# Some Permafrost-Related Terrain Features and Associated Design Considerations along the Proposed Southern Rail Alignment, Mary River Project, Baffin Island, Nunavut



Vladislav E. Roujanski & Kevin W. Jones EBA Engineering Consultants Ltd., Edmonton, Alberta, Canada James Haley & Kevin Hawton Knight Piésold Ltd., Vancouver, British Columbia and North Bay, Ontario, Canada Carolyn Fitzpatrick Canarail Consultants Inc., Montreal, Quebec, Canada

# ABSTRACT

A railway is proposed to connect the Mary River Iron Ore Mine, located in the central northern portion of Baffin Island, to a proposed port facility at Steensby Inlet, approximately 145 km to the south. As a part of the feasibility study, aerial photography interpretation (API) was undertaken in the vicinity of the railway corridor, along with terrain mapping at a scale of 1:30,000. The findings of the API were substantiated by the analysis of geotechnical borehole logs, helicopter-supported route reconnaissance and the results of geophysical surveys conducted along the rail alignment. A variety of permafrost-related features were identified in the study area, including the near-surface occurrence of massive ground ice bodies, in addition to a variety of surficial features, including polygonal patterned ground, thermokarst, thermal erosion features and several types of mass movement. These features present challenges to the construction and long-term operation of the railway in terms of differential settlement of the embankments, slope instability and erosion. Possible adverse effects of these features are to be mitigated through innovative embankment designs and foundation treatments, thus reducing their potential impacts on the railway.

# RÉSUMÉ

Une voie ferrée est proposée pour lier le site minier de Mary River Iron Ore, situé dans la partie centre-nord de l'île de Baffin, à une nouvelle installation portuaire proposée dans la baie de Steensby, à environ 145 km au sud. Dans le cadre de l'étude de faisabilité, l'interprétation de photographies aériennes (IPA) a été entreprise dans les environs du corridor ferroviaire, ainsi qu'une cartographie du terrain à l'échelle 1:30,000. Les conclusions de l'IPA ont été confirmées par l'analyse des coupes de sondage géotechnique carotté, une reconnaissance d'itinéraire par hélicoptère, et les résultats de relevés géophysiques effectués le long de la voie ferrée. Une variété de caractéristiques liées au pergélisol a été identifiée dans la zone d'étude, y compris la présence de corps de glace souterrain massif près de la surface, de plus une variété de caractéristiques de surface a été identifiée y compris une structure de sol en forme de polygone, des thermokarsts, des éléments d'érosion thermique et plusieurs types de mouvement de masse. Ces caractéristiques liées au pergélisol présentent un défi pour la construction et la maintenance sur le long terme d'une voie ferrée en termes de tassements différentiels du remblai, l'instabilité des pentes et l'érosion. Les éventuels effets indésirables de ces caractéristiques doivent être mitigés par des concepts innovateurs de remblai et de traitements des fondations, pour réduire leur impact potentiel sur la voie ferrée.

# 1 INTRODUCTION

The Mary River iron mine site is located at approximately 71°33'N and 79°38'W in the central northern portion of Baffin Island, Nunavut. A railway is proposed to connect the mine site to a new port facility located at Steensby Inlet, on the south coast (Figure 1). The proposed rail alignment, hereafter referred to as the Southern Rail Alignment (SRA), is approximately 145 km long.

Baffinland Iron Mines Corp (BIMC) retained Canarail Consultants Inc. (Canarail), Knight Piésold Ltd. (KP) and EBA Engineering Consultants Ltd. (EBA) to complete a feasibility study of the railway construction. The study included mapping permafrost-related terrain features along the SRA; geophysical and geotechnical investigations of the SRA, including soil and rock sampling and testing; and a preliminary helicopter-supported reconnaissance along the SRA.

This paper discusses some of the permafrost-related terrain features that were identified along the SRA and the associated risks to the proposed railway, as well as the embankment design approaches that are intended to mitigate the potential impact of permafrost on the railway during its operation. The chainage references in the paper start at zero at the mine site and increase going south towards the port site.



Figure 1. Mary River Southern Rail Alignment site location map.

Note: Background imagery and map provided courtesy of Google Earth and Google Map and are for presentation purposes only.

# 2 STUDY METHODS

## 2.1 Aerial Photography Interpretation

The air photos studied comprised black and white contact prints, taken along the SRA at a scale of 1:30,000. The stereo pairs were examined with a stereoscope. The mapping carried out by KP and EBA incorporated the delineation of terrain units and permafrost-related geomorphic features in the vicinity of the rail alignment, and was carried out a scale of 1:30,000. The base maps used for the mapping included the 0.5 m contours from the LiDAR survey and the orthorectified imagery, taken as part of the LiDAR Survey. The terrain maps were prepared using the *ArcView* GIS software program. Figure 2 shows a sample of the SRA air photo interpretation terrain map.

#### 2.2 Geophysical Investigation

The geophysical investigation of the SRA was carried out by EBA between April 14 and May 2, 2008. Two complementary geophysical survey systems (Ground Penetrating Radar (GPR) and a Geometrics TR5 OhmMapper Resistivity System) were used in the field to allow imaging of the boundary between overburden and bedrock as well as shallow soil lithology at a high resolution, with an emphasis on identifying areas of icerich soil and discrete bodies of massive ground ice (EBA, 2008).

#### 2.3 Geotechnical Investigations

Geotechnical investigations were conducted by KP in 2006, 2007 and 2008 to evaluate soil, bedrock and permafrost conditions along the SRA. These investigations included an extensive soil and bedrock coring program using diamond drills and test pitting.

A total of 75 geotechnical boreholes were completed along the SRA in 2007 (KP, 2007) and 315 borings in 2008 (KP, 2008). The core recovered from each hole was logged and photographed. The logging consisted of general engineering descriptions, as well as descriptions of the frozen soil characteristics such as bonding state and ice content by volume, in accordance with ASTM (KP, 2007). Thermistor cables were installed in select drill holes to collect ground temperature data associated with various locations and soil types.

## 2.4 Helicopter-Supported Reconnaissance

Preliminary helicopter-supported reconnaissance was carried out along the SRA by a project team from September 13 to September 15, 2008. The objective of the reconnaissance was to ground-truth some of the permafrost-related features identified during the air photo interpretation study.

## 3 PHYSIOGRAPHIC SETTING

## 3.1 Climate

A long-term climatic record is not available for the Mary River mine site and the SRA corridor. Meteorological stations were established at Mary River in the summer of 2005 and at Steensby Inlet in the summer of 2006. Reference is therefore made to long-term regional climatic data from the nearest community of Mittimatalik (formerly Pond Inlet), sourced from Environment Canada (2004).

The yearly average temperature at Mittimatalik is -15.1°C. The warmest month is July with a daily average temperature of 6°C and an average daily maximum temperature of 9.2°C. The coldest month is February with an average daily temperature of -30.6°C and an average daily minimum temperature of -37.5°C. Frost-free conditions last from late June to late August though snow may occur at any time throughout the year. The mean annual precipitation at Mittimatalik is 190.8 mm of snowfall (equivalent to 105.4 mm of rainfall) and 85.4 mm of rainfall (Environment Canada, 2004).

3.2 Geology

## 3.2.1 Bedrock Geology

According to the bedrock geology map (NRC, 2006), the northern part of the proposed SRA follows the toe of a fault escarpment as far as approximately km 25. On the north side of the fault, Archean gneisses are intruded by massive and foliated granites. On the south side, the bedrock is mapped as dolomites and sandstones. Further south along the SRA, the bedrock consists of gneiss as far as approximately km 48 followed by predominantly metasedimentary rocks of the Mary River Group to km 62. South of km 62, the bedrock is mapped as migmatite intruded by foliated granodiorite and locally by massive granite.



Figure 2. Air photo interpretation terrain map of the SRA (km 33.5 to km 36.5).

#### 3.2.2 Surficial Geology and Permafrost

The surficial geology along the SRA is quite variable with the materials encountered consisting of organic soils, alluvium, colluvium, marine and glacio-marine deltaic sediments, glaciofluvial deposits, glaciolacustrine and lacustrine deposits, glacial deposits and highly fractured to competent bedrock outcrops.

The SRA corridor lies within the zone of continuous permafrost, which is likely more than 500 m thick in the central portion of the project area. The thickness of the active layer varies from less than 0.3 m in organic soils to just over 2.0 m in coarse-grained soils and bedrock outcrops. The preliminary ground temperature data indicates that permafrost temperatures below the depth of zero annual amplitude (typically 9 to 14 m below ground surface) range from -8 °C to -10.5 °C (KP, 2007).

## 4 PERMAFROST-RELATED TERRAIN FEATURES ALONG SOUTHERN RAIL ALIGNMENT

#### 4.1 Ground Ice

Ground ice refers to all types of ice formed in permafrost. It occurs in pores, cavities, voids and other openings in frozen soil and rock and includes 'massive ground ice'. 'Massive ground ice' is a comprehensive term, used to describe large masses of ground ice, including ice wedges, buried ice and predominantly horizontal beds of segregated ice (Glossary of Permafrost, 1988). In this paper, predominantly horizontal beds of ground ice penetrated by borings along the SRA are referred to as 'massive ice' if their thickness exceeds 0.3 m; whereas, layers of ice less than 0.3 m in thickness are termed 'ice lenses'.

The amount of ice in frozen ground determines its physical and mechanical properties. Permafrost with little or no ice generally does not cause engineering problems, but permafrost that is ice-rich can cause serious problems if allowed to thaw (Ferrians & Hobson, 1973).

Permafrost along the SRA was generally found to be ice-rich, with the amounts of ground ice in perennially frozen soils varying greatly from place to place (KP, 2007, 2008; EBA, 2008). Some of the massive ice types were readily identifiable on the air photos, for example areas underlain by ice wedges, which were interpreted by the presence of a prominent polygonal pattern on the ground surface (Figure 3).

The API and helicopter-supported reconnaissance along the SRA showed that approximately 22.1 km (15%) of the proposed 145-km long rail alignment is characterized by well-defined polygonal ground that may contain large accumulations of massive ground ice in the form of ice wedges. However, some of the wedge-shaped features that formed in thermal contraction cracks in the polygonal ground terrain may be composed of sand or may be of a composite nature with variable ice and soil contents, especially within the glaciofluvial sandy soils.



Figure 3. Hummocky polygonal patterned ground, km 37 to km 37.5 of the SRA.

Other types of the massive ground ice, such as massive ice beds are not revealed by any characteristic surface relief and could not be directly identified on the air photos. Their near-surface presence along the SRA was interpreted by indirect indicators, such as small ovalshaped thaw lakes and isolated drained depressions resulting from the melting of discrete bodies of massive ice (Figures 4a,b).



Figure 4a. Oblique photo of an oval-shaped thaw lake indicative of the near-surface presence of discrete bodies of massive ice in glaciofluvial deposits, km 7.5 to km 8.0 of the SRA.



Figure 4b. An oval-shaped thaw lake indicative of the near-surface presence of discrete bodies of massive ground ice in glaciofluvial deposits, km 7.5 to km 8.0 of the SRA: a fragment of the air photo interpretation terrain map of the area.

The inferred presence of discrete bodies of massive ground ice in permafrost along the SRA from the API and the geophysical surveys (EBA, 2008) was confirmed in 46 boreholes drilled along the SRA in 2007 and 2008. Figure 5 shows the inferred presence of discrete bodies of the massive ground ice, which were interpreted between km 34.0 and km 34.5 of the SRA from a GPR survey and confirmed by geotechnical drilling.

The air photo interpretation and analysis of the GPR and borehole data showed that approximately 52.4 km (36%) of the proposed 145 km long rail alignment, mostly in its northern and central portions is underlain by ice-rich soil that contains discrete bodies of the massive ground ice.

The thickness of the massive ice bodies, which were encountered in the boreholes in the upper 10 m of the ground, ranged from less than 1 m to more than 17.3 m. The tops of the massive ice bodies were encountered at depths ranging from at or just below the ground surface to more than 10 m below the ground surface.

Figure 6 shows that gravelly and sandy soils predominate both above (65%) and below (57%) massive ice beds encountered in the boreholes drilled along the SRA. According to Mackay (1973a,b), the widespread occurrence of massive icy beds above sands and gravels in the western Canadian Arctic suggests that these sediments played a major role in facilitating the localization and growth of the ice. They have been the normal groundwater aquifers along which water has moved in large quantities to feed the growing ice bodies. Freezing of sands and gravels in adjacent areas may have supplied some excess water, by means of water expulsion, for the growth of the ice. This mechanism looks plausible for the formation of some of the massive ice bodies encountered along the SRA, suggesting they had a segregated or intrusive origin. However, the presence of bedrock beneath massive ground ice in 10 of the 46 boreholes, which penetrated massive ground ice, suggests that some of the massive ground ice bodies along the SRA have a buried origin, i.e. they comprise buried glacial ice.

#### 4.2 Mass Movement

Mass movement (mass wasting) is the down slope movement of soil or rock on or near the ground surface under the influence of gravity. In permafrost regions, such as the Mary River site, this process is influenced by annual cycles of thawing and freezing, the relative amount of ice present in the upper portion of the permafrost and by the presence of a relatively thin iceenriched layer, usually present at the permafrost table (i.e. at the base of the active layer).



Figure 5. Ground Penetrating Radar profile with discrete bodies of the massive ground ice interpreted between km 34.0 and 34.5 of the SRA. Note a massive ice bed 17.3 m thick encountered in Borehole BH2007-13 at a depth of 4.5 m below the ground surface.





Figure 6. The materials above and below the massive ice beds that were encountered in the boreholes drilled by KP along the SRA in 2007 and 2008.

On the terrain maps (Figures 2, 4b), landslides were characterized by two distinct classes: flows and slides, after J.M. Aylsworth et al. (2000). These two classes have different mechanisms of failure that are reflected in their morphology: flows have a fluid character, showing evidence of mobility throughout the failure; whereas slides show evidence of rigid movement.

Mass movements along the SRA that were identified with the API and observed during the helicoptersupported reconnaissance ranged from slow displacements, such as solifluction features, to fast detachments, such as debris flows. Flows along the SRA include active layer detachments (skin flows), largeand small-scale recent retrogressive thaw flows and debris flows. Slides along the SRA include rotational and translational slides, and areas of possible deep-seated instability associated with near-surface occurrence of massive ground ice. One of the most recent slides along the SRA was observed on August 27, 2008 at Km 116+200 (Figure 7).

#### 4.3 Thermokarst and Thermal Erosion

The melting of discrete bodies of massive ground ice and thawing of ice-rich permafrost result in conspicuous irregular surface relief comprising isolated depressions and mounds, known as thermokarst terrain. Thermokarst features along the SRA were identified along those sections, which were found to be ice-rich and contain massive ground ice or were underlain by ice-rich organic soils.



Figure 7. Recent slide observed at km 116.2 of the SRA

Thermal erosion, a dynamic process involving the wearing away of the frozen ground by thermal means (the melting of ice) and by mechanical means (hydraulic transport), has been found to be especially prevalent on the slopes composed of glaciofluvial deposits in the northern portion of the alignment corridor.

## 5 RAILWAY EMBANKMENT DESIGN CONSIDERATIONS

The long term performance of embankments constructed in permafrost regions is subject to potential problems related to the permafrost features discussed above. These potential problems relating to embankment performance are most commonly associated with the presence of massive ground ice, and occur in the form of thaw and/or creep settlements and displacements. Although dominated by ice-rich soils, the permafrost documented along the SRA is generally quite cold with low salinity. While these factors are desirable, the potential for thermal degradation and settlement problems remain. Other environmental problems related to thermal degradation such as erosion, siltation and the formation of unwanted surface water (thermokarst) may Mitigation through the application of also occur. standard embankment design and construction guidelines typical of permafrost regions has been adopted for the Mary River Project rail embankments. A number of these considerations are summarized below;

- Excavations have been minimized, especially in areas of known ice-rich permafrost.
- Prior to embankment construction, ground disturbance will be minimized and vegetative or organic cover left in place to provide the maximum protection of the thermal regime.
- A thermal barrier consisting of a minimum 1.5 m of suitable fill will be placed over the

natural ground surface to cause the permafrost table to aggrade upwards to the base of the fill. In areas where excavation is required, the foundations will be over excavated and back filled with 2 m of thaw stable fill.

- Cut slopes into ice-rich or thaw sensitive materials will be established at a minimum 3H:1V and protected with erosion and thermal protection material as required.
- At localized areas, protection of the underlying permafrost by more elaborate means, (other than a protective embankment) is being considered. These methods may consist of artificial cooling of the foundation through the use, of insulation, graded fills (convective cooling embankment), ducts and thermosyphons, alone or in combination.
- In particularly thaw sensitive areas, the embankment crest may be widened and flatter side slopes used to minimize the effect of permafrost degradation at the toes of the embankments.
- For high embankment fills on ice-rich materials that could be prone to creep displacement, the side slopes may be flattened significantly or buttresses constructed.
- Construction in ice-rich areas would be completed during the winter months to the maximum extent possible.
- For summer construction, woven geotextile may be required over thaw unstable ground.
- Proper runoff collection and diversions systems would be established to control runoff and erosion from affecting the modified thermal regime. Ditching near the toe of the embankments is discouraged due to the influence of the thermal regime leading to localized settlements and ponding of water against the embankment.

Other than considering geometry and costs, the rail alignment has been selected and optimized based on various siting studies and alternate assessments using information on the permafrost conditions collected during the site investigation. The preferred alignment has been selected to reduce the potential risk for construction or long-term problems and in consideration of the ease with which mitigation of these potential problems can be achieved. Further refinement may occur as the project advances.

# ACKNOWLEDGMENTS

This paper is published with the approval of the Baffinland Iron Mines Corp.

The authors wish to thank James Newby of KP for preparing air photo interpretation terrain maps of the SRA, Patrick Finlay of EBA for selecting and interpreting a GPR profile, Jennifer Pyliuk of EBA for assisting with the analysis of numerous borehole logs, and Boris Fichot of KP for translating the abstract into French. REFERENCES

- Aylsworth, J.M., Duk-Rodkin, A., Robertson, T., and Traynor, J.A., 2000. Landslides of the Mackenzie Valley and Adjacent Mountainous and Coastal Regions. *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line For Assessment of Environment Change*. Edited by Dyke, L.D. and Brooks, G.R., GSC Bulletin 547, pp. 167-176.
- EBA Engineering Consultants Ltd., 2008. Geophysical Site Investigation – April 2008 Mine, Rail Alignment and Port Facility Areas, Mary River, NU. Submitted to Baffinland Iron Mines Corporation. File No.: E11101026, October 2008.
- Environment Canada, 2004. Climate Normals (1971 2000). Pond Inlet, 25 Feb. 2004.
- Ferrians, O. J. Jr., and Hobson, G.D., 1973. Mapping and Predicting Permafrost in North America: A Review, 1963-1973. In North American Contrib., Proc. 2<sup>nd</sup> Int. Conf. on Permafrost, Yakutsk, USSR. Washington, D.C.: National Academy of Sciences, pp. 479-498.
- Glossary of Permafrost and Related Ground-Ice Terms, 1988. NRCC, Technical Memorandum No. 142, 156 pp.
- Knight Piésold, November 2008. 2008 Rail Alignment Site Investigation Program Results, Memorandum, 780 pp.
- Knight Piésold, June 2008. Air Photo Interpretation Southern Rail Alignment (Figures 1 to 47). Submitted to Baffinland Iron Mines Corporation.
- Knight Piésold, February 2008. Steensby Inlet Port Site 2007 Site Investigation Summary Report (Ref. No. NB102-00181/8-1). Submitted to Baffinland Iron Mines Corporation.
- Knight Piésold, February 2008. Mine Site Infrastructure, Pit Overburden and Waste Dumps 2007 Site Investigations and Foundation Recommendations Summary Report (Ref. No. NB102-00181/8-2). Submitted to Baffinland Iron Mines Corporation.
- Knight Piésold, December 2007. Rail Infrastructure 2007 Site Investigation Summary Report (Ref. No. NB102-00181/8-3). Submitted to Baffinland Iron Mines Corporation.
- Mackay, J. R., and Black, R. F., 1973. Origin, Composition, and Structure of Perennially Frozen Ground and Ground Ice: A Review In North American Contrib., Proc. 2<sup>nd</sup> Int. Conf. on Permafrost, Yakutsk, USSR. Washington, D.C.: National Academy of Sciences, pp. 185-192.
- Mackay, J. R. 1973. Problems in the Origin of Massive Ice Beds, Western Arctic, Canada. In North American Contrib., Proc. 2<sup>nd</sup> Int. Conf. on Permafrost, Yakutsk, USSR. Washington, D.C.: National Academy of Sciences, pp. 223-228.