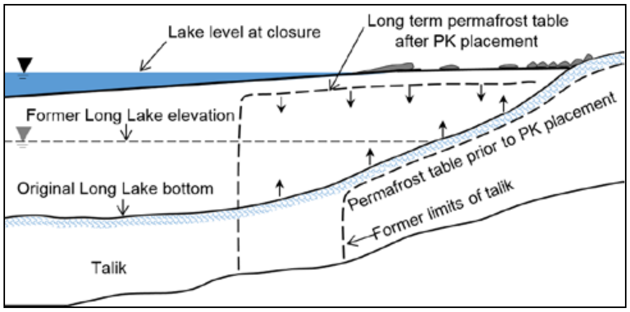

Figure 5. Conceptual Permafrost Development in the LLCF

At closure, a talik will remain in those areas of the LLCF where long-term ponded water depths exceed 1.5 m. Where FPK is deposited over original tundra or where original lake water depths were less than 1.5 m, permafrost aggradation will occur from above and below, whereas in the deeper water zones, where a talik originally existed, permafrost aggradation will occur only from the top downward (EBA, 2013).

The seasonal active layer will act as a conduit for water, conveying water as either surface or shallow groundwater flow. The permafrost will act as a near–impermeable water barrier meaning that surface water will either flow down gradient and pond in topographic lows, or be lost to evaporation / transpiration.

Except in those areas of the LLCF where taliks are expected, permafrost is expected to develop to an approximate thickness of 300 to 400 m, consistent with the natural permafrost regime at Ekati.

5 INVESTIGATION HISTORY

Prior to the 2013 investigation, five investigations were completed in Cell B to evaluate the in situ properties of the deposited FPK. Previous investigations are summarized in Table 1. All investigations have shown the development of permafrost conditions in the LLCF to some degree.

Table 1. Cell B Investigation History

Investigation Program	No. of Boreholes	Borehole Numbers
1999 (July)	2	99-1,99-2
2001 (March)	5	01-1 to 01-5
	3	01-A, 01-G, 01-J (Rollo, 2003)
2005 (March)	4	05-1 to 05-4, CPT4
2006 (August)	4	06-1 to 06-4

A total of three ground temperature cables (GTC) were installed during these investigations. Two were installed in 2001, and one in 2005. The locations of the boreholes and GTCs are shown on Figure 6.

The 1999 investigation was completed early in Cell B development using a power auger. Two boreholes were advanced 1.4 m and 1.5 m in the north end of Cell B to characterize the FPK. The investigation data provided information on the in-situ properties of the deposited FPK but didn't provide significant insight into permafrost growth in the LLCF.

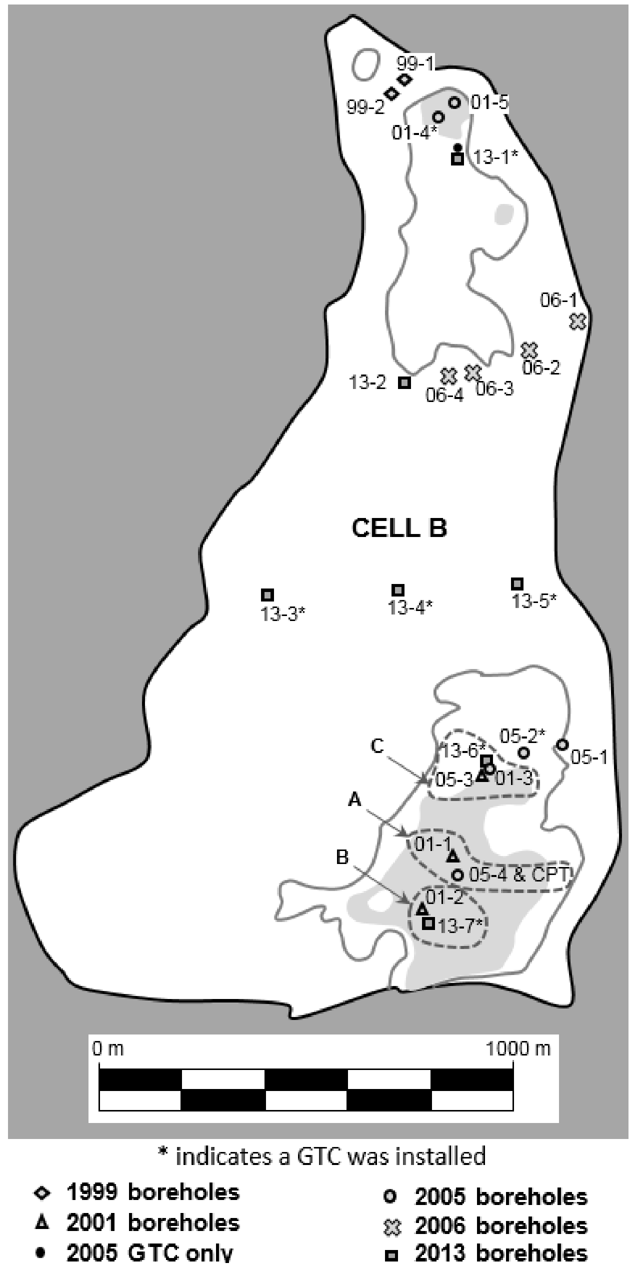

Figure 6. Borehole locations in Cell B of the LLCF

The 2001 and 2005 investigations were completed using a coring drill rig, and boreholes were advanced through the entire FPK column. This enabled the retrieval of continuous undisturbed samples, the identification of frozen and unfrozen zones, and the quantification of permafrost development and ice growth in Cell B. Ground temperature cables were installed to monitor ground temperatures and permafrost growth post investigation. GTC locations are also shown in Figure 6.

The 2001 boreholes were drilled within the Nancy Lake and Long Lake footprints and encountered both frozen and unfrozen materials. The FPK thickness within the Long Lake footprint ranged from 8.3 to 15.0 m. Frozen PK, 4.9 m and 6.0 m thick, was encountered in the two boreholes where FPK was found at the surface (01-1 and 01-3). Ice lenses 6 mm to 400 mm thick were found in the FPK, and two ice layers, 3.8 m and 0.8 m thick, were found in these boreholes. Borehole 01-02 had 4.25 m of water/ice overlying the FPK material and, as expected, none of the underlying PK was frozen.

The FPK thickness ranged from 11.6 m to 12.8 m in the two boreholes drilled within the Nancy Lake footprint. Ice lenses of 5 mm to 50 mm were found in the frozen FPK. Ice lenses occupied approximately 25% of the total volume of FPK. In Borehole 01-04 there was 1.2 m of frozen FPK at the surface which was underlain by 4 m of ice with interbedded FPK lenses. In Borehole 01-05 frozen FPK and ice was encountered to a depth 4.0 m, and from 6.0 m to 6.9 m; the remainder of the borehole was unfrozen.

An additional investigation was completed in 2001 by Queen's University (Rollo, 2003). Monitoring wells were installed at borehole locations in the north end of Cell B so that pore water could be sampled. Rollo's investigation showed permafrost to be aggrading in the LLCF; however, a layer of unfrozen saturated FPK was noted at depth. The rate of permafrost aggradation was not clear due to deposition of FPK on the surface. The solute concentration of water taken from the active layer was greater than the solute concentration of water taken from spigot discharge.

Four boreholes were drilled during the 2005 investigation All drilling was done near or within the perimeter of Long Lake. One borehole (05-04) was drilled within the talik area. The thickness of FPK in the boreholes ranged from 9.2 m to 16.8 m. Outside of the talik area, the FPK was frozen to a depth of 9.0 m to 9.5 m. The area within the talik was frozen to approximately 2 m.

The 2001 and 2005 investigations were completed prior to FPK deposition from the west side of the road. Recovered samples were composed of FPK predominantly from Koala / Panda kimberlites.

In 2006, a geochemical investigation was performed in the northern area of Cell B. FPK samples were collected at four locations along a transect from the outer to the inner edge of the PK beach. Samples were collected via hand sampling and analyzed for pH, redox potential, total metals, density, particle size and water content. Pore water was analyzed for dissolved metals.

6 2013 SITE INVESTIGATION

6.1 Investigation Methodology

The 2013 investigation was designed to characterize FPK in the LLCF, evaluate permafrost growth and characterize the chemical properties of FPK pore water. The investigation was completed in March of 2013, when the cell surface was frozen and could be readily accessed.

Boreholes were drilled using a ML Fraste drill rig with a compact sonic core barrel operated by ConeTec Investigations Ltd. (ConeTec). The rig is a small, track mounted portable rig mounted on an aluminum skid which was outfitted with a tent and heater. The boom of the rig extended above the tent. The drill rods and equipment were contained on the skid and the tent was outfitted with lights for night work. The skid was assembled in a climate controlled building then dragged to site using mobile equipment.

The sonic drill rig was selected for this investigation for several reasons:

- The ground thermal conditions in Cell B were unknown. The drill could accommodate drilling in a variety of ground conditions, including both frozen and unfrozen;
- The drill satisfied sampling requirements for both the geotechnical and geochemical evaluations;
- The drill had a proven track record of sampling low-strength and soft materials; and
- The rig was mobilized to site via winter road but was small enough to ship off site via air freight if required.

Drill locations and access paths were cleared of snow to allow truck and equipment access. Drill locations were equipped with light plants to allow for safe working conditions with limited available daylight.

Seven sampling locations were selected around Cell B (BH13-1 to BH13-7). The locations were chosen due to proximity to previous boreholes and to sample different locations around the cell. The purpose for each borehole is summarized in Table 2. Borehole locations are shown on Figure 6.

Two holes were drilled at each location: one borehole for geotechnical sampling and core logging and a second hole was advanced a few metres away to obtain representative samples for geochemical testing by ERM.

Table 2. Borehole Locations

Borehole	Borehole Purpose
13-1, 13-2	Located in the oldest FPK deposit in north end of Cell B. Located near former lake perimeter
13-3, 13-4, 13-5	Located on transect through Cell B, includes materials from both deposition periods
13-6	Located near 2001 and 2005 investigations, Borehole intended to evaluate any changes since previous investigations
13-7	Located in suspected talik. Near 2001 borehole 01-2. Located in most recently deposited material

6.2 Sampling and Testing

The sonic drill was selected because of its ability to sample in both frozen and unfrozen conditions; however, considerably less unfrozen processed kimberlite was encountered than anticipated. In general, geotechnical sampling was performed with a modified sonic core barrel. Cutting teeth were attached to the shoe which would cut frozen materials when rotated. The bit was advanced by rotating the core barrel without vibration through frozen material which was then captured within the piston sampler. This method of sampling had a high rate of sample recovery. Very little sampling was done with the sonic drilling method.

The drill program used a stainless steel modified sonic coring device, to obtain FPK core samples at various depths for pore water extraction. An adapter was attached to the piston sampler to allow the cores to be extruded into 24" PVC tubes without handling the sample, thereby minimizing environmental exposure.

A four inch CRREL barrel was used to retrieve surface samples at two locations. The CRREL samples were only recovered from depths of 4 m or less.

A static CPT was carried out at the borehole advanced in the talik area of Long Lake, near the south end of Cell B (BH 13-7).

Recovered samples were tested for water content, excess ice content, bulk density, specific gravity and particle size. X-ray diffraction was performed on select samples. ERM extracted pore water throughout the samples for geochemical testing.

Sample intervals were selected based on the location and distribution of ice lenses and FPK. Where possible, samples were collected in discrete areas of ice, and materials above and below the ice, to observe potential variations in pore water and ice chemistry. Samples collected from the LLCF contained ice lenses, frozen FPK, and unfrozen FPK.

6.3 Investigation Results

Boreholes were advanced through the FPK and into underlying foundation soils. The investigation showed that permafrost had largely aggraded into the central and northern portion of the cell. The CPT was only possible in the southernmost borehole where significant unfrozen PK was observed.

The five northern boreholes (13-1 to 13-5) were generally frozen through the entire processed kimberlite column and into the foundation soils. In Borehole 13-05 two unfrozen layers were encountered: the first 0.7 m thick at a depth of 1.9 m, and the second 0.2 m thick at a depth of 5.7 m. In Borehole 13-6, frozen conditions were encountered through most of the processed kimberlite, with the exception of an unfrozen zone from 5.7 to 6.4 m. The southernmost borehole (13-7) had 3.4 m of frozen material at the surface and was underlain by unfrozen material extending to the end of hole at 13.9 m below ground surface. The generalized investigation findings are summarized in Table 3.

Table 3. 2013 Investigation Results

BH	Depth (m)	FPK Thickness	Unfrozen FPK (m)	Massive Ice within FPK (m)
13-1	7.40	7.40	None	2.10-2.45 2.90-3.25
13-2	6.55	6.40	None	3.80-4.54 4.80-5.30
13-3	4.22	3.70	None	3.20-3.60
13-4	11.05	9.40	None	7.70-9.05
13-5	7.90	7.80	1.90-2.65 5.65-5.85	7.40-7.80
13-6	13.05	14.00	5.65-6.35	2.80-3.22
13-7	23.55	13.90	3.40-13.90	None

The processed kimberlite consisted of layered sand and clay, consistent with previous investigations. The layers of kimberlite had either: visible ice, ice lenses or massive ice. The frozen bulk density ranged from 955 kg/m^3 to 1962 kg/m^3. Massive ice layers in the FPK was seen in two boreholes.

Ground temperature cables were installed in all but Borehole 13-2, to monitor ground temperatures in Cell B.

7 DISCUSSION

Permafrost is developing in the LLCF. Data from previous investigations show an increase in the amount of frozen material over time. Prior to its burial in approximately 2008, data from a 2001 GTC (BH 01-04) showed permafrost aggrading at a rate of 0.55 to 0.58 m/year over a 5 year period.

The current investigation shows permafrost has developed through the entire northern half of Cell B, with unfrozen material remaining in the southern portion of the cell, around Borehole 13-7. This area corresponds to the former Long Lake footprint and is the location where all surface water from the cell ponds and collects prior to flowing southwards through Dike B. It also overlies a suspected pre-construction talik.

There are three areas in Cell B where overlapping investigations have been completed, allowing for changes in the Cell B conditions to be evaluated over time.

All three locations are located within the former Long Lake footprint: two within the expected talik (Area A and B), and one on the talik perimeter (Area C). These locations are marked on Figure 6.

In area A, a borehole was drilled in 2001 (01-1) and nearby a borehole was logged in 2005 (05-4). Between 2001 and 2005, the surface of the PK increased almost 3 m from active deposition in the cell. No permafrost was seen growing within the PK. This is expected to be a function of ongoing deposition between investigations, and the area's locations with the talik zone. In area B, a 2013 borehole (13-7) was advanced a 2001 borehole (01-2). The surface of the PK was raised almost 4 m between investigations. The ponded water observed in 2001 has been replaced by FPK; however, apart from the seasonally frozen active layer observed in Borehole 13-7, permafrost aggradation was not observed within the 14 m of PK deposition.

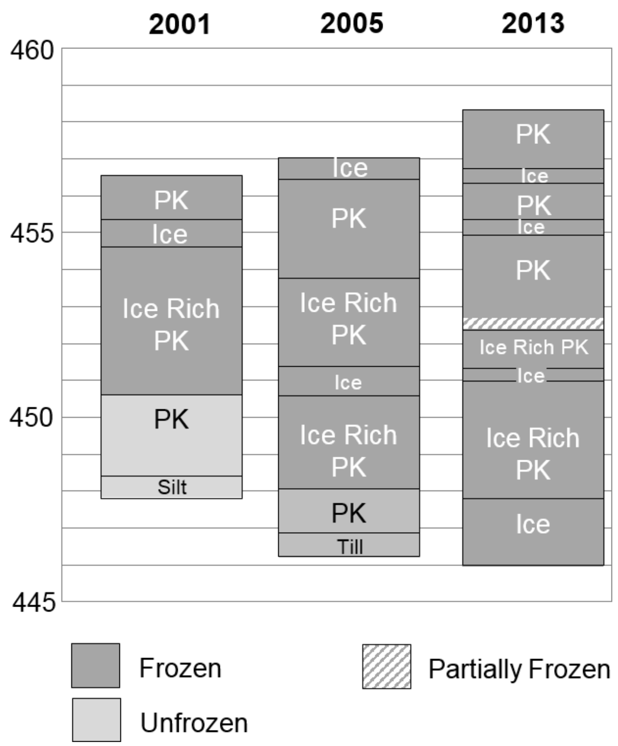

Figure 7. Borehole profiles in area C

Three boreholes have been drilled in location C. One was drilled in 2001 (01-3), one in 2005 (05-3) and one in 2013 (13-6). The generalized soil profile for the three boreholes is shown in Figure 7. An increase in the FPK elevation over time was seen in this area. The FPK elevation increased by 0.5 m in 2005 and almost 3.5 m in 2013. In 2001, no permafrost was seen in the 8.3 m of FPK. In 2005, frozen conditions had progressed a depth of 9.0 m below the surface. This permafrost growth corresponded to a period of minimal deposition in the area. The 2005 borehole terminated in unfrozen material.

In 2013, permafrost extended to approximately 13.1 m below ground surface, with the exception of a thin unfrozen zone (0.6 m) at 5.7 m. From 2005 to 2013, the surface elevation of the PK increased approximately 3 m. The unfrozen material is thought to be a function of heat transference during subsequent deposition. The 2013 borehole was terminated due to refusal and the temperature condition of the material beyond the end of this borehole was not known.

No readings in Borehole 13-7 have been made since the cables installation. The borehole's location in low lying wet terrain has made it difficult to monitor permafrost growth since cable installation; however, efforts are being made to read the cable over the winter to see how permafrost has aggraded in the area.

After the 2005 investigation, the ice lenses forming in Cell B were extensive. As a means of limiting captured ice Ekati implemented a strategy of sequential spigot discharge. The borehole records from 2005 and 2013 were examined to compare FPK ice content between 448.1 m to 453.9 m in area C. In 2005, there was massive ice at 452.1 m to 452.9 m and the excess ice content was estimated to be 75%. In 2013, the massive ice at 452.1 m remained; however, the overall excess ice content from 448.1 m to 453.9 m was approximately 40%.

Geochemical testing performed by ERM during the 2013 investigation suggests that solute expulsion is occurring during formation of the ice in the LLCF (EBA and ERM, 2014). Pore water from unfrozen FPK showed higher concentrations of some solutes (Br^-, Cl^-, NO_3, SO_4^{2}, Ca, Mg, Ni, and Sr) than in the adjacent frozen FPK material. Solute-rejection can lead to the freezing of clean water in the pores first and may, when coupled with porewater expulsion, cause either migration of solutes out of the freezing FPK or an increase in porewater pressures.

Elevated porewater pressures can also lead to ice-rich permafrost and terrain instability. The 2013 site investigation completed a CPT in one location (Borehole 13-7). Elevated porewater pressures were not observed in the unfrozen material, which is consistent with pore water dissipation testing performed with a CPT in the adjacent Cell C in 2010.

Terrain stability can be affected by both the development and melting of ground ice. Common types of ground ice that could affect the LLCF FPK include segregated ice, wedge ice, pingos, and captured ice. Previous observations have identified the formation of wedge ice in the north end of Cell B. What was thought to be captured ice was identified in the 2005 site investigation. Geotechnical drilling and sampling has also identified the presence of segregated ice in the form of thin lenses. Due to winter deposition of FPK in Cell B and Cell C there is the potential for instability as a result of captured ice.

Terrain instability has been seen in the vegetation test area in Cell B. The instability, in the form of heave, emphasizes the need for a closure plan to accommodate site conditions. Cover strategies such as local vegetation and various types of rock cover are flexible and self-healing to allow for frost heave or settlement that may occur within the LLCF after closure.

ACKNOWLEDGEMENTS

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