

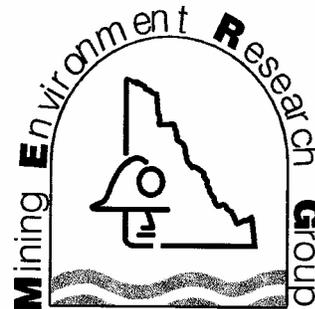
MERG Report 2004-1

# **Permafrost Considerations for Effective Mine Site Development In the Yukon Territory**

By Eba Engineering Consultants Ltd.

March 2004

MERG is a cooperative working group made up of the Federal and Yukon Governments, Yukon First Nations, mining companies, and non-government organizations for the promotion of research into mining and environmental issues in Yukon.



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## **PERMAFROST CONSIDERATIONS FOR EFFECTIVE MINE SITE DEVELOPMENT IN THE YUKON TERRITORY**

Submitted To:

Mining Environment Research Group  
Government of Yukon

Prepared by:

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Project No. 1200036

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## **EXECUTIVE SUMMARY**

The presence and proper classification of permafrost is essential to mine planning, operation, and abandonment in the Yukon Territory. This paper discusses the current state of practice regarding permafrost delineation and classification, presents information regarding design and monitoring of structures on permafrost (with particular reference to mining), and includes examples of Yukon and other northern mines where permafrost has affected operations.

Permafrost in the Yukon is particularly sensitive to disturbance, as it is generally “warm” and discontinuous. It is therefore extremely critical that planning for new mines include provisions for the proper classification of permafrost on the mine property, as it will directly affect operations and abandonment of the site, with corresponding financial implications.

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## **1.0 INTRODUCTION**

### **1.1 General**

This report summarizes information gathered from a desktop review of permafrost considerations as they relate to the development of northern mines, with particular emphasis on sites in the Yukon Territory. The report is modified and updated from an earlier draft report<sup>1</sup> prepared by the Yukon Conservation Society (YCS) for the Mining Environment Research Group (MERG).

### **1.2 Project Objective**

This report is intended to provide guidance for regulators and developers considering mine development in regions of the Yukon underlain by permafrost soil and rock. It provides commentary on issues that need to be considered during “cradle to grave” planning for new mines. It also provides guidance for ongoing operation as well as for advanced sites and those in the abandonment and restoration phase.

The study is intended to be consistent with the following MERG primary objective:

*“To coordinate projects which will provide useful information leading to increased confidence in predictions of environmental performance of the opening, operation, and closure of mining facilities in the Yukon”*

### **1.3 Methodology**

This study includes a brief review of relevant literature, a summary of information obtained from informal interviews, information from EBA company files, and descriptions of previous projects in permafrost areas to obtain a description of permafrost and its implications for mining operations. The report also includes pertinent information collected by the Yukon Conservation Society and included in their original draft report.

The body of literature on the dynamics of permafrost is extensive and new data is being collected as a result of climate change. The scope of this report is limited to the review of the available research and information related specifically to mining. The case studies

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<sup>1</sup> Yukon Conservation Society. September 2002. *Permafrost and Freezing: Implications for Northern Mine Sites*. Unpublished report prepared for the Mining Environment Research Group, Government of Yukon

focus specifically on permafrost and other ground conditions related to cold temperature mining, with specific emphasis on Yukon properties.

#### **1.4 Historic Practice**

The Klondike Gold Rush provides much of early experiences of developing mines in Yukon. Placer gold had been regarded as easier to mine, because unlike quartz gold it was not a mineralization zone within host rocks. However, in the Klondike, permafrost added to the complexity of placer mining by locking the ore into perennially frozen gravel. Prior to 1897, Yukon mining was primarily a warm weather activity, when riverbanks and streams thawed sufficiently to allow for placer mining. The workings were generally less than one or two metres deep, because permafrost prevented working deeper underground.

In the 1890s, “fire thawing” became common practice among miners to work the ground deeper - all the way to the bedrock. This technique was primarily used in winter and involved setting fires to melt a shaft down to the bedrock. Gravel liberated from the permafrost by heat from the fires was then stockpiled and sluiced in the summer. This method required over one cubic yard of wood per cubic yard of gravel melted and excavated, restricting the practice to the richest gravel deposits.

As the price of wood increased and wood scarcity became a problem, miners searched for a new way of dealing with permafrost. Steam thawing emerged as a preferred option. Under high pressure, steam was forced through the points of pipes as they were driven full length into the face of a surface to be thawed. The pressure was then reduced and the points left to sweat or slowly thaw the surrounding ground. Miners melted only what was needed. Most of the barren ground could be left frozen. With proper care, underground workings remained frozen and stable. Thawing was originally for sinking and drifting, but was soon extended to dredging.

Although mining techniques have evolved with time, permafrost has always presented itself as a challenge to miners in the Yukon. Permafrost was once disregarded in mine planning, but experience has demonstrated the need to understand the distribution and nature of permafrost prior to establishing a mine. Failure to deal with the possible effects of permafrost degradation on structures can result in environmental and technical challenges. Alternatively, there are opportunities to use frozen ground to advantage when planning and developing northern mines.

## **2.0 THE NATURE AND DISTRIBUTION OF PERMAFROST**

### **2.1 Fundamental Concepts of Permafrost**

#### **2.1.1 Definition of Permafrost**

Permafrost or perennially frozen ground is defined, on the basis of temperature, as soil or rock that remains at or below freezing temperature (0°C) for at least two years. Permafrost sensitivity is usually described in terms of temperature (warm or cold), ice content (ice-rich or ice-poor) and type of ground ice (visible or non-visible). Permafrost has an active layer, which freezes and thaws each year, and a perennially frozen layer. Permafrost should never be considered “permanent” as it is always in a dynamic equilibrium with the surrounding temperature boundary conditions.

Permafrost can refer to ground types with high or low moisture content. Ice-poor permafrost is frozen ground with low moisture content and just sufficient ice to bond the soil particles. Ice-rich permafrost can be predominantly ground ice with some entrapped soil. Some soils and rock have insufficient ice to provide a frozen bond. These friable frozen soils are sometimes referred to as dry permafrost. All moisture in the pores of a permafrost soil may not be frozen. Pore water and ice will coexist at temperatures below 0°C to an extent that depends on temperature, grain size and pore water chemistry. The presence of unfrozen water within warm permafrost can substantially affect the behavior of the otherwise frozen mass.

Permafrost is sometimes considered a geologic manifestation of past or present climate. It makes up close to 30% of the earth’s land surface and can range in thickness from a few metres to hundreds of metres. Aggrading permafrost refers to permafrost that is “growing” and degrading permafrost refers to permafrost that is “regressing”, becoming thinner and/or deeper, with a thickening active layer. It is not uncommon for permafrost to be aggrading and degrading in close proximity near the southern fringe of the permafrost zone or in regions where permafrost has been disturbed by development.

#### **2.1.2 Formation of Permafrost**

Several environmental factors influence the presence of permafrost at a given location – these include mean annual air temperature (MAAT), geothermal heat,

past glaciation and climate, presence or absence of water bodies, vegetation cover, snow cover, slope aspect, and elevation.

Permafrost in Yukon was formed during the Quaternary period in periglacial areas (areas close to glaciers). The distribution of present day permafrost in Yukon is the result of past and present climates, as well as past and present hydrogeologic characteristics.

### 2.1.3 The Active Layer

The active layer is the near-surface thickness of soil or rock, above the permafrost, that freezes and thaws each year. In Yukon, the mean annual ground temperature at permafrost depth is typically about 4°C warmer than the mean annual air temperature. Ground temperature near the surface fluctuates greatly during the year, but below about three metres depth shows a general warming gradient.

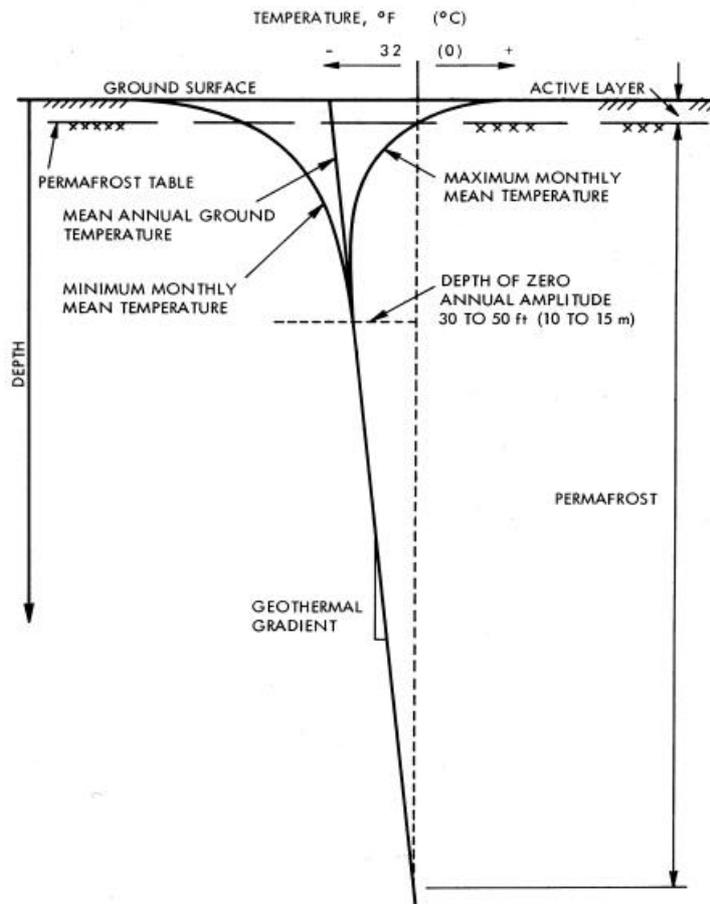


Figure 2.1.3 Typical Ground Temperature Curve in Permafrost Area

The thickness of the active layer is primarily affected by both mean annual air temperature, and the surface characteristics of the site. A north-facing site with a thick, insulating organic layer will have a thinner active layer than an un-vegetated south-facing site. To a lesser extent, vegetation affects the thickness of the active layer due to evaporation that may lower the ground temperature.

In general, the active layer decreases in thickness with increasing latitude and the permafrost thickness increases. In southern Yukon, the active layer can be as thick as 4.0 m, whereas in the north, may be as little as 0.15 m.

#### 2.1.4 Ground Ice Content

Ground ice forms in various ways and can occupy a significant proportion of the overall permafrost volume. A core of permafrost soil recovered from any site, and then allowed to thaw, will either retain its pore water or the pore water will drain from the soil core. When water in excess of that normally retained in a thawed soil is encountered, the permafrost is identified as containing “excess ice”. Excess ice can be distributed or segregated into lenses within the frozen soil. In extreme cases, the ice can form massive inclusions that exceed the volume of soil particles. It is the nature and genesis of ground ice that determines how the permafrost will behave under load and its sensitivity to thawing. An early assessment of ground ice conditions is critical to developing a strategy for all types of construction over permafrost soils.

#### 2.1.5 Ground Ice Classification

The National Research Council of Canada (NRCC) has produced a guide that is commonly used to classify permafrost based on ground ice conditions. The two basic classifications are N (non-visible ice) and V (visible ice). A summary of this classification system is presented in Table 1 below.

Table 1  
NRC Permafrost Classification System

GROUND ICE DESCRIPTION			
ICE NOT VISIBLE			
GROUP SYMBOLES	SYMBOLS	SUBGROUP DESCRIPTION	
N	Nf	Poorly-bonded or friable	
	Nbn	No excess ice, well-bonded	
	Nbe	Excess ice, well-bonded	

VISIBLE ICE LESS THAN 50% BY VOLUME			
GROUP SYMBOLES	SYMBOLS	SUBGROUP DESCRIPTION	
V	Vx	Individual ice crystals or inclusions	
	Vc	Ice coatings on particles	
	Vr	Random or irregularly oriented ice formations	
	Vs	Stratified or distinctly oriented ice formations	

VISIBLE ICE GREATER THAN 50% BY VOLUME			
GROUP SYMBOLES	SYMBOLS	SUBGROUP DESCRIPTION	
ICE	ICE + Soil Type	Ice with soil inclusions	
	ICE	Ice without soil inclusions (greater than 25 mm (1 in.) thick)	

**NOTE:**

1. Dual symbols are used to indicate borderline or mixed ice classifications
2. Visual estimates of ice contents indicated on borehole logs  $\pm$  5%
3. This system of ground ice description has been modified from NRC Technical Memo 79, Guide to the Field Description of Permafrost for Engineering Purposes

**LEGEND**

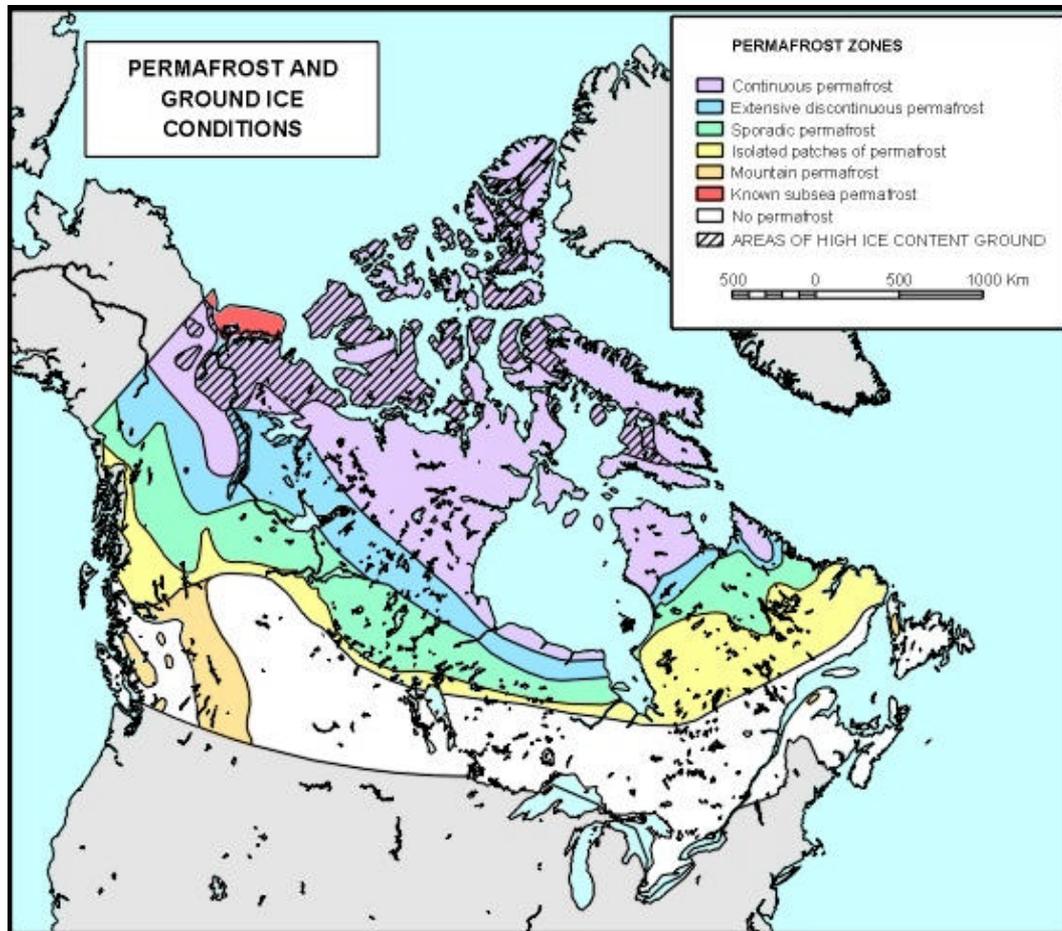
Soil  Ice 

## 2.2 Distribution of Permafrost in Canada

Permafrost underlies more than 50% of the ground surface of Canada – this area is further subdivided into continuous permafrost and discontinuous permafrost. In the continuous permafrost zone, permafrost occurs everywhere beneath the ground surface except large bodies of water. In the far north, it may be more than 500 m thick. The discontinuous permafrost zone is further subdivided into two other areas -- the widespread permafrost zone, where permafrost underlies 50-90% of the land area, and the sporadic permafrost zone, where it occurs mostly in peat lands and underlies 10-50% of the land area. Permafrost can also occur in localized areas, where it is found in small isolated lenses in peat and affects less than 10% of the land area. Figures 1 and 2 indicate the distribution and thickness of permafrost within Canada, as mapped by the Geological Survey of Canada (GSC).

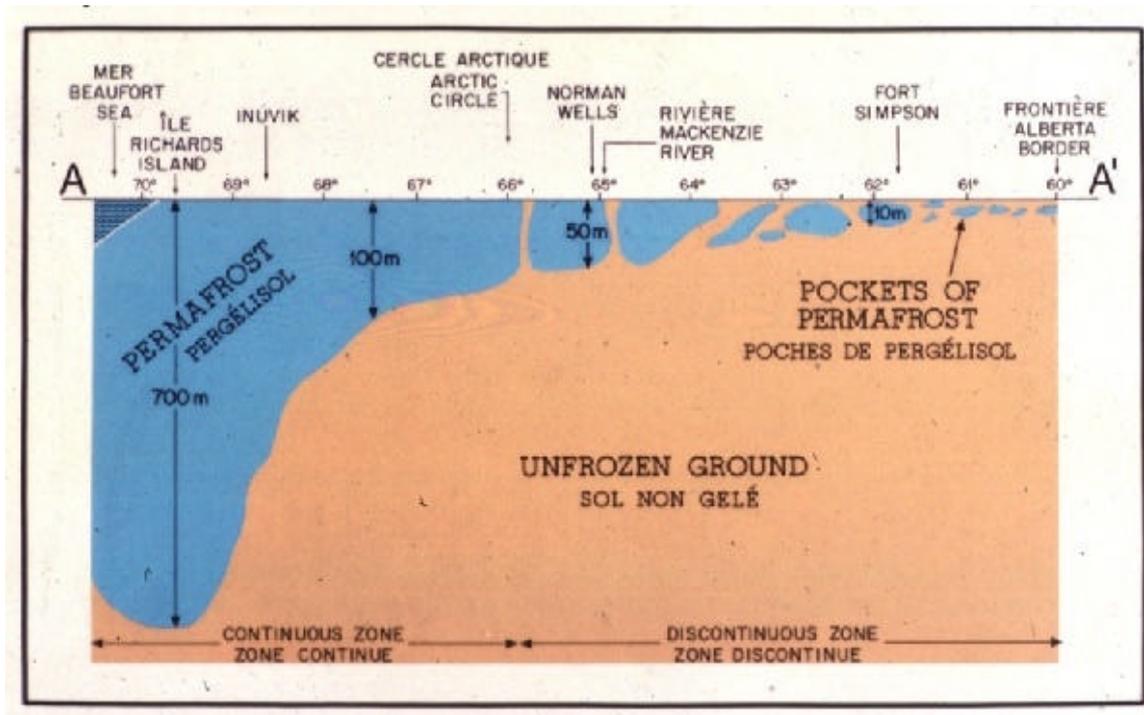
Permafrost can range from the thin layers up to a metre or so thick that remain frozen for one winter to the next, or to extremely thick frozen sediments thousands of years old. For

example, permafrost on Richards Island in the Mackenzie Delta is over 700 m thick and may be over 1000 m thick in the high Arctic Islands.



(Map Courtesy of Geological Survey of Canada)

Figure 2.2a: Distribution of Permafrost within Canada

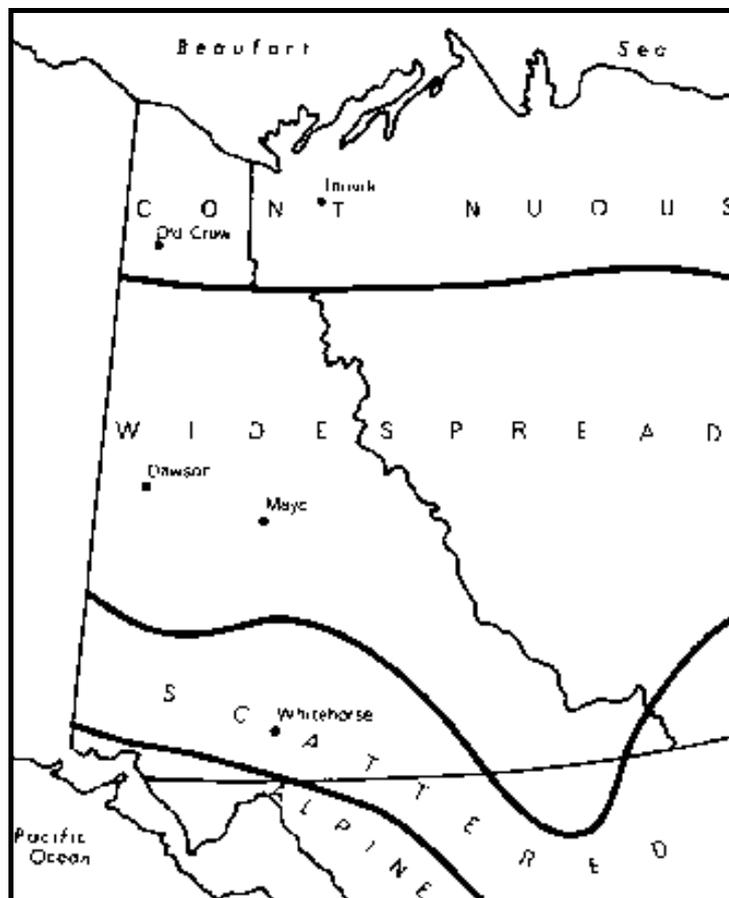


(Map Courtesy of Geological Survey of Canada)

Figure 2: Thickness and distribution of permafrost along a north-south transect from the Beaufort Sea to the Alberta border

### 2.3 Permafrost Distribution in Yukon

Continuous permafrost is present along the arctic coast and inland as far as Old Crow and the northern extent of the Dempster Highway in Yukon., Most of the Yukon hosts discontinuous and/or relatively thin permafrost. This is regarded as the most fragile and sensitive to disruption. Permafrost thicknesses of less than two metres have been recorded in Teslin, Yukon, while near Mayo thicknesses of 40 m have been found. Thicknesses of 60 m have been recorded near Dawson City and near 100 m in the 1982 water well completed in Old Crow. Figure 3 below shows the distribution of various permafrost regimes within the Yukon.



(Map courtesy of Yukon Geological Survey)

Figure 3: Permafrost Distribution in Yukon (after Brown, 1978).

The type of permafrost is important to consider in determining the implications of different thermal regimes and appropriate management techniques at mine sites. In general,

discontinuous (widespread and/or sporadic) permafrost is “warm”, and is the most susceptible to thaw caused by surface disturbance (removal or compression of insulating organic cover). Discontinuous permafrost is also almost always found in valley bottoms that contain insulating organic soil cover.

Continuous permafrost is generally “cold” and less susceptible to surface disturbances.

Alpine permafrost is present at mid to high elevations in most mountain ranges, particularly on north to northwest facing slopes. Alpine permafrost can be either “warm” or “cold”.

## **2.4 Some Unique Aspects of Permafrost in Yukon**

The mountainous terrain of central Yukon and neighbouring Alaska is prone to thermal inversion. The mean annual air temperature is commonly lower in the valley bottoms. This is a common feature of Fairbanks, Alaska where the more desirable residential districts are on the terraces and flanks of hills rather than the valley bottoms. These microclimatic effects result in thicker, near continuous permafrost in the valley bottoms and sparse permafrost at higher elevations on slopes. The permafrost distribution is very sensitive to slope aspect. It is common for south facing slopes to be well drained and permafrost free whereas the opposite side of the valley where the slope is north facing will be wet with a thin active layer. The different permafrost regimes from valley bottom to neighbouring slopes with differing solar aspect can be very evident from the observations of forest types.

## **3.0 CHARACTERIZATION OF PERMAFROST TERRAIN**

Characterization of permafrost at a specific site involves the following stages:

- collection and review of maps, including surficial geology maps,
- acquisition and review of stereo airphoto coverage for identification of landforms and surficial features indicative of permafrost,
- completion of site reconnaissance to “ground truth” the airphoto and map interpretation, log natural exposures, and identify logistical or environmental constraints for subsurface investigation,
- planning and organization of an appropriate site investigation program using geotechnical drilling, test pitting and, where appropriate, geophysical surveys.
- implementation of site investigation program, and
- evaluation and reporting of data.

### **3.1 Airphoto Interpretation and Terrain Analyses**

Surficial and bedrock geology maps, in conjunction with an analysis of stereo airphotos of the site, can be used to produce a map of terrain types. Certain terrain types can be associated with permafrost landforms. A person with local experience in geomorphology or geotechnical engineering can use these methods to develop a reasonable interpretation of permafrost distribution on any particular site.

### **3.2 Geophysical Methods**

Geophysical methods, such as ground penetrating radar or electromagnetic surveys are also useful in determining the distribution and relative ice content of permafrost. These may be conducted by snowmobile, ATV or walking. Geophysics by itself is not conclusive, and must be calibrated by ground truthing from boreholes or testpits.

### **3.3 Soil and Rock Sampling**

Drilling with either auger, air-rotary, wet-rotary or hammer drills is the preferred method of determining site-specific permafrost conditions. Care must be taken to ensure that the drilling method is adapted to sampling or coring the permafrost and returning it to the surface for inspection and logging. Test pits, shallow probing, and water jetting are effective for confirming the presence and depth of a permafrost horizon but are not an acceptable method of obtaining samples.

Samples from drill rigs are obtained from specially adapted auger core barrels, from split spoon drive samplers, or from hammer drill barrels. Samples of permafrost that contain cobbles and boulders require diamond drilling using double or triple tube core barrels of H or P size. In order to preserve the samples for logging and testing, the drilling mud must be saline and controlled to a temperature of typically  $-4^{\circ}\text{C}$ . This is accomplished by using a saline solution and portable refrigeration plant in summer. Winter operations can be successfully undertaken during cold winter months by a simple air to mud heat exchange system.

### **3.4 Ground Temperature Measurements**

After soil sampling is complete, and before the borehole is backfilled, it is usually prudent to install a ground temperature cable. This is a pre-manufactured cable with thermistor beads at predetermined intervals. The cable is suspended down the hole with or without a PVC access tube, and the hole is then backfilled with dry sand. Temperatures on each bead

are measured using a multimeter to record resistance (directly proportional to temperature) and a switchbox to cycle between thermistor beads. The thermistor cable is calibrated in the laboratory before shipment to site. Temperatures are recorded on a daily basis as soon as the cable is installed -- the backfill reaches equilibrium with the surrounding terrain after about 72 hours.

### **3.5 Laboratory Testing**

A selected portion of the soil and rock samples must be retained in a frozen condition, in insulated containers, for transport to a testing laboratory.

The primary laboratory tests completed on permafrost samples are moisture content and frozen bulk density. Both of these parameters are used to obtain an indication of volumetric ground ice content. Other tests that may be conducted include grain size distribution (for frost heave/thaw settlement susceptibility) and thaw-strain or thaw consolidation testing to determine the magnitude of potential surface movements if the permafrost should thaw.

## **4.0 MINE PLANNING AND DEVELOPMENT IN PERMAFROST TERRAIN**

### **4.1 General Principles**

The distribution, ground ice content and temperature of permafrost at a northern mine site are critical factors in mine planning. In addition to this, the following information should also be gathered, for at least three years before mine construction.

1. Daily and mean monthly air temperatures.
2. Amplitude of ground temperature variation in the active layer.
3. Stable permafrost temperature distribution at depth.
4. Snow cover and precipitation measurements.

There are four approaches to dealing with permafrost in the design and construction phase of a northern mining project:

1. Locate mine infrastructure where permafrost will have the least risk to construction. Removal of all overburden and constructing directly on bedrock is a common remedy.

2. Assume the permafrost will thaw or encourage pre-thawing by stripping the insulating vegetation cover, and either allowing sufficient time for permafrost to degrade (this could take several years) or incorporating predicted future surface settlement into the design of the structures.
3. Remove it. This is only practical if the permafrost is thin, and there are readily available non-frost-susceptible backfill materials available. This was a common methodology during construction at Faro YT.
4. Preserve it. This is the most common practice where permafrost is thick and stable. Implementation requires engineering analyses to select an appropriate heat exchanger for incorporation into the foundation systems. Common heat exchangers include a naturally ventilated crawl space below an elevated structural floor, or use of forced ventilation using air ducting and passive means such as heat pipes (Thermosyphons or Cryo Anchors). These are passive refrigeration systems that remove heat from the ground by conduction through pressurized steel pipes buried in the ground, and then convection by dissipating the heat through radiators at surface. These systems only work when the air temperature is colder than the ground temperature. The effects of natural variations in winter air temperature or warming trends must also be considered when designing any system to maintain the permafrost. This is best accomplished by analyzing the temperature data trend over the past 30 to 50 years, then predicting the ground temperature at the end of the design life of the structure.

Specific design and construction issues related to mining in permafrost are discussed in the following sections. Where applicable, examples from existing mines are also presented.

## **4.2 Roads and Airstrips**

There can be significant impact from linear development and removal of surface insulation during road or airstrip construction. Exposure to sunlight after right-of-way clearing can lead to increased thaw and degradation of permafrost. In turn, this can increase erosion and the road maintenance required over the life of the mine and after abandonment

In general, it is best not to remove surface vegetation under these structures. The preferred construction method is to place separating layer such as a geotextile directly over low vegetation (cut larger trees and lay them flat over the alignment) and then pad over the area with at least 1.5 m of fill. This work is best completed in the winter when the ground is already frozen. If properly designed, the new fill will preserve the permafrost in a new equilibrium, after a few years. Maintenance will be required for these first several years, prior to the new equilibrium being achieved.

Airstrips with design criteria including heavy loads or jet aircraft must be engineered. Site-specific data must be collected along the proposed alignment and the fill structure designed to provide both thermal stability and structural stability for the design aircraft. The base course and surface course must be selected to meet aircraft operating requirements using processed construction materials that are available at the site.

### **4.3 Building Foundations**

Site-specific geotechnical information is required at all building sites. This data must include, at a minimum:

- An examination of stereo aerial photographs of the proposed building sites to determine the potential for permafrost, as well as slope instability, drainage issues, and general site suitability.
- Geotechnical boreholes (or testpits if bedrock is within about 6 m of surface) to approximately 12 m (deeper if piles are required).
- Determination of permafrost ground ice content and temperature (thermistor cables should be installed in representative boreholes)
- Determination of active layer thickness and lithology
- Consistency/density of any unfrozen soils
- Ice content of bedrock, if bedrock is encountered. The rock must be cored using chilled drilling fluid to evaluate ice content in fractures.

### **4.4 Yukon Experiences**

Most mining projects in the Yukon will likely encounter permafrost and ice-rich sites at some point during their exploration or development program.

Viceroy's Brewery Creek site developed a road evaluation and site characterization process. Initially, test pit programs were used along proposed road alignments to search for ice-rich soils. Roads on this site were mostly routed to avoid ice-rich areas, or thick rock fills were used to minimize thaw. One road crossing, a haul road in a valley from Golden to Lucky pit, crosses ice-rich permafrost. A minimum number of trees were cut, and vegetation left as intact as possible in order to minimize risk and control the disruption of permafrost. This road was constructed on a base of geotextile filter fabric, and included a rock drain, attempting to protect the permafrost at depth.

In the Mayo region, soil moisture content and organic layer thickness are related to permafrost occurrence (Williams, 1996). Williams established a test for the presence of permafrost, which was accurate at over 60 test sites. He established that where the critical soil moisture content was greater than 25%, and organic layer thicknesses were greater than 110 mm, permafrost was likely present. This generalization worked for the Mayo region because the soil moisture content supplied water for evapotranspiration, which cools the ground surface and the organic layer, which further insulates the ground. These two factors aid in sheltering permafrost from thaw in summer heat. Many other factors must also be involved, such as active layer thickness and permafrost thickness.

The type of vegetation is typically indicative of the presence of permafrost. For example, dwarf Black Spruce is an indicator, as are “drunken forests” (trees falling over and leaning on each other due to shallow root mats caused by permafrost).

In the Yukon, weathered shales, organic rich and silt rich materials, fine-grained alluvial and lacustrine deposits, organic rich wetlands or thick colluvial deposits with high fines content commonly contain ground ice or are classified as ice-rich permafrost.

At the Clinton Creek mine site, in central Yukon, initial observations at the site indicated that neither seasonal frost movements nor permafrost thaw potential were considered to be of significant concern. However, during construction, segregated ice, in the form of large crystals and thick lenses in alluvial valley deposits and near surface bedrock, was commonly encountered in undisturbed ground (Stepanek et al., 1992). This created foundation and slope instability at the mine.

Clinton Creek mine site is a good example to illustrate how crucial the initial assumptions used in design considerations are to the long-term stability of the mine site. Clinton Creek Mine was constructed in the 1960's and 70's. At that time, most mining engineers assumed permafrost would remain permanently frozen forever. Permafrost thaw settlement was not considered to be a significant design consideration. Documented slumping at this site is extensive as a result of thawed ice rich soils and the tailings remain unstable.

At both the Faro mine and the Brewery Creek gold mine alternative locations for structures were chosen as a result of discovering permafrost in the originally intended areas. In both cases, the location was changed from the initial planning stage to avoid problems that could arise from instability.

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At Brewery Creek mine site, Viceroy agreed to excavate any permafrost soils with a water content greater than 17 % from beneath the heap leach pad. Initially, the site was cleared in one location for construction of the pad before detailed foundation conditions were investigated. It was then determined that a lower soil moisture content was present higher up on the hill than the cleared site and would be more appropriate to ensure the stability of the heap leach pad.

During the initial construction of the tailings dam at BYG's Mount Nansen site (NW of Carmacks), stripping of ice-rich soils was insufficient. This has led to concerns about the integrity and stability of the dam and impounded tailings. Work is still underway in 2004 to monitor the permafrost surface – the long-term effect of inadequate stripping is still to be determined. It may be that the tailings have to be removed to another location for abandonment of the mine, or significant remedial works must be undertaken to ensure that the remaining permafrost beneath the dam remains frozen.

#### 4.4.1 Yukon Foundations

Refrigerated foundations operate on the principle of maintaining underlying permafrost in a stable frozen state by passive or mechanical means. For example, the Ross River School uses Thermosyphons, which are passive heat pipes used to dissipate heat from beneath the insulated school to the outside environment, thus keeping the soils frozen.

Another system available for use is the placement of corrugated metal pipe culverts in above ground granular pads. The culverts are oriented to the prevailing winds, which refreeze any thawed soils. These have been used in structures in Ross River and Old Crow, YT.

Heat pumps such as those used in hockey arenas and curling rinks are used in Ross River in garages and truck bays. Although the operational costs of these units are high, the advantage of these systems is that heat collected can be used to heat the building.

Deep footings involve excavating down to stable, usually granular, soils. At a Dawson City apartment building, ice rich permafrost soils were removed by backhoe to the stable granular materials at approximately 4.0 metres below grade. Precast concrete pads and steel columns were installed directly into the granular base. Granular backfill reduced the potential for future uplift problems due to frost jacking. Main support beams for the building rest on the pile caps and a clear airspace is maintained beneath the building to keep any remaining permafrost frozen (Trimble, 1996).

Most buildings at mines in the Yukon are founded on concrete footings placed on a compacted granular fill pad (engineered fill).

Some structures may be most effectively constructed during the winter season to ensure minimal impact on the permafrost and active layer.

## **5.0 THE ROLE OF PERMAFROST IN MINE WASTE CONTAINMENT**

### **5.1 Water and Tailings Ponds**

Soil and rock caps are commonly used as protective covers over tailings and waste rock piles. They serve two purposes – to minimize surface water (or air) infiltration that could potentially mobilize acidic drainage that can carry heavy metals, and to assist in preserving underlying permafrost (or create freezeback from below). DEW line landfills in the northern Yukon have experienced full freeze back within 18 months.

At Rankin Inlet Nickel Mine (NWT), pore water content in impounded tailings has evolved over 30 years of containment and has a very high total dissolved salt content, which depresses the freezing point of the pore water. It is possible that a thicker cover is required to shelter the tailings in the summer and to enhance the potential for freeze back of permafrost. Due to incremental freezing of contained water, the last water to freeze will be the highest in salinity. Higher salinity content results in higher unfrozen water content, as well as lower hydraulic conductivity, and potentially a complex pore water chemistry that is difficult to accurately predict. Thus, design for rapid and full freezeback of a tailings area is a useful strategy to reduce potential for future contamination from a mine site.

The impacts of thawing permafrost on dam structures and waste impoundment areas can be summarized as follows:

- increased pore water pressure and seepage;
- settlement of structures;
- loose saturated materials that may liquefy during earthquakes;
- increased potential for piping

Overfilling of tailings impoundments, dam instability caused by permafrost thaw, and excessive seepage through the tailings dam created significant challenges for operators at the abandoned Mt. Nansen mine. The initial design called for seepage reduction through

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the dam by beaching tailings on the dam face. However, this did not happen as quickly as designed, and excessive seepage initiated permafrost thaw, resulting in increased seepage and downstream slope instability. This was partially corrected by creating a “seepage collection dam” which included Thermosyphons to protect a permafrost core. Water collected above this dam is pumped back into the main tailings pond.

At the Red Dog mine, the tailings dam is an earthen dam with HDPE plastic liner on the face to control seepage losses. The lined rockfill dam was constructed on permafrost shale bedrock that contained fractures filled with ground ice. Heat from the reservoir resulted in thaw of the bedrock foundation resulting in a porous structure that allowed substantial underseepage. Mitigation measures included installation of an upstream blanket of fine-grained soils. It is the view of the Red Dog management plan that nothing can be done to prevent the impact of permafrost thaw on the dam. Although the dam was not designed as a frozen embankment, the effect of thaw of the fractured shale bedrock foundation was not considered.

BHP elected to construct several frozen core dams as part of their tailing and waste water disposal plan at Ekati, NWT. One of the dams is small, while the other stands 20 m high, spanning 250 m across at the top and wide enough to have a tote road on top of it. The tailings impoundment area, formerly a lake, is divided into five cells. Dividers separate each cell, with soil filter curtains designed to entrap contaminants and prevent their migration between cells or into the environment. Ekati is one of the first northern mine sites in Canada where frozen core dams have been seen widespread use for water storage. The dams are designed with a core of frozen gravel that will remain at a temperature below  $-2^{\circ}\text{C}$  over the life of the structure for a range of possible climatic conditions, including a general warming trend.

A typical frozen core dam consists of a frozen core keyed into a frozen foundation, an upstream sandy prism overlain by a rock fill blanket, and a downstream rockfill prism. In addition a freezing column may be necessary at some stages of dam construction. The frozen core zone can be constructed from compacted earthfill or from hydraulically placed material. The dam profile is similar to that of an unfrozen rockfill dam. The primary design issue is to ensure freezing of the core, the foundation, and seepage barriers. Frozen core dams are practical in regions of continuous permafrost (ground temperatures typically below  $-5^{\circ}\text{C}$ ). They are an unlikely option for the southern and central Yukon where mining activity is currently clustered.

BYG has been monitoring the permafrost temperatures and its changes in and below the core of the dam at the Mount Nansen mine site,. This is accomplished with a string of

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thermistors drilled into the permafrost below the foundation of the dam. BYG feels that it will eventually freeze back, but others do not anticipate full freezeback at this latitude (Stepanek, McAlpine, 1999).

The engineering design of landfills in the Arctic at Canadian DEW line sites may provide some useful information for mine site design. If permafrost is very cold and continuous, it may be possible to use permafrost as a component of a buried waste containment plan. DEW line experiences indicate that such sites in the Yukon occur only in the far northeastern part of the territory. Some DEW line landfills have witnessed full freezeback of wastes, however, high liquid content tailings will impact the permafrost integrity more extensively than solid landfill wastes.

If there remains uncertainty that permafrost will freeze back and encapsulate the impounded waste, then design must allow for permafrost thaw and eventual release of water from pore ice.

## 5.2 Control of Runoff from Sites with Potential for ARD

Mines located in regions of permafrost may use the permafrost as part of a strategy to control acidic drainage from tailings and waste rock. Pyrite oxidation is an exothermic reaction, meaning that heat is given off during the reaction. This has implications for permafrost, and tailings encapsulation in permafrost. Available data and modeling show that there may be a considerable decrease in the rate of oxidation of pyrite as the temperature approaches 0°C .

Frost shattering, and frost weathering refer to the physical breakdown of rock and soil into smaller particles. This is a mechanism in cold climates that may actually increase the rate of acid generation. Others have determined that mineral disintegration and exposure of new reactive surfaces still occurs in frozen mine materials.

There are different control strategies for prevention of acid rock drainage (ARD) in permafrost regions. Some strategies are unproven in practice therefore caution must be exercised when selecting the most appropriate one for a specific site. Some of the more common control strategies that have been advocated include:

- *Freeze control* – immobilizes fluids controlling ARD reactions and migration. This system does not necessarily stop ARD production in tailings, and it is important to note that freezing large quantities of mine waste can be problematic. In continuous permafrost, total freezing could be achieved once the containment

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area is filled or by freezing thin layers during filling. Allowing tailings to freeze back after filling requires perimeter dykes.

- *Climate Control* – low annual precipitation levels and cold temperatures of permafrost are natural buffers to ARD production. Some engineered strategies can be used to control, to some extent, the production of ARD in the permafrost climate.
- *Engineered Dry Cover* - can be used to restrict water and oxygen from entering the waste piles. There is a need for the development of lower cost dry covers, as well as the exploration of the use of different materials for the dry cover.
- *Subaqueous Disposal* – this is the disposal of potentially ARD creating materials under a water cover to restrict the ingress of oxygen into the material. Low oxygen availability hinders oxidation.
- *Blending and Segregation* - blending and segregation of acidic and alkaline materials can result in a net neutral waste product that produces a non-acidic leachate. If sufficient quantities of alkaline materials are not economically available, blending ratio is not adequately maintained, or blending is not achieved, this is not an effective strategy.
- *Collection and treatment* – Collecting and treating leachate is a proven and demonstrated control strategy, however post-closure it is less feasible and problematic because of the logistics and high cost of long term operation of a seasonal treatment facility, and no cash flow upon closure to facilitate long term care.

### 5.3 Waste Water Management

Open pit and underground mines generate wastewater that is seldom of acceptable quality for direct discharge to the environment. Water must be temporarily stored in sumps or sedimentation ponds and treated to remove surplus ammonia from blasting residue and other suspended or dissolved minerals. Innovative methods for passive treatment of mine water include natural wetland processing and atomization by snowmaking. Wetland disposal of sewage pond effluent has an experience base in municipal systems in Yukon communities such as Teslin.

Atomization and snowmaking is planned on an experimental basis at Ekati Diamond Mine in NWT beginning in 2004. The system will atomize water from a sedimentation pond where the water has the potential to be high in ammonia, nitrates and suspended solids. Volatile ammonia is dissipated to the atmosphere during atomization and solutes that are

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predominantly nitrates will be distributed over the tundra vegetation similar to the application of fertilizer. The system is also designed for winter operation making snow similar to an installation at the municipality of Westport, Ontario.

## **6.0 CLOSURE AND RECLAMATION PLANNING**

### **6.1 Permafrost as a Closure Control Measure**

The reclamation and decommissioning phase needs to be an early part of a plan for any proposed new mine. Early consideration of the role of permafrost during post mining closure can affect the choice of tailings disposal methodology. A tailings system that can be configured to encourage permafrost aggradation during operations can result in a fully frozen tailings impoundment at the end of operations. This is a very effective approach to creating a “walk away” closure scenario. The strategies that have been used in the past to maximize the extent of frozen tailings include dewatering at the process plant to a paste-like consistency, alternating winter and summer disposal cells and spreading in thin lifts for winter freezing during placement.

The preferred management technique for dealing with mine cuts in a permafrost region is to allow natural degradation of the permafrost slopes and slumping of the cuts to aid in reclamation. This method first allows the natural vegetative mat on the surface to melt, slough, slump and drape over the disturbed area in a way that increased the stability of the cut. Subsequently, the sheltering of the exposed permafrost serves to insulate it from further thermal degradation of the permafrost (slumping and thawing) thereby enhancing long term stability. It also provides a layer of organic material that already has root systems and integrity to help prevent erosion. In contrast, to mechanically decrease the side slopes of a mine cut requires a much larger land disruption and the stripping of the vegetative layer. Rather than aiding stability, this can result in increased erosion. The experience of Alaskan mine sites has been that natural slumping processes of permafrost can reclaim a mine cut area in four to ten years depending on site specific considerations such as degree of disturbance, presence of ice wedges, soil and vegetation types, etc.

Adits, which are used to drain fluids throughout the winter season, commonly form ice plugs. This can lead to a build up of pressure from the accumulation of unfrozen liquid behind the ice plug, and can lead to explosive destruction of the integrity of the adit. Adits in Roger's Pass, in Yoho National Park, all experienced problems with frozen plugs. United Keno Hill Mine (UKHM), in the central Yukon, has several adits that are seeping water, some seepage possibly related to ice plugs. This has resulted in the construction of water treatment ponds to collect and treat the water before distribution to the environment.

At Mount Skukum, the adit is very long and there are lakes in the surrounding terrain that are nearly 100 metres above the adit. This can lead to a high pressure situation if the water that flows out of the adit becomes blocked by ice.

The potential for ice plugs needs to be recognized during mining, and the water source sealed off or diverted elsewhere, before closure.

Burn and Freile (1989) determined at their test sites near Mayo that, "succession toward a closed-canopy spruce forest is well under way about 40 years after a disturbance" in their study of revegetation. This has implications for reclamation planning. Although the study area is known to host permafrost, the explicit investigation of permafrost was not a component of the study. The study concluded that non-toxic placer tailing could successfully host vegetation, depending on slope and other environmental factors.

## **6.2 Climate Change and Other Long Term Effects**

Most discontinuous permafrost south of Eagle Plains is warmer than  $-2^{\circ}\text{C}$ . This permafrost is easily disturbed and its degradation can be readily initiated by any construction activity that disturbs the natural surface vegetation or drainage. There is a growing concern that global warming may be influencing this type of warmer permafrost (Osterkamp, 1999; Yongjian, 1998). In China for example, the southernmost limit of permafrost has moved northward (Yongjian, 1998). Much of the undisturbed discontinuous permafrost south of the Yukon River in Alaska, where the Yukon River roughly follows the same latitude, has warmed significantly and some of it is thawing (Osterkamp, 1999).

It is widely accepted that climate change is more than a theory and that as temperatures change, the north will likely be affected by a greater range of temperatures on an annual basis, as well as an overall warming trend. If these predictions are accurate, the Yukon's discontinuous permafrost may be most sensitive to the thermal disruption and may thaw.

The impact of climate change is often predicted using general circulation models (GCMs). "In northwest Canada topographic influences on climate are substantial, but not well represented at the scale of most GCMs" (Burn, 1993:182). Because of this, no clear picture has yet emerged of what effects climate change will have on the Yukon.

Climate trends are one more variable that must be considered in planning any engineering, construction or mining activities on permafrost that is sensitive to small temperature changes. Current engineering practice is to treat climatic warming as a probabilistic

variable in geothermal analyses for structures on permafrost. The trend can usually be determined by careful analyses of long-term historical records from the nearest meteorological station.

### **6.3 Monitoring**

Early detection of permafrost disruption is critical in avoiding catastrophic unplanned events such as dam failure or structural deformation in buildings. Monitoring devices such as temperature sensing equipment can be built into structures, liners, etc, to act as an early warning system. Probing, drilling and retrieving undisturbed core is an indicator of a sound structure with permafrost integrity intact. Geophysical techniques with ground – truthing can also be effective (Johnson et. al., 1984). Periodic ground surveys are an essential element of any earth structure monitoring system in order to identify deformations and track trends that may be attributable to thaw-settlement or frost heave.

Ground temperature and water pressure instrumentation are commonly used to measure and monitor changes in mine site structures. Thermistors monitor changes in temperature. Piezometers measure changes in water pressure within unfrozen zones that may be recently thawed or material such as tailings placed in a thawed condition and currently freezing. Piezometers are not effective within permafrost. At Ekati Diamond Mine, numerous thermistors were installed into the frozen core dams to allow confirmation of the comprehensive geothermal analyses carried out during design of these structures. BYG uses pneumatic piezometers for water pressure measurements, and thermistors to monitor the thermal regime within the dam. At Brewery Creek, Viceroy used thermistors to ensure that the process solutions remain unfrozen and effectively extract the minerals from the heap leach pad.

## **7.0 SUMMARY AND CONCLUSIONS**

It is hoped that this paper demonstrates that the proper delineation and classification of permafrost is a critical consideration for the planning, operation and abandonment of mines in the Yukon Territory. Information has been presented which will assist the readers in determining the proper methodology to verify the presence and classification of permafrost on a prospective site. This paper has also presented information demonstrating that permafrost in the Yukon is particularly sensitive, as the majority of permafrost here is discontinuous and “warm”, thus extremely susceptible to surface disturbance. Where applicable, examples of Yukon and other northern mine sites have been used to illustrate key points.

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Respectfully submitted,  
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## BIBLIOGRAPHY

ANDERSLAND, O.B. and ANDERSON, D.M. (Editors), 1978. *Geotechnical Engineering for Cold Regions*. McGraw-Hill, New York, N.Y.

BROWN, R.J.E., 1970, *Permafrost in Canada: Its Influence on Northern Development*.  
University of Toronto Press, Toronto

BURN, C.R., 1993. "Permafrost, Tectonics, and Past and Future Regional Climate Change, Yukon and Adjacent Northwest Territories." *Canadian Journal of Earth Science*, Vol. 31, 1994. pp. 182-191.

BURN, C.R. and FREILE, P.A., 1989. "Geomorphology, Vegetation Succession, Soil Characteristics and Permafrost in Retrogressive Thaw Slumps near Mayo, Yukon Territory." *Arctic*, 42, 1:31-40.

JOHNSON, T., McROBERTS, E. and NIXON J., 1984. *Design Implications of Subsoil Thawing*, American Society of Civil Engineers, pp. 45-104

JOHNSTON, G.H. (Editor), 1981. *Permafrost Engineering Design and Construction*. National Research Council of Canada, Associate Committee on Geotechnical Research, Permafrost

OSTERKAMP, T., 1999. "Thawing of Warm Permafrost in Response to Climatic Change and Human Activities. Published on the world wide web at  
<http://gi.alaska.edu/snowice/frost4.num>

STEPANEK, M and H.F. McALPINE, 1992. "Landslide Dam at Clinton Creek." *Geohazards '92*. pp. 291-298

TRIMBLE, J. R. and JACOBSEN, N.A., 1996. "Experience with Foundation Design in the Yukon Territory." Paper presented at the 49<sup>th</sup> Canadian Geotechnical Conference of the Canadian Geotechnical Society.

WILLIAMS, J. and BURN, C.R., 1996. "Surficial Characteristics Associated with the Occurance of Permafrost Near Mayo, Central Yukon Territory, Canada." *Permafrost and Periglacial Processes.*, 7 , pp.193-206.

YONGIAN, D., 1998. "Recent Degradation of Permafrost in China and the Response to Climatic Warming." Proceedings of the 7<sup>th</sup> International Conference on Permafrost, Yellowknife, NWT

