Mine Waste Covers in Cold Regions

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Executive Summary

This report examines phenomena that could affect the performance of soil covers constructed on mine wastes located in cold regions. It reviews the state of knowledge about such phenomena, and their occurrence in existing mine waste covers. It also identifies priorities for research to develop soil cover design and construction methods suitable for cold regions.

Soil covers are widely used in the management of mine tailings and waste rock. However, current soil cover design and construction practices are based largely on experience from temperate regions, and on the theoretical basis provided by agricultural soil physics, which is also derived largely from experience in temperate regions. As a result, they do not take into account many potentially important features and processes that are common in cold regions.

Several dozen features or processes affecting soils have been identified in cold regions. The most widespread processes are ground freezing and ground ice formation, ground thawing and thaw settlement, and freeze-thaw cycling. Cryoturbation, solifluction, gelifluction and convective cooling can also occur in limited conditions. Combinations of these processes with specific soil or hydrologic conditions can result in terrain features such as ice wedges, pingos, thermokarst, patterned ground, boulder fields, mounds or hummocks, and mudboils, as well as a number of less common features. The rates of these processes can be slow enough that they would not be obvious in current observations of soil covers, but fast enough that they might have significant effects over a cover's design life.

Cold regions also exhibit distinct hydrologic phenomena. The effect of freezing conditions on infiltration is one example of importance to cover design and performance. Other less obvious effects may also be important in particular circumstances.

Nearly 100 examples have been found of soil covers either proposed for or constructed on mine wastes in cold regions. Detailed information is seldom available, but it appears that very few of the constructed or proposed covers have been reviewed from a cold regions perspective. The limited cases where cold regions considerations have affected cover design and cover performance are reviewed.

There is a need for additional research on fundamental cold regions phenomena, for development of predictive and design tools that take cold regions phenomena into account, and for the development of best practice guidelines. Several large-scale cover trials are currently underway in cold regions. Coordination of those programs offers opportunities to make significant advances in the understanding of the effects of cold regions phenomena on soil cover performance.

Résumé

Dans ce rapport, l’on examine les phénomènes qui pourraient toucher le rendement des couvertures de sol construites sur des rejets miniers situés dans des régions froides. L’on passe en revue le savoir sur ces phénomènes et leur présence dans les couvertures existantes. L’on identifie aussi les priorités pour la recherche qui vise l’élaboration de méthodes de conception et de construction de couverture de sol qui conviennent aux régions froides.

Les couvertures de sol sont très utilisées dans la gestion des résidus miniers et des stériles. Toutefois, les méthodes actuellement exploitées pour concevoir et construire des systèmes de couverture de sol s’inspirent largement de l’expérience provenant des régions tempérées, et aussi des fondements théoriques de la physique des sols appliquée à l’agriculture, une discipline qui, elle aussi, découle grandement de l’expérience accumulée dans les régions tempérées. Par conséquent, ces méthodes ne tiennent pas compte de nombreux processus et caractéristiques éventuellement importants et généralement présents dans les régions froides.

Plusieurs douzaines de caractéristiques ou de processus touchant les sols ont été identifiés dans les régions froides. Les processus les plus fréquents sont la congélation du sol et la formation de glace dans les sols, le dégel du sol et le tassement dû au dégel, et le cycle de gel et de dégel. La turbation périglaciaire, la solifluxion, la gélifluxion et le refroidissement par convection se produisent quant à eux dans certaines conditions. La combinaison de ces processus et de certains sols ou de certaines conditions hydrologiques entraîne quelquefois la formation de traits caractéristiques de terrain, par exemple des blocs de glace, des pingos, du thermokarst, des terrains réticulés, des champs de blocs rocheux, des buttes ou des hummocks, et des marmites de boue, ainsi que de caractéristiques moins courantes. La progression de ces processus est quelquefois si lente que les processus sont imperceptibles lors des observations ordinaires des couvertures de sol mais elle peut être si rapide que les processus ont un impact important sur la durée de vie théorique des couvertures.

En outre, les régions froides abritent des phénomènes hydrologiques distincts. L’effet du gel sur l’infiltration est un exemple de phénomène important pour la conception et le rendement des couvertures. D’autres effets moins évidents peuvent, eux aussi, s’avérer importants dans des circonstances particulières.

L’on a identifié une centaine de couvertures de sol dont la construction sur des rejets miniers situés dans des régions froides a été proposée ou est terminée. De l’information détaillée est rarement disponible, mais il semble que très peu de ces couvertures construites ou proposées aient été examinées pour les régions froides. L’on examine dans le rapport les quelques cas où le lieu, soit une région froide, est entré en ligne de compte dans la conception et le rendement de la couverture.

Il y a lieu de poursuivre la recherche sur les phénomènes fondamentaux des régions froides, afin de créer des instruments de prévision et de conception qui tiennent compte des phénomènes particuliers aux régions froides et d’élaborer des lignes directrices sur les meilleures pratiques. Plusieurs essais de couvertures à grande échelle sont en voie d’exécution dans des régions froides. La coordination de ces programmes offre des possibilités de réaliser des progrès importants dans la compréhension des effets, sur le rendement des couvertures de sol, des phénomènes particuliers aux régions froides.

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1 Introduction

1.1 Background

Current soil cover design and construction practices are based largely on test and full-scale experience from temperate regions and on the theoretical basis provided by agricultural soil physics, which is also derived largely from experience in temperate regions. As a result, they do not take into account many potentially important phenomena that are common in cold regions. This report examines cold regions phenomena that could affect the performance of soil covers, reviews the state of knowledge about such phenomena and their influence on covers constructed on mine wastes, and identifies priorities for research to develop soil cover design and construction methods suitable for cold regions.

1.2 Acknowledgements

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1.3 Report Structure

Chapter 2 of this report provides a summary of cold regions phenomena that were identified by the authors to have particular relevance to covers. The potential impact of these phenomena on cold regions covers are discussed in Chapter 3. Ongoing and recommended research stemming from the information in this report is described in Chapter 4, and finally Chapter 5 summarizes the report conclusions.

The report includes a detailed bibliography, which not only lists references cited in this report but also references related to cold regions cover case studies and general cold regions phenomena literature. A detailed glossary of cold regions terminology is included at the back of this report.

2 Cold Regions Phenomena

2.1 Cold Regions

2.1.1 Geographic Extent

There are many definitions for what constitutes a cold region. These include definitions based on air temperature, snow depth, ice cover on lakes, depth of ground freezing and vegetation distribution. The different definitions arise from the different contexts within which various groups have studied cold regions. In the context of mine waste covers, an appropriate definition of cold regions would include any area where there is a regular occurrence of ground frost sufficient to affect cover performance. Ground frost can directly affect the rate at which precipitation infiltrates through a cover system, and can physically alter soil properties and thereby indirectly affect cover performance.

In the northern hemisphere, the southern limit of significant ground frost extends to about the 40th parallel. Engineers identify this southern limit by a 300 mm depth of frost penetration. However, actual data on frost depth is limited (Andersland and Ladanyi, 2004). Therefore, frost depth is often estimated from the freezing index, which uses only meteorological data to assess the combined duration and magnitude of below-freezing air temperatures during a year (Brown and Kupsch, 1974). The 300 mm frost penetration depth corresponds to a freezing index of 55^{o}C-days. That estimate is approximate only, as many other factors such as soil mineral and textural composition, snow cover and vegetation can also affect frost depth.

According to Andersland and Ladanyi (2004), cold regions are typically subdivided based on whether the ground is only seasonally frozen, and whether permafrost is continuous or discontinuous. The transition from seasonally frozen ground to discontinuous permafrost is somewhat arbitrarily based on the -5^{o}C isotherm, measured at the depth of zero annual temperature amplitude. Continuous permafrost requires an annual freezing index of at least 3,900^{o}C-days.

Cold regions typically experience extreme climate, the most obvious of which is prolonged cold air temperatures. Site climate is extremely important to the performance of cover systems, and along with the availability of cover materials, is one of the two key inputs to cover design. In temperate regions, the importance of climate relates predominantly to moisture transfer between the atmosphere and the ground. In cold regions, the importance of climate extends to heat transfer between the atmosphere and the ground. Other cold regions climate factors affecting cover performance include snow cover, surface radiation, convective heat flow and evaporation and condensation.

At sufficient altitude, climate and ground frost conditions are similar to those found in northern cold regions. High altitude locations are scattered all around the world, including areas that would not generally be considered cold regions. Parts of the southern hemisphere would also be considered cold regions on the basis of latitude or altitude, or both.

2.1.2 Distribution of Cold Regions Ground Features and Processes

In cold regions, there is a distinct link between climate and the ground surface. Extreme climatic conditions result in the ground surface reacting in ways not experienced in other temperate regions of the world. Washburn (1973) stated that where a climate is sufficiently cold it will leave physical evidence of its influence. Table 1 presents the summary of cold regions ground surface phenomena developed by Washburn. Although he refers to the table as being “tentative and highly subjective”, it remains useful to illustrate both the diversity and geographic extent of cold regions phenomena. Most of the phenomena listed in Table 1 are discussed in more detail in Section 2.2 below.

Table 1: Cold Regions Phenomena (after Washburn, 1973)

The numbers in the table represent the relative occurrence of the cold regions phenomena listed, with (1) denoting most frequent and lesser frequency denoted by (2), (3) and (4). (R) indicates rare or absent, whilst (-) indicates no data available to categorize.

Phenomena	**Lowland**			**Highland**			
	Polar	**Sub-polar**	**Middle Latitude**	**Polar**	**Sub-polar**	**Middle Latitude**	**Low Latitude**
Frost action							
Frost wedging	2	1	3	2	1	2	3
Frost heaving & thrusting	1	2	3	2	1	3	4
Mass displacement	1	2	R	2	1	3	R
Seasonal frost cracking	2	1	3	2	2	3	R
Permafrost cracking	1	2	R	2	3	R	R
Mass-wasting							
Slushflow	1	2	R	2	3	4	R
Gelifluction	1	2	3	2	1	3	4
Frost creep	2	1	3	2	1	2	3
Rock-glacier creep	R	R	R	2	1	2	4
Nivation	1	2	R	2	1	2	3
Fluvial action							
Ice rafting	1	1	3	4	3	3	R
Lacustrine action							
Ice shove	1	2	3	4	3	3	R
Ice rafting	1	2	3	4	3	3	R
Marine action							
Ice shove	1	2	R	-	-	-	-
Ice rafting	1	2	R	-	-	-	-
Wind action	1	2	3	1	2	3	3
Permafrost	1	2	R	1	2	3	4
Patterned ground							
Non-sorted circles	1	2	R	2	2	3	R
Sorted circles	1	3	R	2	1	R	R
Small non-sorted polygons & nets	1	2	3	2	1	2	2
Large non-sorted (ice wedge) polygons & nets	1	2	R	2	3	R	R
Small sorted polygons & nets	1	2	4	2	1	3	2
Large sorted polygons & nets	1	3	R	2	3	R	R
Small non-sorted & sorted stripes	1	2	4	2	1	3	2
Large non-sorted & sorted stripes	1	3	R	2	1	4	R
Involutions	1	2	R	2	3	4	R
String bogs	2	1	2	R	2	4	R

Phenomena	Lowland			Highland			
	Polar	Sub-polar	Middle Lati-tude	Polar	Sub-polar	Middle Lati-tude	Low Lati-tude
Palsas	2	1	R	R	2	3	R
Pingos	1	2	R	R	R	R	R
Slushflow fans	1	2	R	2	3	4	R
Gelifluction lobes, sheets, streams							
Small	1	2	3	2	1	3	3
Large	1	2	R	2	1	3	4
Block fields, slopes and streams	2	2	R	1	1	3	4
Rock glaciers	R	R	R	2	1	3	4
Taluses	3	3	4	2	1	3	3
Protalus ramparts	R	R	R	2	1	1	3
Grezes litees	2	3	R	2	1	3	4
Nivation benches and hollows	1	2	R	2	1	3	4
Altiplanation terraces	2	2	R	3	1	R	R
Asymmetric valleys related to permafrost	1	2	R	1	2	R	R
Dells	1	2	R	1	2	R	R
Cold climate varves	2	1	3	3	2	2	R
Lacustrine ice shove ridges	1	2	3	4	3	3	R
Marine ice-shove ridges	1	2	R	-	-	-	-
Beaded drainage and thaw lakes	1	2	R	R	R	R	R
Loess	2	1	3	4	4	4	4
Dunes	1	2	4	R	3	4	R
Ventifacts	1	2	R	1	2	3	4

It is helpful to note that there are both cold regions features and processes within Table 1. Features are the final landforms and terrain patterns that can be observed; while processes are the (often invisible) underlying causes. For the purpose of this report, the term “cold regions phenomena” is used as the collective term for all cold regions processes and features.

One limitation of Table 1 is that it presents only cold regions phenomena related directly to the ground surface. The following sections will discuss the broader list of cold regions phenomena related to cover performance, in the following groups:

- Frozen ground phenomena,
- Cold regions hydrologic phenomena, and
- Other factors.

This categorization is particular to the subject of covers and may not be accepted by all members of the larger periglacial research community.

2.2 Frozen Ground Phenomena

2.2.1 Basics

Ground Temperatures

In broad terms, air temperature, heat flow from the interior of the earth, and soil thermal properties define ground temperature. Ground temperature will fluctuate sinusoidally, both daily and seasonally. Figure 1 illustrates the typical ground temperature profile in perennially frozen soil.

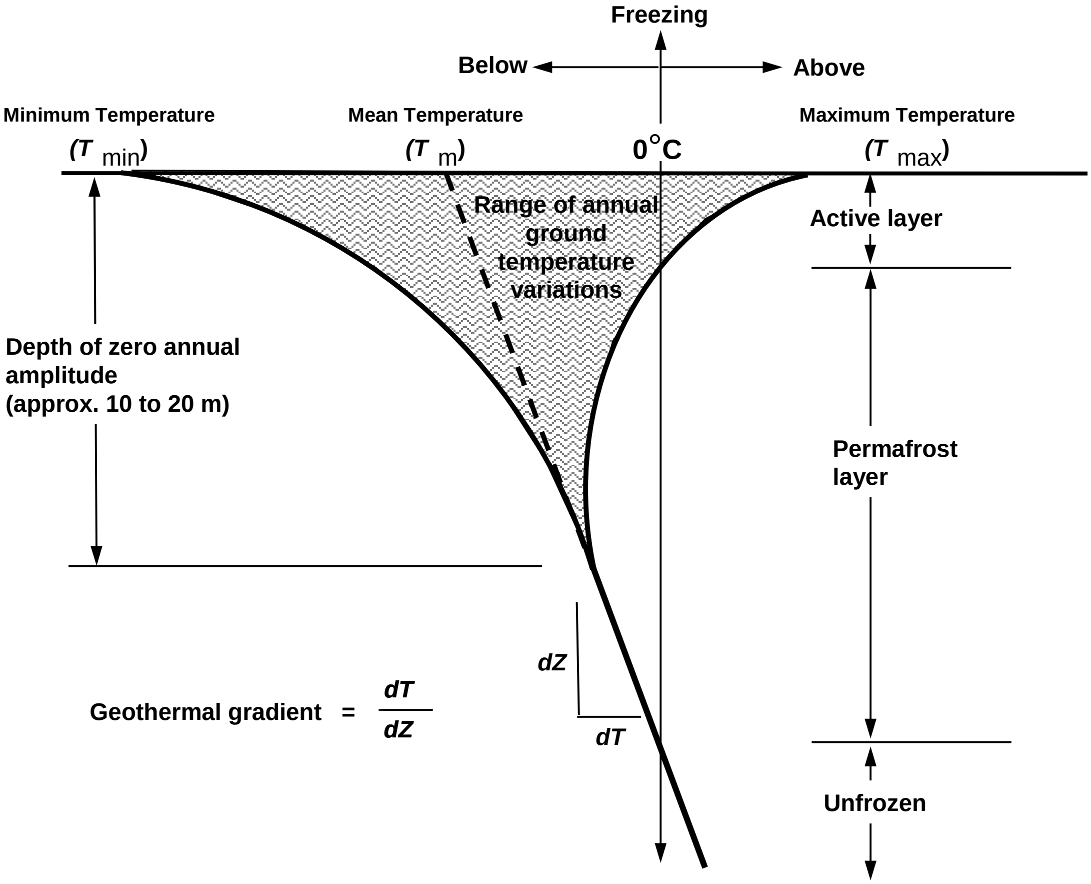

Figure 1: Ground Temperature Profile in Perennially Frozen Soil (after Andersland and Ladanyi, 2004)

Empirical tools have been developed to use meteorological data to calculate the mean annual ground surface temperature and amplitude. These empirical tools do not account for the effects of soil latent heat, differences in frozen and thawed thermal properties, non-homogeneity of the soils and non-symmetrical surface temperatures as a result of seasonal snow cover, vegetation and other localised climatic influences. Analytical closed-form solutions that include these elements to calculate ground temperature do not exist; however, researchers have developed computer models that take some of these elements into consideration (Andersland and Ladanyi, 2004).

Permafrost

Permafrost, also known as perennially frozen ground, is defined as ground (soil or rock) that maintains a temperature below 0°C for two consecutive years or more (French and Karte, 1988). Generally, permafrost forms when the seasonal depth of freezing exceeds the depth of thaw. Permafrost is a thermal condition dependent on climate, ground thermal properties, and surface conditions including vegetation and snow depth (Smith, 1993).

Distribution of permafrost is related to latitude and longitude and underlies 25% of the earth's surface (Tucker *et al*., 2004). Permafrost is geographically divided into two zones; continuous and discontinuous. Discontinuous permafrost occurs in scattered islands ranging from a few square meters to several hectares and its thickness will range from a few centimetres to up to 100 m where it forms a boundary with the continuous permafrost region. Typical permafrost profiles are illustrated in Figure 2.

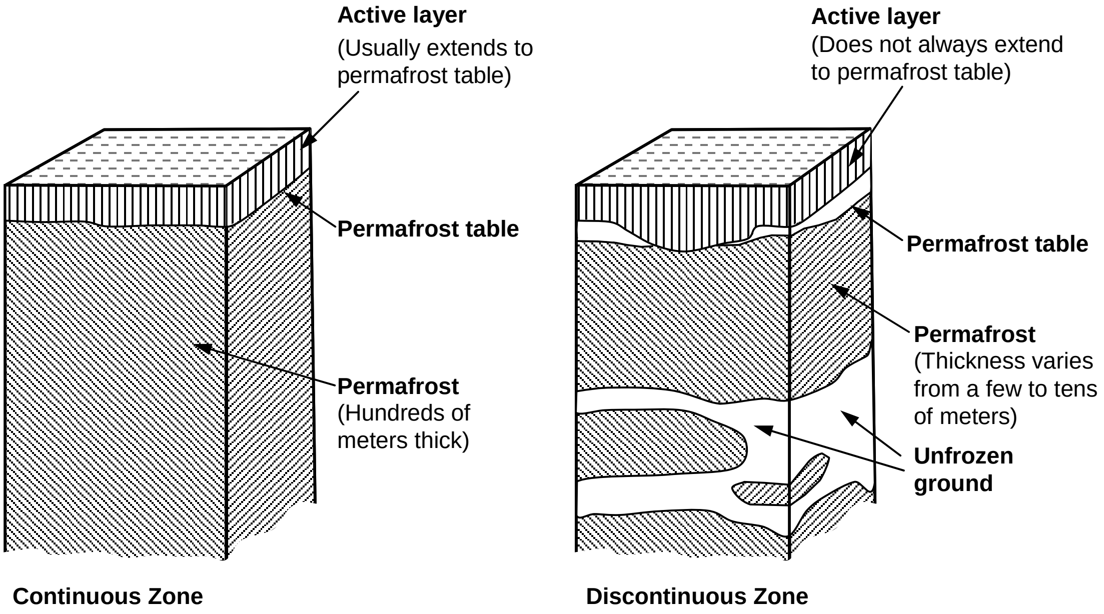

Figure 2: Typical Permafrost Profiles (after Andersland and Ladanyi, 2004)

Smith and Riseborough (2002) concluded that although permafrost is ultimately a climatic phenomenon, the southernmost limit of discontinuous permafrost is controlled by ground thermal conductivity, while the southern limit of continuous permafrost is controlled by nival offset (i.e. insulation due to snow cover). Andersland and Ladanyi (2004) state that the somewhat arbitrary boundary between discontinuous and continuous permafrost is the -5^{o}C isotherm of mean annual ground temperature measured just below the level of zero annual variation.

Physically demarcating the boundaries and thickness of permafrost is not easy, and therefore although generalized definitions are useful, site specific characterization of permafrost conditions are important when trying to evaluate environmental performance. Leverington (1995) presented results of field surveys for depths to frozen ground near Mayo, Yukon Territory, and noted that relatively few areas have been thoroughly sampled. Part of the reason is the lack of reliable remote, non-invasive techniques to do this. King and Gorbunov (1992) provide an example of the work that is carried out in this area, but specifically related to mapping of mountain permafrost. Permafrost distribution under streams has been accurately measured with ground penetrating radar (Bradford *et al.*, 2005); however, the use of geophysical techniques to define permafrost conditions is less than satisfactory.

The definition of permafrost is based only on ground temperature and does not necessarily imply the presence of frozen water or ground ice. However, freezing of water can occur in permafrost, and in fact leads to many of the effects on cover performance.

Active Layer

The surface layer of soil where temperatures fluctuate around 0^{o}C during the year is called the active layer. More specifically the active layer consists of the upper soil layer that thaws and re-freezes each year (Brown and Kupsch, 1974). This zone is also called seasonally frozen ground, seasonal frost, or annually thawed layer. The active layer thickness varies regionally and depends on many factors such as the severity of the winter (freezing index), soil and rock type, ground moisture content, snow cover, surface vegetation, drainage, and the degree and orientation of slopes (Andersland and Ladanyi, 2004).

In the continuous permafrost region, the active layer typically reaches the permafrost table, except in the vicinity of water bodies (see Figure 2). There are also areas where the active layer may be separated from the permafrost by a layer of permanently thawed ground. In the discontinuous permafrost region, the active layer may or may not extend to the permafrost table. An active layer could exist in non-permafrost cold regions due to sufficiently cold surface ground conditions driven by cold air temperatures, wind and thin snow cover.

The active layer directly and immediately affects any structure built in or on it if the soil is frost susceptible. This could include a cover. As the active layer freezes and thaws it undergoes significant volume change which in turn could result in heave and settlement. These issues are further exacerbated by the formation of ice lenses as water migrates by capillary action through the soil pores towards the freezing front.

2.2.2 Processes

Ground Freezing and Ground Ice Formation

Water present in void spaces of moist or saturated sand or gravel will freeze *in situ* when the temperature in the soil profile is below the freezing point. Water in the void spaces of saturated silt, or silty sand, can also freeze *in situ*, provided that the temperature is lowered rapidly. In both these cases ice lenses do not form.

It is more common for the temperature within a soil to decrease slowly enough that water has time to re-distribute itself, resulting in the accumulation of ice parallel to the freezing surface. The formation of ice is referred to as ice segregation, and the layers as ice lenses.

The tendency for ice lenses to form depends principally on three factors, the rate of cooling, the soil grain size and the availability of water. As noted above, ice segregation will not occur if freezing is very rapid. The dependence on soil grain size is more subtle. Silts appear to have the optimum grain size for ice segregation; the pores are fine enough to develop the capillary pressures that move water to the freezing front, but also conductive enough for flowrates to be significant. Coarser materials are less susceptible to ice segregation because of the weakness of the capillary effects. When there is a constant supply of moisture beneath the freezing front, ice lenses can become substantially thicker. If the vertical distance between the water table and the freezing depth is smaller than the height of the capillary rise of the soil, there is an opportunity for massive ice lens formation and frost heave (Andersland and Ladanyi, 2004). In fine-grained soils, ice growth can continue even when the soil is uniformly below 0^{o}C. The capillary tension of the fine pores causes water to remain liquid, so it can continue to move through the pore space to the freezing front.

Figure 3 illustrates formation of ice lenses under different conditions of water availability and capillary effects. Figure 3(a) illustrates the formation of ice lenses. Figure 3(b) illustrates how the combination of free water and a soil fine enough to exert capillary suctions can lead to continued growth of the ice lenses, resulting in heave of the ground surface. Figure 3(c) illustrates that coarse-grained zones can prevent the capillary effects that draw water to the ice lenses.

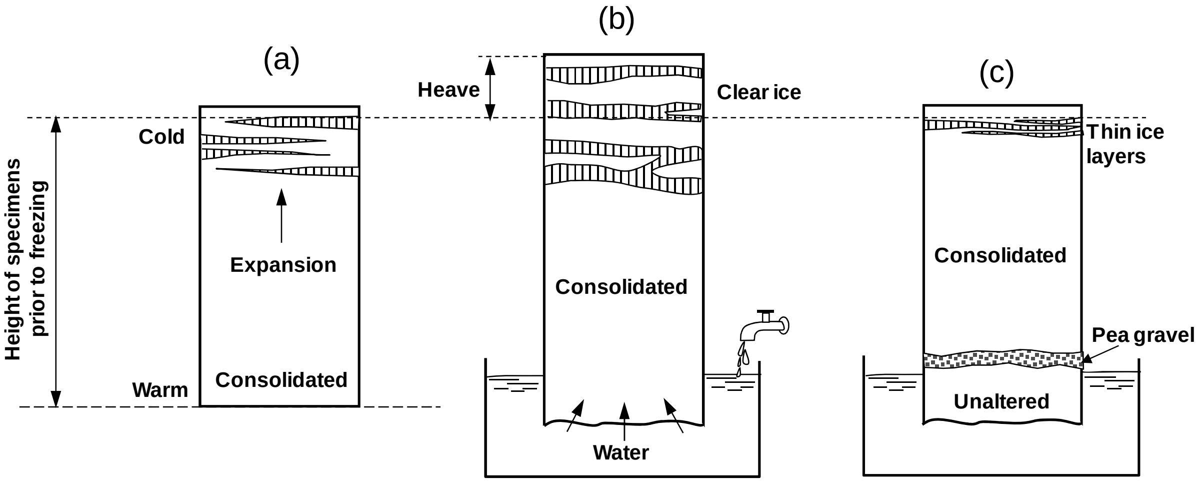

Figure 3: Schematic Presentation of Ground Ice Formation in Silty Soils (after Andersland and Ladanyi, 2004)

Othman *et al.* (1994) described the processes involved in freezing of clay soils, and states that large pore water suctions are generated next to the growing ice lenses, pulling water from unfrozen soil into the freezing zone, resulting in drying and consolidation of soils adjacent to the ice lenses.

Furthermore, a film of water next to clay particles remains unfrozen, even at low temperatures, and ice lenses may continue to develop even after the soil reaches temperatures uniformly less than 0^{o}C.

The growth of ground ice in permafrost zones occurs due to cycles of freezing and thawing of the active layer. Mackay (1980) summarized the work of Parmuzina (1978, in Russian), who found that as the active layer thaws, moisture may migrate down to frozen ground, resulting in the growth of ice lenses at the bottom of the active layer in late summer (also supported by Mackay (1983)). Unfrozen pore water may then migrate upwards from the top of permafrost after freeze back is completed and subsequently downward to the top of the permafrost when the thaw period is nearly complete.

As water freezes its volume increases by about 9%, which can lead to different types of soil displacement. Vertical soil movements associated with the freezing of water are referred to as frost heave and lateral movements are referred to as thrust (Washburn, 1973). Frost wedging is a term used for the prying apart of materials by the expansion of water upon freezing.

A different process is responsible for frost cracking, which is fracturing of the ground by thermal contraction at temperatures below 0^{o}C. Generally, low temperatures and rapid cooling create larger contractive stresses. The stresses are also higher where ice content is high, because the expansion coefficient for ice is five times that of most soils. Cracking occurs when contractive stresses exceed the frozen soil’s tensile strength.

A number of researchers have developed mathematical models to simulate soil freezing. Nakano (1999) presented such a model to study the expulsion of water from saturated soils during freezing. Newman and Wilson (1996, 1997) presented a model to predict heat and mass transfer in freezing, unsaturated soils without frost heave, whilst Konrad and Morgenstern (1982) and Black (1995) developed models for frost heave specifically. Padilla *et al*. (1997) presented a model called MELEF for simultaneous water, heat, and solute transport in saturated-unsaturated media. Li *et al*. (2002) presented a model for heat, moisture, and deformation of frozen soils.

Soil freezing is linked to cold regions soil hydrology. Farouki (2004) found that soil freezing is a dehydration process that is analogous to the drying process that occurs in soils above 0°C. Kane and Chacho (1990) and Hohmann (1997) presented more refined views of the freezing process in soils, but with a specific focus on frozen soil hydrology. This aspect is described in greater detail in Section 2.3 of this report.

Ground Thawing and Thaw Settlement

Thawing of frozen soil typically occurs when a frozen soil is heated at the surface by solar radiation, warm water, and/or by warm air. Thawing of a soil profile can progress from the top down, but also from the bottom up. The rate and depth of thaw depend on the duration and intensity of the applied heating, and on the insulation effects of snow and vegetation.

Ice in frozen ground is contained in several forms, ranging from massive deposits, to lenses of various thicknesses and coatings of individual particles. During thaw, ice will disappear and the soil matrix must adapt to a new equilibrium void ratio. Thaw of ice lenses contained in the soil will produce water that may be re-absorbed by the soil. Rapid thaw of ice may produce water that cannot be immediately re-absorbed by the soil. This sudden release of water may lead to high pore water pressures and a reduction in soil strength upon thawing (Andersland and Ladanyi, 2004).

The resultant effect of thaw is a process referred to as thaw settlement. Over time the soil will tend to revert back to its original volume and continues to consolidate even further if draining conditions exist. The original density of the material prior to freezing will determine how much additional consolidation will occur. For fine-grained soils subjected to slow freezing and significant ice lensing, the amount of soil moisture available during thaw far exceeds the moisture content of the soils in an unfrozen state. Therefore, these soils undergo volume change and settlement under their own weight.

Freeze-Thaw Cycles

Repeated freeze-thaw cycles break down soil structures in cold regions (as do wet-dry cycles in temperate regions) and can result in soil aggregates with fissures between them (Farouki, 2004). Although air temperature may cycle above and below 0^{o}C, the number of freeze-thaw cycles experienced by the soil is infrequent (French, 1993). More than one investigator has concluded that there are no freeze-thaw cycles for soils at depths below a few centimetres, aside from the annual cycle. For example, Nyberg (1993) found that the diurnal freeze-thaw cycles did not affect ground below a depth of 0.1 m on a mountain slope in northern Scandinavia, and concluded that the annual freeze cycle was more important to deep frost shattering of rocks. Cases have been documented where ground thawing occurs at negative air temperatures, and ground freezing at positive air temperatures (Washburn, 1973). Estimates of ground temperature from climatic data are available, but it is recommended that assessments of soil freeze-thaw activity be based on *in situ* measurements, rather than on meteorological data (Nyberg, 1993).

Researchers have started to develop models that can be used to predict soil moisture migration during freeze-thaw cycles. One example is Shoop and Bigl (1997), who modeled soil moisture migration during freeze-thaw using the FROSTB model, a coupled heat and moisture flow model.

Weathering is the breakdown of rocks and soils under the influence of various physical and chemical effects. Freeze-thaw weathering of rock materials has been subject to several investigations including Dhakal *et al*. (2004), Goudie (1999), and Konischeve and Rogov (1993). Prick (1997) recommended the use of a critical degree of saturation as a rock weathering parameter.

Cryoturbation

Cryoturbation is the general term for the small scale mixing of soil accompanying seasonal and/or diurnal freezing and thawing (French, 1993). The mixing is caused by frost expansion and thaw settlement and generally leads to disturbances on the scale of a metre or less. Cryoturbation can lead to highly variable conditions over scales of hundreds of metres because of the heterogeneous nature of most soils and frost action.

Solifluction/Gelifluction

Solifluction is the process of slow, gravitational, downslope movement of saturated, unfrozen/frozen sediments under the influence of gravity (Gorbunov and Seversky, 1999). Harris and Lewkowicz (2000) suggested that solifluction was responsible for gradual reduction of shear strength, resulting in active layer detachment and slide failures on slopes on Ellesmere Island, Nunavut.

Numerous factors cause solifluction, including perennial or deep seasonal freezing, prolonged thawing, soil type, moisture content, slope aspect, gradient, vegetation, depth of active layer, and permafrost. Gorbunov and Seversky (1999) divided solifluction into three basic types of movement: frost creep (classic solifluction), flow (*aka* gelifluction), and massive sliding of blocks (*aka* plug flow).

Frost creep is the ratchet-like downslope movement of particles produced by frost heave and subsequent thaw settlement, with heave normal to the slope and settlement nearly vertical (French, 1993). Matsuoka (1996) found that the combination of a thin debris mantle, and periodic precipitation during periods of freeze-thaw resulted in shallow frost creep.

Flow is the viscous behaviour that can occur on slopes of less than 10^{o} and may (Eigenbrod, 1993) or may not (Harris *et al*., 1995) be related to excess pore water pressures. Massive sliding of blocks generally occurs in the upper 1 m of the soil profile.

Washburn (1973) coined the term gelifluction, under the assumption that it implies solifluction associated with frost action. This has however not been well received (Gorbunov and Seversky, 1999). Harris (1996) and Harris *et al*. (1995) used the term gelifluction to mean flow of saturated soils near or above the liquid limit. Thawing of ice-rich soils leads to a loss of frictional strength, or softening, which results in viscous flow of near-surface soils, rather than slope failure as determined by traditional slope stability analysis.

Harris (1996) proposed a continuum of processes with frost creep dominating at lower rates (millimetres per year), and flow (defined as turbulent soil flow where grains rotate) dominating at higher rates (tens of centimetres per year). Matsuoka (1998) presented two empirical models for frost creep formation. Actual measurement of solifluction rates were reported by Lewkowicz (1992), who presented a device to measure solifluction, using manual or automated data recording.

Convective Cooling

Convective flow of cold winter air through coarse rock materials can cause significant cooling. The convection is driven by the difference in temperature between the air and the rock, which retains some of the heat it gains during summer. Air within the rock pore space is slightly warmed by contact with the rock, which causes it to rise. The rising air pulls colder air into the toe of the rock deposit. The resulting convective cycle continues until either the rock is cooled to the same temperature as the surrounding air, or summer conditions cause the air temperature to rise above that of the rock. The phenomenon has been studied as a means to prevent permafrost degradation beneath roadways, railways and other linear features constructed from coarse-grained material.

Harris and Pedersen (1998) observed that coarse materials were 4 to 7^{o}C colder than adjacent finer grained mineral soils in the upper 50 cm of profiles at Plateau Mountain, Alberta. Likewise, data from the Tian Shan Mountains, China indicated that near surface coarse, blocky materials were significantly cooler than adjacent fine grained soils, and 2.5 to 4°C cooler than mean annual air temperatures. Gorbunov *et al*. (2004) stated that coarse blocky materials were natural accumulators of cold, and have a considerable cooling influence on the thermal regime of adjacent soils. In fact, formation of permafrost below coarse materials was possible, even with a mean annual air temperature of 4 to 5°C.

Goering (2003, 2004) modeled the convective flow of air through a porous embankment and concluded that passive cooling during winter could overcome warming due to construction. In a similar numerical modeling study, Goering and Kumar (1996) showed that convective flow through a porous embankment resulted in cooling in winter, but that convection stopped during the summer months, limiting heat loss to conduction. The effects result in preservation of basal permafrost layers by cooling during winter months. These results were later confirmed in field scale experiments (Goering, 1997).

Yu *et al*. (2004) carried out laboratory tests and modeling to show that that the cooling effect of coarse rock depended on the thickness of the layer, climate, and permafrost conditions. They also reported that a cover with a mean particle size of 7 cm was more effective at cooling than a cover with a mean particle size of 22 cm, possibly due to surface boundary effects on air flow.

2.2.3 Terrain Features

Ice Wedges

Ice wedges are vertically orientated, relatively pure ice that occur close to the permafrost surface, and generally are only formed in continuous permafrost regions. Ice wedges are wider at the top than at the bottom and can range in height from 1 cm to 10 m (Harry and Gozdzik, 1988; Andersland and Ladanyi, 2004). The process is started through the formation of a single crack formed as a result of thermal contraction, desiccation, differences in salt concentrations, or frost cracking (Washburn, 1973) during the winter and may only be a few millimetres wide but can be several metres deep. During spring, meltwater fills these cracks, freezes, and a vertical ice wedge in the permafrost is formed.

Temperatures rise during the summer, and the permafrost expands, causing horizontal compression and upturning of adjacent soil. The following winter, thermal contraction re-opens the crack because it is now a zone of weakness. In the spring, more water, and subsequently ice, is added to the wedge. This process repeats itself for hundreds of years resulting in substantial subsurface ice formations. The original ice wedge crack will originate at ground surface; however, subsequent reoccurring cracks during the growth process appear to start at the permafrost surface, i.e. below the active layer.

Ice wedge growth results in upturning of surface strata within 3 m of the wedge, creating surface ridges. Although ice wedges can occur singly, they generally appear in clusters connected at the surface, referred to as ice wedge polygons. Local frozen surface soil strength and the width of the stress relief zone adjacent to individual cracks determine the polygon diameters.

Pingos and Palsas

A pingo is a mound or hill with a core of massive ground ice covered with soil and vegetation. Pingos occur in continuous and discontinuous permafrost zones (Brown and Kupsch, 1974). Pingos develop in thick alluvial, deltaic, or glaciofluvial sands with negligible fractions of coarser or finer grained sizes. Typically these sands are not frost susceptible, lacking sufficient fines to produce either frost heave or thick ice lenses.

Generally pingos are classified as closed-system (hydrostatic) or open-system (hydraulic). Closed-system pingos, such as those in the Mackenzie delta area of Canada, form as a result of hydrostatic pressure of water from permafrost, and commonly form in shallow lakes (lakes that completely freeze in winter), drained lakes, or river channels. Permafrost aggrades into the drained body's former floor and pore water is expelled in front of the rising permafrost. The resulting pressure causes the frozen ground to rise, and an ice core forms. Closed-system pingos can be symmetrical conical domes or asymmetric, elongate hills.

Open-system pingos (also known as Greenland type pingos) result from water flowing from an outside source (e.g. sub-permafrost or intra-permafrost aquifers). Hydrostatic pressure initializes the formation of the ice core as water is pushed up and subsequently freezes. There is no limitation to the amount of water available for an open-system pingo, unless the aquifers freeze. These pingos often occur at the base of slopes, and the groundwater source is put under artesian pressure where it forces the ground up while forming an expanding ice core. It is not the artesian pressure itself that forces the ground up, but rather the ice core that is being fed by the aquifer. These pingos are often oval or oblong shaped.

Palsas are elongated mounds (maximum height of 10 m) composed of a peat layer overlying a mineral soil. Palsas have a frozen soil core and are found mainly in regions of discontinuous permafrost, often occurring in bogs (Brown and Kupsch, 1974). Palsas contain ice lenses, distinguishing them from pingos, which contain a massive ice core, and can be mound shaped or have straight or winding ridges (Washburn, 1973). There are two types of palsas; those with a peat core and those with a core of mineral soil, usually silt.

Palsas usually develop in bogs where the winter freezing front penetrates relatively faster than surrounding areas, often due to an unusually thin cover of snow (Seppala, 1986). The lack of thermal insulation allows much deeper winter freezing and subsequently, the frost will last longer through the summer, resulting in a persistent *bump* of up to several centimeters due to frost heave. The elevated surface ensures less snow cover in subsequent winter seasons, allowing greater winter cooling, while in summer the surface material (especially if organic) will dry out and provide thermal insulation. Thus, the interior temperature is consistently lower than that of adjacent ground. This contributes to the formation of an ice lens which grows by drawing up surrounding water.

Palsas occur as mounds, moderately straight ridges, and winding ridges. Pingos are generally isolated, while palsas commonly develop in groups called a palsamoor.

Thermokarst

Thermokarst covers a broad range of surface features resulting from differential melting of ground ice in permafrost (Brown and Kupsch, 1974; French, 1993). Disruption of the permafrost thermal regime, leading to thermokarst development can occur on two scales; broad-scale environmental change such as climate warming, or local environmental changes such as cyclic changes in vegetation, shifting of stream channels, fire, and human interaction such as farming, construction, or clearing of vegetation.

Andersland and Ladanyi (2004) describes thermokarst from a geomorphological point of view, the origin of thermokarst can be divided into two groups: lateral permafrost degradation (backwearing) and permafrost degradation from above (downwearing). Fluvial, lacustrine and marine erosion is largely the cause of backwearing. Examples include rivers in permafrost areas undercutting banks during spring thaw, and exposing ground ice that subsequently melts and collapses.

Downwearing is generally restricted to relatively flat areas and the thermokarst features depend on the amount and type of ice present. Forest fires often result in downwearing as described by Andersland and Ladanyi (2004), where the active layer increased from 40 to 80 cm as a result of a forest fire, which in turn may lead to ground settling of some 20 cm. Burn (1998) examined the effect of forest fires on permafrost in the Takhini River Valley, Yukon Territory. Beneath an unaffected area of trees from the forest fire the active layer was 1.4 m thick, and permafrost was 18.5 m thick. Approximately 35 years after the forest fires, the active layer had increased to 3.75 m.

Patterned Ground

The collective term for the characteristic geometrical ground surface patterns common to permafrost is patterned ground. It can be divided on the basis of circles, polygons, nets, steps and stripes, as well as on the presence or absence of sorting (i.e. segregation of fines and stones) (Washburn, 1973). Most patterned ground forms are named for their shape, but competing terminologies may be based on the process of formation.

Drying and/or frost cracking is the likely initiating process in creating polygonal patterns, while local differential heaving could be the origin of circular patterns. Frost heave and thrust is the principal cause of sorting. Although these definitions are generally accepted, formation of patterned ground is not well understood, either quantitatively or qualitatively (Washburn, 1973).

Price (1972) theorized that in heterogeneous material, there would be areas with greater concentration of fines than in others. These areas will have a greater potential to retain moisture, and as a result of freezing, will experience greater expansion. Upon thaw, the material will contract and the fines will be drawn back together by surface tension forces; however, the coarser material will not contract as much. With every subsequent freeze-thaw cycle, more fine material is drawn in, and the coarse material pushed further away. This process is continuous, resulting in sorted circles or polygons. This process also applies to slopes; however, the features will generally be elongated by the down-slope movement of materials due to gravity.

Sorted circles range from a few centimetres to 3 m in diameter, and extend to a depth of 1 m. Stone size typically increases with circle size, and the largest stones tend to be at the surface. Bare circular areas with a vegetative border, generally 0.5 to 3 m in diameter, are referred to as non-sorted circles. Sorted and non-sorted circles may occur singly or in groups and are mostly on level ground. If they do occur on slopes they are referred to as non-sorted or sorted stripes.

A border of stones surrounding a central area of finer material defines a sorted polygon. Stone size in the border increases with polygon size and decreases with depth. Rocks in the borders are oriented parallel to the border and are often on edge.

Non-sorted polygons are identified as polygonal-shaped surface features, often delineated with a crack or furrow, and without a border of stones. Often vegetation will concentrate in the cracks, emphasizing the feature. In middle latitudes, non-sorted polygons often appear in dried up mudholes and are associated with desiccation cracking. Large non-sorted polygons are found in permafrost and are associated with ice wedges. These ice wedges form the polygon border, which may be raised or depressed, with respect to the central area, depending on whether the wedges are actively growing or thawing, and erosion dominates.

Sorted and non-sorted polygons never occur singly and form best on horizontal surfaces. Sorted polygons range in size from 10 cm to 10 m in diameter, and non-sorted polygons range in size from a few centimetres up to 100 m in diameter.

Sorted stripes can range from a few centimetres to 1.5 m wide, but can be more than 100 m long. Steeper slopes result in straighter stripes. Likewise, non-sorted stripes range in size from a few centimetres to 2 m wide and can extend downslope for several tens of metres.

Steps are developed from sorted or non-sorted circles and polygons, and are observed as a terrace-like feature that has a downslope border of vegetation or stones. The downslope border of a step consists of a low riser fronting a tread, the gradient of which is less than that of the general slope (Washburn, 1973).

Patterned ground features also vary with drainage patterns. Van Vliet-Lanoe (1988) defined five drainage classes and linked them to classes of patterned ground as summarized in Table 2.

Table 2: Soil Drainage Classes and Patterned Ground (Van Vliet-Lanoe, 1988)

Unfrozen Soil Drainage Class	Equivalent Frozen Ground Drainage Class (with resultant patterned ground)
Shallow Pond	Palsas
Poorly drained soil with shallow water table at less than 5 cm in sands or with pF <1 close to the surface.	Flat mudboil or stone circles, poorly expressed, low centre polygons, heaved blocks
Imperfectly drained soil with a capillary fringe allowing a stable field capacity at 50 cm depth (1<pF<2.5, except in organics).	Most of the patterned grounds associated with a flat micro-topography
Moderately well drained soil with a capillary fringe allowing a stable field capacity at 50 cm in depth. Surface pF is usually above 2.5.	Hummocky soils, high centre patterned ground
Well to extremely well-drained soil, no detectable water table. Profile only slightly humid (normal surface pF >3)	Hummocky soils, high centre patterned ground

Note: pF = unit of soil-water suction expressed in log of cm H_2O

Boulder Fields/Pavements

Vertical, rotational, and lateral movements of stones have all been attributed to frost action. Repeated action may result in sorting of soil and rock particles. For natural systems, frost heave has been observed to act on rocks within a mass of finer grained soil (Gozdzik and French, 2004). The thermal conductivity of the rocks is higher than fine soil, causing the soil beneath the rocks to be chilled more intensely. Water migrates to the freezing front, freezes, and thereby lifts the rock. During thaw, the migration of water and fine soil prevents the rock from completely returning to its original location. Repeated freeze-thaw cycles result in the heaving of rock material within the active layer and may eventually form boulder fields. The same mechanisms have been observed to heave poles out of the ground (Yershov, 1998).

Pissart and Francou (1992) documented vertical movements in an alpine sub-nival boulder pavement (i.e. below a snow cover), and proposed that upheaval occurs in autumn, and sinking occurs in spring. Berthling *et al*. (2001) noted that the majority of boulder heave at a site in Norway happened during late autumn and early winter. Viklander (1998a) compared frost heave of stones and related direction of heave to void ratio of the soil. He found that stones moved down in a dense till, and upward in a looser till. Viklander and Eigenbrod (2000) found that frost heave of stones was much greater in open systems with access to water, compared to closed systems.

Mounds and/or Hummocks

Cold regions literature uses the terms mound and hummock synonymously. Frost mound is a generic term for all mounds involving: (1) volumetric expansion of water when changing to ice; (2) hydrostatic and/or hydraulic pressure of groundwater; and (3) forces of crystallization during freezing. The variety of frost mound structures (perennial and seasonal) includes pingos, hydrolaccoliths, palsas, hummocks, frost and icing blisters, and icing mounds.

According to Mackay (1980), hummocks are low mounds that are either vegetated or have bare centres, which may develop non-sorted forms of nets (Brown and Kupsch, 1974). The formation of hummocks is complex and no mechanism of formation has been agreed upon (French, 1993). Hypotheses for the formation of hummocky ground include the cryostatic hypothesis, an equilibrium model, frost churning, and a density gradient or diapir model.

The cryostatic hypothesis for the formation of hummocky ground involves soil circulation driven by the generation of pore water pressures upon freezing. Unfrozen pockets of soil are said to be trapped between a downward advancing freezing plane and the frozen ground beneath, generating a hydrostatic pressure driving soil circulation (Washburn, 1973). However, the cryostatic hypothesis for hummock formation was rejected due to evidence provided by Mackay and MacKay (1976) who found that during freezing, mud froze from the outside (top, bottom, and sides), towards the inside of the hummock resulting in ice lens formation around the edges of the hummock, with the centre of the hummock becoming desiccated and over-consolidated during freezing. It was concluded that soil mobility is greatest in summer when there are volume changes from the melting of ice lenses (horizontal) and thermal contraction from ice veins (vertical) with the release of excess water (Mackay and MacKay, 1976; French, 1986). Mackay (1980) however disagreed with the cryostatic hypothesis on the basis that: (1) moisture in the unfrozen zone of the hummock was under suction, (2) cryostatic pressures had never been measured in field conditions, and (3) cell circulation appears to occur in late summer when the active layer is fully thawed.

Mackay (1980) proposed an equilibrium model for hummock formation whereby the freeze-thaw at the top and bottom of the active layer produced a cell type of circulation because the two freezing surfaces have opposite curvatures. Mackay (1980) distinguished hummocks from mudboils on the basis of soil type and also mechanism of formation. Hummock soils have higher clay contents, liquid limits, and plasticity indexes than mudboil soils. Mudboils are much more active than hummocks, with a tendency to liquefy and flow in response to changes in moisture content or stress. Hummocks are more stable, and may persist for several thousands of years. The frost table beneath hummocky ground is bowl shaped; the bare ground having a deeper active layer than adjacent vegetated ground. Mackay (1980) also presented laboratory evidence for development of a mound in a kaolin clay slurry. This slurry was placed in a bowl subjected to upward and downward freezing.

Another hypothesis on the formation of hummocky ground is frost churning, where repeated frost heaving and ice segregation within the active layer results in non-sorted circles (French, 1986). The frost churning hypothesis has been rejected for certain sites due to indications of rapid feature formation, rather than slow, incremental growth. Key to the mechanism of frost churning is that frost heave tends not to be fully reversible upon thawing (Hallet and Waddington, 1992). Frost churning may be similar to the equilibrium model described by Mackay (1980), and may be applicable to hummocks, rather than mudboils.

Seasonal Frost Mounds

Seasonal frost mounds are somewhat different in nature as they are generally ephemeral, grow rapidly over a short timeframe (single season) and their genesis appears to be an injection of groundwater under pressure (Dijkmans, 1988). Three types of seasonal frost mounds are distinguished: frost blisters (surficial icing overlain by ground, ice, a water filled or empty cavity and frozen ground respectively); icing blister (icing overlying a water-filled or empty cavity); and, (3) icing mound (icing blister lacking the cavity).

Dijkmans (1988) described an example of seasonal frost mounds occurring in stable aeolian sand formations within one season, measuring 12 m long, 4 m wide and 50 cm high. Frost mound degradation will lead to relict forms of depressions, and Dijkmans (1988) presents examples where such frost mound scars can be observed in nature.

Mudboils, Circles, Diapirs

The terms mudboil, circle, and frost boil are treated as synonymous for this report. As per the definition of Mackay (1980), mudboils are associated with rapid formation; however, mudboils may result from the same mechanism in either a single event, or a cumulative process (Walker *et al*., 2004). Mudboils are associated with a diapir type action involving the flow of finer soils to the surface, and Shilts (1978) described mudboils as elongate 1 to 3 m diameter soil patches that form on perennially frozen materials with significant silt or clay content.

Swanson *et al*. (1999) examined a phenomenon where fine grained soils move upward through overlying soils by viscous flow upon thawing. No agreement to the mechanism of action for the formation of so-called “soil diapirs" has been made, but several hypotheses have been presented.

Shilts (1978) documents that the natural moisture content of mudboils are near the liquid limit so that the mud liquefies and flows in response to slight changes in moisture content or stress (internal or external). When stress cannot be relieved by down-slope movement, mud may burst through a rigid surface layer, creating and/or maintaining a mudboil. The upwelling of mud at the centre of a mudboil is called a diapir. Shilts (1978) attributed the formation of mudboils to hydrostatic or artesian pressures on a slope, excess pore pressures due to rain or thawing ice lenses, or to loading by surface traffic.

Another hypothesis for the formation of mudboils is reversed density gradient, where higher density soils overlie lower density soils with high moisture content. Saturation of the active layer may be sufficient to produce reverse density gradients, which, when coupled with liquefaction, result in injection of underlying sediments to the surface. The formation of such structures would occur in late summer, with the development of relatively high pore water pressures (French, 1986).

Hallet and Waddington (1992) modeled thaw consolidation with respect to buoyancy forces and found that the density profile of a soil can be gravitationally unstable for much of the thaw season. The model results correspond to field evidence indicating that fine grained soil commonly moves upward in periglacial areas, particularly when groundwater conditions are favourable. Buoyancy effects occur when bulk density differences are significant, and these effects are two orders of magnitude greater than the effect of water density variances as a result of temperature variance from 0°C to 4°C. Hallet and Waddington (1992) provided a mathematical argument to support their conclusion that buoyancy is generally incapable of driving wholesale soil circulation in a laterally uniform active layer. However, buoyancy may incrementally contribute to cryoturbation/frost churning, and may provide a significant and persistent upward force on frost-susceptible soil at depth (Hallet and Waddington, 1992).

Hallet *et al*. (1988) documented horizontal soil movements in 3 m to 5 m diameter sorted circles made of a fine grained inner portion surrounded by gravel. The movements suggested intermittent soil convection in the active layer, possibly driven by buoyancy forces resulting from a vertical gradient in soil moisture that arises from thawing of ice rich soil. Another potential mechanism thought to induce convection was settling of gravel borders in sorted/non-sorted circles during summer that were previously elevated by frost heave.

Involutions

The terms “periglacial involution”, “involution,” “Brodelboden,” and “cryoturbation” refer to commonly described distortions in near-surface soils thought to be due to intense frost action (Washburn, 1973; French, 1986; Vandenberghe, 1988). The method of formation is not well understood, and little study has been completed on the near-surface soil profiles of involutions (Washburn, 1973).

Involutions form mainly at the thaw unconformity, i.e. where active and frozen layers meet. Murton (2001) suggested that if involutions are less that 80 cm below surface, they could be a result of frost and heave actions. Deeper involutions are usually associated with degradation of permafrost and deformation of soft sediment during active layer deepening. It is also thought that when the active layer is trapped at the start of winter between the frozen surface and the permafrost, the resulting pressure will distort the trapped strata, causing involutions. Another theory suggests involutions may result from pressure exerted by expanding ice segregations.

Rock Glaciers

Rock glaciers are lobate or tongue shaped bodies of perennially frozen, unconsolidated material supersaturated with interstitial ice and ice lenses. Rock glaciers move downslope or down valley by creep as a consequence of the deformation of ice contained in them. Rock glaciers are found in all major high mountain systems of the world, and are typically derived from sources such as talus slopes, moraine deposits, and occasionally, from mine waste rock dumps. They are categorized as tongue shaped if length is greater than width, or lobate if width is greater than length. Shape is typically controlled by the surrounding topography and by input of rock fragments. Rock glacier movement is relatively constant, with rates of movement ranging between 10 mm/year to 2,000 mm/year depending on the rock glacier (Barsch, 1996).

Typically, active rock glaciers have a blocky mantle, 2 to 5 m thick, overlying an ice saturated core, 30 to 50 m thick, with mainly fine-grained material. Ice content is typically 50 to 70% of the entire mass, but may approach 100% by volume. Rock glaciers are generally found in continental and cold mountain areas, which experience dry winters. They are not well developed in high maritime and humid tropical mountains (Barsch, 1992). Tenthory (1992) examined the hydrology of rock glaciers by tracer test and concluded that the supply of water to a rock glacier is from perennial névés, or snowmelt.

Ploughing Boulders

Ploughing boulders are rocks on surface that move down slope faster than adjacent soils, leaving a furrow or groove upslope, and a wave or ridge of material immediately downslope. Ploughing boulders are only found in areas of active solifluction, on frost susceptible soils with low plastic and liquid limits. Movement is thought to be related to thaw of soil downslope and beneath the boulder (Ballantyne, 2001). Berthling *et al*. (2001) correlated boulder height heave with the square root of the freezing index for five ploughing boulders in Norway.

2.2.4 Rates of Frozen Ground Phenomena

The significance of frozen ground phenomena for cold regions covers will depend on the time scales under consideration. Rates of frost heaving in roadbed materials have been extensively studied in the laboratory and in the field. Figure 4 illustrates the rates of frost heaving observed in soils with various percentages of fine material.

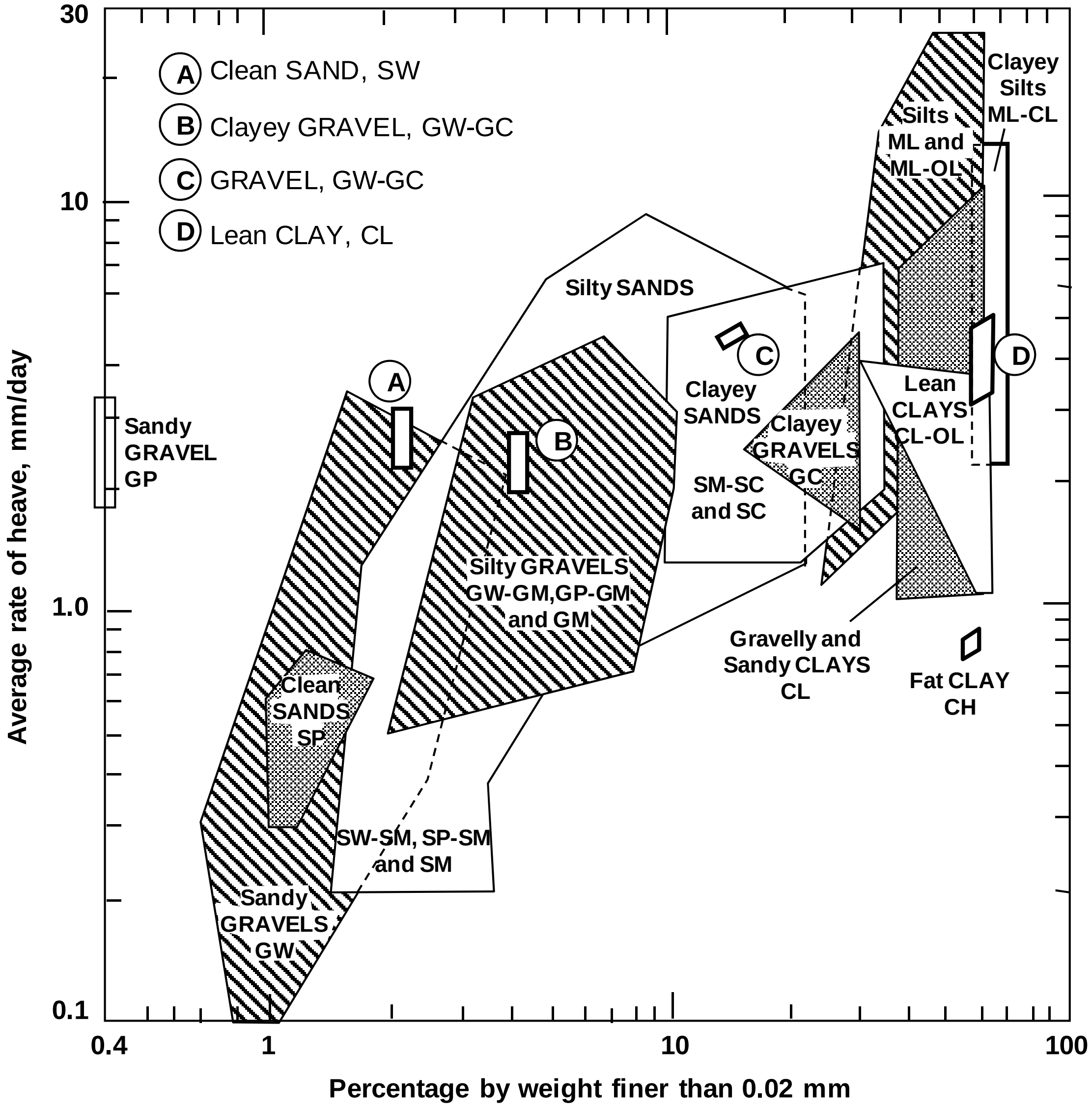

Figure 4: Chart for Estimating Frost Heave Rate in Subgrade Soils (AASHTO, 1993)

Unfortunately, much of the periglacial literature focuses on explaining observed features, without reference to their rates of formation. The rates of some frozen ground processes occurring in natural systems in the Tianshan mountains of central China were measured by Zhu (1996). Table 4 presents a summary of rates and time scales reported by Zhu (1996) and others.

Table 3: Rates of Selected Cold Regions Phenomena (after Zhu, 1996 and Others)

Process	Condition	Rate or Time Scale
Bedrock cracking	Schist	19 mm/year dilation
	Gneiss	4 mm/year dilation
Limestone weathering (Konischev and Rogov, 1993)	Saturated	1 to 10 mm/year
	Dry and locally saturated	0.1 to 0.01 mm/year
Frost heave of diorite	Diorite	8 to 40 mm/year
	Lomborinchen (2000)	7 to 25 mm/year
Movement of boulders	Pissart and Francou (1992) – vertical heave	-12 to 120 mm/year
	Berthling *et al*. (2001)	30 to 70 mm/year
Alluvial talus	South facing	1460 mm/year
	North facing	730 mm/year
Rockfall talus		1000 mm/year
Block slopes	Sunny or semi-sunny	96 mm/year
	Shady or semi-shady	72 mm/year
	Average	81 mm/year
Rock glaciers	Tongue shaped	400 mm/year
	Lobate 8	10 to 490 mm/year
	Average	60 mm/year
	Barsch (1992, 1996)	10 to 5000 mm/year
Mudboils, soil diapirs	Swanson *et al*. (1999)	1 to 12 days
Hummocks	Hallet and Waddington (1992)	20 years (0.3 to 300 yrs)
Sorted circles	Hallet *et al*. (1988)	10 years (lasting up to 500 yrs)
Solifluction/Gelifluction	East Tianshan (21° dip)	250 mm/year
	West Tian Shan (29° dip)	490 mm/year
	Gengnian *et al.* (1995) (12-31° dip)	8 to 111 mm/year
	Gorbunov and Severski (1999)	1 to 300 mm/year
	French 1976, Washburn 1999, Jahn 1975	4 to 27 mm/year
	Banks Is. 14-22° dip	9 to 37 mm/year
	Mesters Vig 10-14° dip	15 to 120 mm/year
	Spitsbergen 11-15° dip	20 mm/year
	Lapland 15° dip	9 to 380 mm/year
	Norra Storfjall 5° dip	60 mm/year
	Okstindan 4-17° dip	93 to 210 mm/year
	Karkonosze Mt. 8-39° dip	30 to 50 mm/year
	Grytviken 21° dip	50 to 100 mm/year
	Northern Canada (French 1993)	5 to 100 mm/year
	Canadian Rockies (Smith 1992)	4 to 5 mm/year on average
	High Arctic (Washburn 1999) (7° dip)	28 mm/year
Pingos		Few cm per year

2.3 Cold Regions Hydrologic Phenomena

2.3.1 Precipitation

On a continental scale, annual precipitation generally decreases with increasing latitude due to the inverse relationship between the moisture holding capacity of an air mass and temperature (Sellers, 1965). Within North America, mean annual precipitation generally decreases from 400 mm in the sub-arctic to less than 200 mm in arctic regions (Environment Canada, 1993). At a regional scale, precipitation generally increases with elevation in response to orographic lifting of an air mass to ascend a mountain slope.

Smaller scale topographic effects are not as obvious but may be significant in some situations. In rugged terrain, precipitation is not only related to elevation, but to aspect, slope, distance from moisture source, temperature and wind characteristics. Windward slopes may exhibit a well-defined pattern of increasing precipitation with elevation; however, this relationship would not be apparent on leeward slopes and sheltered valleys. There are also significant differences between rainfall and snowfall patterns in mountainous terrain (Sellers, 1965). The greatest short duration rainfall intensities occur during convective storms, which are associated with relatively small air mass cells that produce isolated patterns of rainfall. Convective events of this nature would not generally be subject to elevation effects. Snowfall over an area tends to be more uniform than rainfall, but its accumulation and retention tends to be highly variable.

2.3.2 Snow

Accumulation and Ablation

Pomeroy and Gray (1995), Marsh *et al*. (1999) and Woo *et al*. (2000) provide summaries of recent work that characterize the spatial variation of snow cover. Variations in snow cover occur at scales ranging from a macro (10 to 1,000 km), meso (100 m to 10 km) scale to a micro (10 m to 100 m) scale (Pomeroy *et al*., 2002). At the macro scale, snow accumulation variations are due to variations in snowfall as a result of effect of latitude, elevation, orography and water bodies. At meso scales, snow accumulation is influenced by topographic features and vegetation cover, and at micro scales, due to interception and wind redistribution. Snow accumulation varies significantly between forested and open environments because of variations in interception, sublimation and wind redistribution.

In a forest environment, the spatial variation in accumulation is primarily a result of variations in canopy coverage and proximity to individual trees that influence the interception and sublimation processes (Pomeroy *et al*., 1998). Comparison of snow accumulation amounts between coniferous forest stands and clearings show snow accumulation to be greater in clearings. Toews and Gluns (1986) found snow accumulation to be 4 to 118 % greater in forest clear-cuts in south-eastern British Columbia. Golding and Swanson (1986) found snow accumulation in Southern Alberta forest clearings to be 20 to 45% greater than adjacent forest stands. Pomeroy *et al*. (1998) found interception by Northern Saskatchewan boreal forests to be up to 67% of annual snowfall. Of this amount 10 to 45% was found to sublimate depending on tree species. A four-year study in a spruce forest in Yukon's Wolf Creek Research Basin, showed seasonal snow interception ranging between 46 and 70%, and sublimation ranging from 38 to 45% (Pomeroy *et al*., 1999).

In open environments, spatial variations in accumulation are strongly related to wind exposure and vegetation. Topographic features that produce major divergence in airflow patterns result in differential ablation and deposition rates affecting snow accumulation patterns. Wind will redistribute snow cover from an area of greater exposure to more sheltered locations, with some sublimation of blowing snow. Above the tree line (or areas devoid of vegetation such a mine sites and associated features such as waste rock dumps and tailings ponds), snow is blown from exposed sites to areas with sharp slopes, such as depressions, gullies, and hill slopes in the lee of dominant wind flows, or vegetated areas of grass cover or shrub land.

As the snow is transported, some of it sublimates and never reaches the accumulation site. When vegetation extends above the snow cover, the site acts as a sink and will trap more snow than is eroded. With the opposite scenario, a snow cover over the vegetation, acts as a source, with further accumulations more easily eroded and transported to more sheltered or vegetated sites. Snow surveys across hillcrests and through the lee side of abrupt slopes indicate greater variability than those on flat or gently rolling terrain.

The effect of vegetation on snow accumulation can be great. Gray *et al*. (1979) show accumulation on brush covered hill slopes to be 10 times greater than bare slopes. The variability in accumulation over landscapes with vegetation taller than brush (1 to 2 m) is generally lower as vegetation tends to dampen the variability. Pomeroy and Gray (1995) found up to 75% of snow cover to be transported from fallow fields with fetches in the excess of 4 km in southern Saskatchewan.

Pomeroy *et al*. (1999) found sublimation and transport losses from fallow fields to be 24 and 15% of seasonal snowfall, respectively. Transport to shrub filled valleys increased snow water equivalent by 50 to 150% of seasonal snowfall (Pomeroy *et al*., 1998a). In a four-year study of sublimation in northern Alaska, Liston and Strum (1997) found sublimation amounts to range from 10 to 25% of winter precipitation. Similarly Pomeroy *et al*. (1997) found sublimation to be 20% of winter precipitation at Trail Valley creek near Inuvik, NT. Pomeroy *et al*. (1999) carried out a four-year study of seasonal blowing snow fluxes in the Wolf Creek Research Basin in alpine tundra and shrub tundra environments, and on the lee side of a hillside downslope of the alpine tundra site. The researchers found the alpine tundra site to have snow transport and sublimation losses that ranged from 39 to 79% of annual snowfall of the four years and found the site to experience blowing snow events on 20% of all winter days. The shrub tundra site was found to have snow transport and sublimation losses that ranged from 17 to 46% of annual snowfall and experienced blowing snow events on 7% of all winter days. The hill slope drift formation was found to have gained 191% of annual snowfall due to blowing snow transport.

Janowicz *et al*. (2006) found average snow depth and snow water equivalent (SWE) to be 56 cm and 126 mm respectively across flat terrain at three waste rock dumps at the Anvil Range Mining Complex near Faro, Yukon, during a late winter snow survey. Areas of hummocky terrain produced by end-dumping of the waste rock had an average snow depth of 89 cm and an average SWE of 247 mm. While snow depth was 59% greater in the hummocky terrain, SWE was 96% greater, indicating that density was likewise significantly greater.

Snowmelt

Spring snowmelt is normally the dominant hydrological event of the year in cold regions, since winter snow storage effectively redistributes six to ten months of precipitation into a short period. The magnitude and timing of stream flow in response to runoff from melting snow is largely controlled by the distribution of the snow pack over the basin, the rate of snowmelt, and the delivery of the melt water to the stream channel.

In any particular snowmelt event only a portion of the melt water will reach a stream channel directly as surface runoff. A portion is returned to the atmosphere through evapo-transpiration. The remainder infiltrates to the ground surface and takes slower pathways through the catchment and may contribute to stream flow as base flow through subsurface flow processes. In addition to slope and travel time, the delivery of the melt water to the channel is affected by the infiltrability of the basin, which is in turn a function of the condition of the soil surface. At the onset of snowmelt the ground is normally frozen, affecting both infiltration and transport within the soil.

Flow within the snow pack itself was studied by Waldner *et al*. (2004), who confirmed preferential and matrix flows, as well as capillary barrier effects where fine snow layers overlaid coarse layers. Coleou *et al*. (1999) presented a capillary model for snow-water retention, and demonstrated that about 3% of total water content of the snow pack can be retained as liquid water within the snow pack. It is common for this water to re-freeze at night, resulting in increasing daily melt rates until the snow is gone.

2.3.3 Energy Balance

The surface energy balance controls the snowmelt and evapo-transpiration processes. At the ground surface the relationship can be represented by $Q^* = Q_E + Q_H + Q_G$, where Q^* is net radiation, Q_E is latent heat flux (evapo-transpiration), Q_H is sensible heat flux and Q_G is soil heat flux.

On a global scale, annual amounts of incoming and absorbed solar radiation, and net radiation decrease with increasing latitude (Rouse, 1990). High albedo surfaces associated with persistent snow covers are thought to be responsible for this trend. Lower amounts of radiation in turn result in less energy available for the snowmelt and evapo-transpiration processes. On a regional basis the variation in the various components of the energy balance is more complex as they are dependent on local topographic and vegetative factors.

2.3.4 Evapo-transpiration

Evapo-transpiration is a major component of global energy and water budgets that is responsible for the exchange of heat and moisture between the earth's surface and the atmosphere. The overall process is a combination of the individual component processes of evaporation from soil and vegetative surfaces, and transpiration by plants. Because the two processes occur simultaneously it is difficult to distinguish the mass of water transferred by each. It is common to consider a composite horizontal vegetative and soil surface, with a net transfer of soil moisture to the atmosphere (Arya, 1988). Specific details of the soil and canopy surface, as well as microclimatic interactions with these elements, are generally not considered and the composite surface is treated as an idealized, homogeneous covering.

Transpiration Process

Transpiration can be defined as the loss of water from the plant system to the atmosphere in the form of vapour. It can be considered an evaporation process dependent on the supply of energy and the vapour pressure gradient between the evaporating surface and the ambient air. If it is viewed strictly as an evaporation process, transpiration is quite simple. However, transpiration is also controlled by processes within the plants (Kramer, 1983).

Evaporation Process

Evaporation is governed by the vapour pressure gradient between the evaporating surface and the atmosphere. The maintenance of this gradient requires a supply of energy and a mechanism to transport water vapour to the atmosphere. The primary meteorological parameters contributing to the evaporation process are radiation, temperature, humidity and wind. Temperature of the evaporating surface is a critical factor in controlling evaporation rates. This temperature is controlled by the energy balance of the surface, which in turn includes energy exchanges in the process of evaporation. In cold regions, frozen ground and cold soils have significant impacts on the surface energy balance through changes in soil heat storage, which in turn affects evaporation rates (Granger, 1999).

The important physical parameters that affect evaporation are those that govern the soil's ability to store and transmit water. The infiltration rate of a particular soil will determine the amount of water that enters the soil. In vegetated surfaces, soil water from deeper levels is available for movement through the plant system. In a non-vegetated surface, soil water from upper soil horizons only is available for evaporation. Soil structure, texture, soil moisture content, and nature of vegetative cover influence infiltration and soil moisture storage capacity. The presence of bedrock, frozen soil or other impenetrable layer limits root depth and subsequent soil moisture storage capacity.

In a four-year study of energy balance at the Wolf Creek research watershed, Granger (1999) found net radiation to vary significantly between forest, sub-alpine shrub land and alpine tundra environments, with the forest having the most net radiation and the alpine the least, largely a result of surface albedo which was least for the forest and greatest for the lightly vegetated alpine site.

Mean annual evapo-transpiration for the four-year study period had a similar trend with values of 373, 253 and 198 mm for the forest, sub-alpine shrub land and alpine tundra environments respectively.

Janowicz *et al*. (2006) carried out water balance investigations of the Faro, Grum and Vangorda waste rock dumps at the Anvil Range Mining Complex near Faro, Yukon. Evaporation was found to commence after snowmelt, peak in June as does solar radiation, and continue into the early fall. Evaporation patterns between the three waste rock dumps were similar; however, annual amounts of evaporation were found to differ significantly between the various land surface types.

Three basic types of surfaces were distinguished in the Janowicz *et al*. (2006) study; bubble dumps, flat surfaces and push-over slopes. Bubble dumps were hummocky areas of alternate mound and depression features created by the successive end dumping of waste material by large dump trucks. The mounds are 3 to 4 m high, while the depressions are 2 to 3 m deep. Flat surfaces were typically smooth, packed surfaces that tend to be driven upon such as roadways, staging areas and storage lots. Push-over slopes were located along dump edges and peripheries of successive dump lifts and were created by haul trucks directly dumping over lift edges, or by dozers pushing material that was end dumped by the trucks. They tend to be 20 to 80 m in length with angles of up to 60 degrees. The least amount of evaporation was found to occur from the north, east and west facing slopes (65 to 76 mm), which received the least solar radiation and had the least available soil moisture. The greatest amount of evaporation was found to occur from the bubble dumps and flat surfaces (159 to 164 mm), which had both significant amounts of energy and available soil moisture.

2.3.5 Surface Water

Drainage Patterns

The majority of surface water activity in cold regions occurs in a much shorter time period than temperate regions (Woo, 1993). The high runoff at freshet is exacerbated because permafrost prevents any potential downward percolation into the ground, forcing runoff at, and very near, the ground surface. On a regional scale, the high runoff results in streams that are more prone to flooding and, if the soil conditions permit, they have higher eroding and silt-carrying capabilities.

On a smaller scale, cold regions surface water drainage patterns often follow the troughs and ridges resulting from hummocks, thermokarst and other patterned ground features. Where these features meet, small pools may form. Pools will be joined by streams, which cause the pools to resemble beads on a string, *aka* beaded drainage.

Aufeis

Aufeis (*aka* nalyd, naled or icing) is seasonal accumulation of ice superimposed on the frozen surface of a stream or landscape (Slaughter, 1990). Aufeis forms when water in or adjacent to a channel rises above the level of existing ice, and as that water loses heat due to exposure to cold ambient air temperatures, it freezes causing thick sheet ice. The most substantial engineering consequence of aufeis formation is blockage of ditches and plugging of small streams.

2.3.6 Soil Water

Phase Composition

The simplest case of flow through a porous medium involves only one solid, i.e. the soil matrix and one fluid i.e. water. This is also called saturated flow. Unsaturated flow introduces another fluid, i.e. air. For frozen soils, yet another solid, i.e. ice, must be considered. Phase changes between these fluids add to the complexity. A soil system that is saturated and below the freezing point of bulk water involves the interaction of the soil matrix, ice and unfrozen water.

An important consideration in understanding the hydrology of frozen soil is that a fraction of the water in the soil matrix remains unfrozen even below the bulk freezing point of the water. Finer soils have greater specific surface area than coarser soils, and as a result have greater unfrozen water content at any given temperature. Therefore, under similar conditions, clay will have more unfrozen water content than silt, and silt will have more than sand. Furthermore, the lower the temperature below the freezing point of bulk water, the lower the unfrozen water content. Solute concentration and confining pressure will also affect the unfrozen water content of a soil.

Infiltration to Unfrozen Soils

Entry of water into an unfrozen soil initially occurs through large soil pores, cracks, and root channels that are directly connected to subsoil levels. Once the large soil pores and conduits are filled, water enters smaller pores where it is conveyed downward by gravity and capillary forces. The major factors affecting the initial entry of water are surface permeability, which is a function of surface conditions such as packing and tillage, and, initial moisture content (Hillel, 1982). Once water is within the soil, its movement is controlled by hydraulic conductivity and the gradient of the total potential. Hydraulic conductivity is a function of the characteristics of the soil, especially the pore size, shape, distribution and continuity. These in turn are a function of particle size distribution, porosity, colloid content, root and animal activity among other factors. The total potential gradient is determined by the combination of elevation and matric suction, which is in turn a function of the soil properties and moisture content.

Infiltration to Frozen Soils

With the additional constraint offered by frozen soil, the complexity of the infiltration process increases significantly. The frozen condition can affect the initial entry of water into the soil surface as well as water transport within the soil. Simultaneous coupled heat and mass transfer processes are important, as are the ice-water phase changes. In addition to the hydrophysical factors that affect infiltration in unfrozen condition, the thermal properties of the soil, the temperature regime, the rate of supply of snowmelt water, and the energy content of the water can all affect infiltration in frozen soils (Granger *et al*., 1984).

Comprehensive treatments of the theory of infiltration into frozen soil include those by Engelmark and Svensson (1993) and Flerchinger and Saxton (1989). The physical mechanisms governing heat and water movement within a homogeneous, unsaturated, frozen soil are heat conduction through soil, ice, liquid, and vapour; heat convection due to liquid flow driven by gravity and capillarity; phase changes for all constituents (solid-liquid, vapour-liquid and solid-vapor); and molecular diffusion in the vapour-air mixture. The major governing relationships are the one-dimensional energy conservation equation for heat flow by conduction and liquid convection with phase change and the continuity equation for capillary liquid flow in one dimension.

Tao and Gray (1994) carried out a rigorous numerical simulation of snowmelt infiltration into an unsaturated, frozen soil using a local volume averaging approach. Their model used a freezing point depression relation introduced by Flerchinger and Saxon (1989). The investigators found the most significant variables affecting a frozen soil's ability to absorb and transmit water are initial moisture content, soil permeability, and freezing point depression characteristics. They found initial soil temperature was not very significant, provided the soil did not contain large macropores.

Soil moisture content affects hydraulic conductivity through pore constriction by ice blockage. This blockage acts to increase tortuosity and lengthen flow path. It is generally accepted that there is an inverse relationship between frozen soil moisture and infiltration. Early work indicated that the basic parameters which govern infiltration into frozen soils are the size and quantity of ice free pores; therefore, the initial moisture content at the time of freezing may be the single most important factor (Gray *et al*., 1970). They found infiltration rate characteristics followed one of four general patterns governed by the initial moisture content, as illustrated by Figure 5.

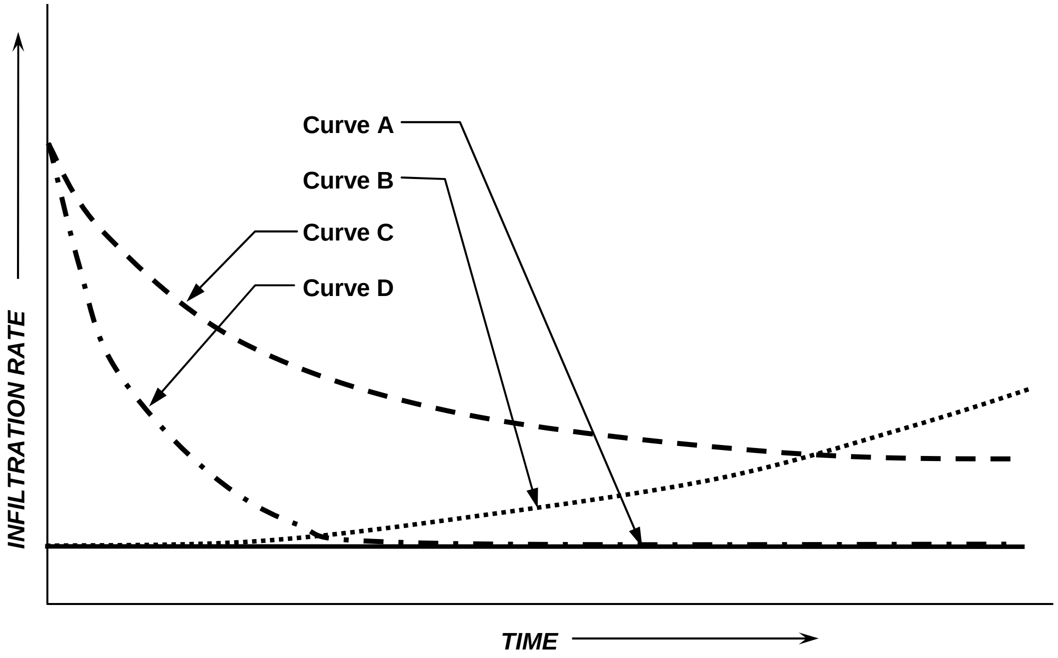

Figure 5: Conceptual Infiltration Scenarios for Frozen Soils (after Gray *et al*., 1970)

Curve A represents an initial saturated scenario with essentially no infiltration; curve B represents an initial high moisture content (70 to 80% of field capacity) resulting in an increasing infiltration rate with time; curve C represents an initially low moisture content, and a temperature nearing the freezing point resulting in infiltration close to unfrozen values; curve D represents an initial low moisture content but with a low temperature resulting in pore blockage by the refreezing of infiltrating water and subsequent rapid decline in rate.

The role of soil temperature is less clear than that of soil moisture. Upon entering a soil with a temperature below 0^{o}C, water will freeze. The amount that freezes is a function of the amount of free water available, the energy status of both the soil and water and the energy exchange between the two media. Freezing of infiltrating water increases the temperature of the soil matrix through the release of its latent heat of fusion which is then transported downward by conduction together with sensible heat from the snow pack.

Work by Komarov and Makarova (1973) found that the depth of freezing has a significant effect on infiltration characteristics. When depth of freezing is shallow, the heat contained in the infiltrating water will quickly thaw the soil, returning infiltration characteristics to those of an unfrozen state. They found 15 cm to be the critical depth of freezing above which the soil acts as if it were frozen during infiltration, while freezing depths beyond 60 cm had no further effect on infiltration. Iwata *et al*. (2008) obtained similar results, where snowmelt infiltrated unimpeded into frozen soil with depths of 10 to 20 cm. In the comparison of two consecutive winters, Bayard *et al*. (2005) found significantly more lateral snowmelt runoff during the colder winter with a greater depth of freezing and the presence of basal ice due to an early spring thaw and subsequent refreezing.

Popov (1973) developed a method for classifying the effects of soil on snow melt runoff. Gray *et al*. (1985) used a similar approach, also as a component of a freshet stream flow forecasting model. The researchers suggested that the infiltration potential of frozen soils could be grouped into three functional categories, which consisted of restricted, limited and unlimited classes. In the restricted class, infiltration is impeded by an impermeable layer such as an ice lens at or near the surface resulting in negligible infiltration. Such a condition may develop with the freezing of a late season rain event, or the refreezing of melt water resulting in a basal ice layer. In the unlimited class, supplied water is quickly accommodated by the soil in question due to a high proportion of large, air filled non-capillary pores. In the limited class, infiltration was found to be governed primarily by ice content with the top 30 cm of soil at the time of melt. A relation was presented with infiltration a function of pre-melt moisture content and snow water equivalent.

Subsequent work by Zhao and Gray (1997a; 1997b) and Zhao *et al*. (1997) led to the development of a parametric relationship that relates cumulative snowmelt infiltration into frozen soils to soil surface saturation, initial matrix saturation, soil temperature and infiltration time using data from Saskatchewan boreal forest and prairie sites. Preliminary work was carried out to assess the variability of snowmelt infiltration to frozen soil at the Wolf Creek Research Basin and to assess the applicability of the parametric relationship to southern Yukon Boreal forest conditions (Janowicz, 2000). The study showed a reasonable trend between estimated and observed infiltration amounts in three years of observations for three study sites (forest, sub-alpine shrub land, alpine tundra).

The infiltration of melt water into a frozen soil tends to follow a diurnal cycle with infiltration occurring during the day and refreezing at night. Steenhuis *et al*. (1977) suggest that soil temperature during melt may be less significant than porosity, which is inversely related to frozen water content. Granger *et al*. (1984) confirmed that the infiltration of water in soils with large effective porosities was not impeded by low temperatures. Gray *et al*. (2001) present a conceptual model for scaling frozen soil infiltration during snowmelt events. They suggest that at macro and meso scales infiltration to frozen soils can be estimated based on the spatial distribution of soil moisture and snow water equivalent.

2.3.7 Groundwater

Sub- and Supra-permafrost Groundwater

Temperate regions have a water table at depth, while cold regions may have permafrost. Permafrost commonly represents a confining layer to groundwater. Dry, frozen ground may be highly permeable, although it is more common that soil pores are filled with ice and permeability is low (Nelson and Munter, 1990).

Groundwater in permafrost zones is defined as either sub-permafrost (below permafrost) or supra-permafrost (above permafrost). Sub-permafrost water is unavailable in zones of continuous permafrost. Supra-permafrost groundwater is rarely used as a water supply because it generally is of poor quality (high salinity), and freezes solid during winter, although taliks have been targeted. Supra-permafrost groundwater is an important water supply to vegetation, and is important to many frozen ground phenomena such as aufeis and frost blisters (Nelson and Munter, 1990; Woo and Xia, 1995; Pollard and van Everdingen, 1992).

Taliks

An important factor controlling the thermal regime of permafrost and groundwater is the presence of natural or man-made water bodies. Small shallow lakes or ponds that freeze completely to the bottom in the winter do not have much of an effect on permafrost. Larger lakes or ponds, generally deeper than about 1.5 m do not freeze to the bottom and a zone of thawed permafrost will be present under the water. If the lake is very large, i.e. with a diameter greater than the regional permafrost depth, the unfrozen zone will extend completely through the permafrost beneath the lake. Rivers on permafrost act as long lakes with similar effects on thawing of the permafrost. These sections of unfrozen ground below water bodies are called taliks (Brown and Kupsch, 1974).

Various forms of taliks have been identified (Woo, 1993): closed taliks are completely surrounded by permafrost; open taliks are surrounded by permafrost, but open to the surface; continuous taliks are surrounded by permafrost, but unfrozen through the depth of the profile; and interpermafrost taliks are laterally open but vertically bound between zones of permafrost. These are illustrated in Figure 6.

Nelson and Munter (1990) demonstrated that taliks may also be formed by hydrothermal or hydrochemical means. A form of talik common in some mining situations is known as a cryopeg, and is a layer of unfrozen ground within the permafrost zone where freezing-point is depressed by the dissolved solids content of the pore-water.

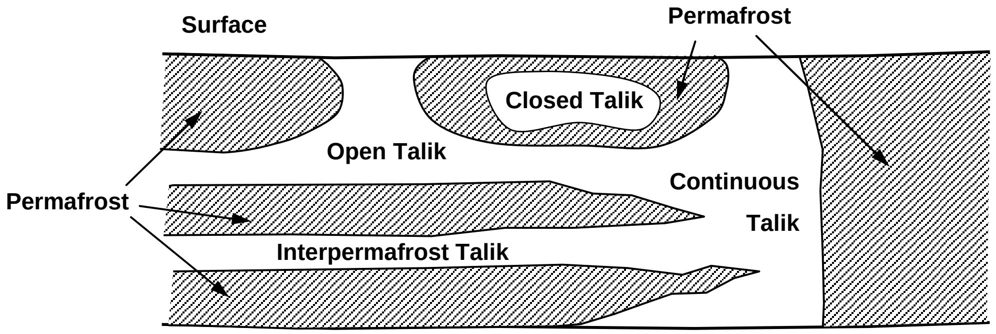

Figure 6: Various Forms of Talik (Modified from Andersland and Ladanyi, 2004)

Ground Aufeis

Ground aufeis is a form of aufeis that develops when unfrozen soil water or groundwater appears at the ground surface during below-freezing temperatures. Ground aufeis formation is initiated by any mechanism that results in impedance of down-slope movement of water within the soil mantle during freezing conditions. Water may seep directly from the ground, or may flow to the surface via cracks in the soil, along tree roots, or animal burrows. The water continues flowing even after it is exposed to the above-ground air; however, it eventually freezes causing ice build-up. Figure 7 illustrates ground aufeis formation.

Aufeis melt is commonly delayed relative to seasonal snowmelt, affecting local infiltration rates. The main concern with aufeis formation is drainage blockage and associated flooding and erosion. Slaughter (1990) provides an extensive discussion of measures to prevent aufeis formation.

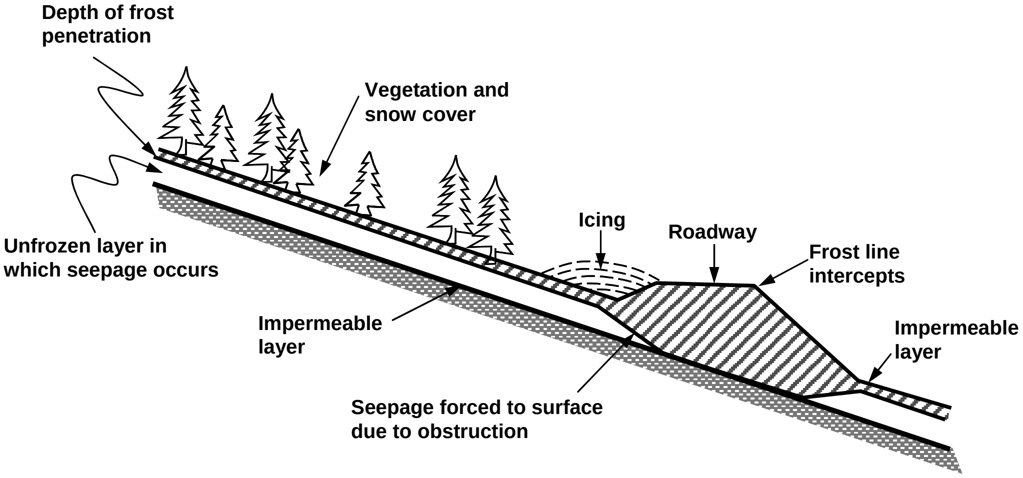

Figure 7: Ground Aufeis Formation (after Slaughter, 1990)

2.4 Other Factors

2.4.1 Vegetation

Cold regions vegetation diversity is a function of landform, climate, parent material and latitude. Higher latitude vegetation is typically stunted, slow-growing and has relative low species variety. Rouse (1993) stated that high latitude vegetation are xerophytic, or adapted to low moisture conditions, with a growth season typically less than six weeks. A good overview of northern vegetation is provided by Ritchie (1993).

Of particular interest to covers, is the fact that lichens, which make up a major part of the high latitude canopy, are non-transpiring and act as a ground cover that naturally inhibits direct evaporation. In cold regions, vegetation provides excellent insulation, resulting in a reduced summer heat flux, and thus a reduced thaw depth. Carpets of moss and organic soil, which are ubiquitous in the sub-arctic and the arctic (Woo and Marsh, 2005) are particularly effective as insulators which helps reduce active layer thickness. Moss and organic matter also increase the water holding capacity of soils (Walker *et al*., 2003).

Studies of natural re-vegetation at northern sites not specific to mining include Burn *et al*. (2001), Jorgensen and Joyce (1994), and Streever *et al*. (2003). Re-vegetation of tailings was studied near Mayo, Yukon, by Wilson *et al*. (1996), who found that slope and age of the tailings deposit were significant environmental variables governing the percent cover and number of species found at the site.

Vegetation plays a very important part in the control of runoff in cold climates. Thick layers of moss will act like a sponge lain over permafrost, slowing down the movement of water across the ground surface.

2.4.2 Animals

Animals are known or suspected to play a role in many soil-forming processes. Animal activities that might be particularly influential in cold regions include burrowing by rodents, browsing of vegetation by caribou, removal of vegetation by beavers, and digging to expose salt licks.

2.4.3 Logistical Constraints

It is well known that working in cold regions provides many logistical challenges. These will primarily affect cover construction, but can also have implications for long-term maintenance and monitoring. The next chapter provides further discussion.

3 Cold Regions Covers

3.1 Industry Experience

Table 4 provides a list of mine waste covers in North America and Europe that have been constructed or are planned to be constructed in cold regions. The list of case studies is not considered to be comprehensive, but is limited to sites familiar to the authors or otherwise identified during research undertaken for this report. The site locations are shown on Figures 8 and 9.

Detailed information relating to the covers at each site is not always available. More importantly for the purpose of this report, very few of the constructed or proposed covers have been reviewed from a “cold regions” perspective, meaning that there are few case histories of direct relevance to this report.

Therefore, the approach taken in the following sections is to discuss cold regions phenomenon that either have been observed to influence or might be expected to influence cover design, performance and construction. Observations from the sites listed in Table 4 are cited where relevant. The discussion is grouped into the following five sections:

- Cover selection and design considerations;
- Frozen ground effects on cover performance;
- Cold regions hydrologic effects on cover performance;
- Other cold regions effects on cover performance; and
- Cold regions effects on cover construction.

Table 4: Examples of Covers in Cold Regions

Site, Location [Waste Type]	Year Completed	Type of Cover					Non-Soil Components
		Water Cover	Barrier Cover	Store-and-Release Cover	Isolation Cover	Insulation Cover	
Aitik Mine, Sweden [waste rock]	1999		✓				-
Arctic Gold & Silver, YT [tailings]	1998/99				✓		-
Meadowbank Mine, NU [tailings]	Proposed					✓	-
Beaverlodge Mine, SK [boil repairs]	2006/07		✓		✓		-
Beaverlodge Mine, SK [tailings]	1983/84				✓		-
Beaverlodge Mine, SK [tailings]	1997		✓		✓		-
Bell Mine, BC [tailings]	?				✓		-
Bersbo Mine, Sweden [tailings]	1987		✓				Flyash
Brewery Creek Mine, YT [heap leach]	?		✓				-
Camlaren Mine, NT [tailings]	1983				✓		-
Colomac Mine, NT [tailings trials]	2004				✓		Geotextile
Colomac Mine, NT [tailings]	2006				✓		Geotextile
Con Mine, NT [tailings]	Proposed			✓	✓		-
Contact Lake Mine, NT [tailings]	Proposed	✓					-
Cullaton Lake Mine, NU [tailings]	2003	✓	✓				-
Cullaton Lake Mine, NU [waste rock]	2001		✓			✓	-
Deloro Mine, ON [tailings]	1987				✓		-
Deloro Mine, ON [tailings]	Proposed		✓				Geotextile
Denison Mine, ON [tailings]	?	✓					-
Detour Lake Mine, ON [tailings]	1998/99		✓		✓		-
Diavik Mine, NT [tailings]	Proposed					✓	-
Discovery Mine, NT [boil repairs]	2005		✓		✓		Liner
Discovery Mine, NT [delta tailings]	1998	✓	✓		✓		GCL^1
Discovery Mine, NT [upland tailings]	1999/2000				✓		-
Doris North Project, NU [tailings]	Proposed	✓					-
East Sullivan Mine, QC [tailings]	Trial/1984				✓		Wood waste
Ekati Mine, NT [tailings]	Proposed					✓	-
Enasen TSF, Sweden [tailings]	1994	✓	✓				-
Equity Silver Mine, BC [tailings]	?	✓					
Equity Silver Mine, BC [waste rock]	1991/94/96		✓				-
Falconbridge Mine, ON [tailings]	1996	✓					-
Falun Mine, Sweden [tailings]	?		✓				
Faro Mine, YT [new tailings trials]	2005				✓		Geotextile
Faro Mine, YT [old tailings trials]	1997	✓	✓				Peat/ Sawdust
Faro Mine, YT [Vangorda waste rock]	1993			✓			-
Faro Mine, YT [waste rock trials]	2005		✓		✓		-
Geco Mine, ON [tailings]	?				✓		-
Giant Mine, NT [tailings]	Trial/2007			✓	✓		Geotextile
Golden Giant Mine, ON [tailings]	?	✓					-
Golden Sunlight Mine, Montana [tailings]	1992		✓	✓			-
Golden Sunlight Mine, Montana [waste rock]	1994			✓			-
Greens Creek Mine, Alaska [waste rock]	Trial/ 2001		✓				-
HBMS, MB [tailings]	Proposed				✓		-
Heath Steele Mine, NB [tailings]	?	✓					-
Heath Steele Mine, NB [waste rock]	Trial/1998		✓				HDPE^2
Isachsen, NU [landfill]	Not built yet		✓				-
Jericho Mine, NU [tailings]	Proposed				✓		-
Key Lake Mine, SK [heap leach]	1993		✓	✓			-
Killingdal Mine, Norway [waste rock]	?		✓				-

Site, Location [Waste Type]	Year Completed	Type of Cover					Non-Soil Components
		Water Cover	Barrier Cover	Store-and-Release Cover	Isolation Cover	Insulation Cover	
Kitsault Mine, BC [pit/waste rock]	2006		✓				Bentonite
Kjoli Mine, Norway [waste rock]	?		✓				Geotextile, HDPE^2, Geonet
Kristineberg TSF, Sweden [tailings]	2002	✓	✓				-
Landfill, QC [aluminium waste]	2003		✓				BGM^3
Les Terrains Auriferes, QC [tailings]	Trial/ 1993		✓				HDPE^2
Les Terrains Auriferes, QC [tailings]	1996		✓				HDPE^2
Lupin Mine, NU [tailings]	1988/95/ 2003-2006		✓			✓	-
McLaren Mine, NT [tailings]	?				✓		-
Mine Louvicourt, QC [tailings]	?	✓					-
Mine Poirier, QC [tailings]	?		✓				HDPE^2, Geonet
Mine Selbaie, QC [tailings]	?		✓				-
Mt. Washington Mine, BC [open pit]	Proposed		✓				BGM^3
Mt. Washington Mine, BC [waste rock]	1988/89		✓				-
Myra Falls, BC [waste rock]	Trial/98		✓				Flyash/ Bentonite
Nanisivik Mine, NU [tailings]	2004/05					✓	-
Nanisivik Mine, NU [trial covers]	1997					✓	-
Nanisivik Mine, NU [waste rock]	2004/05					✓	-
North Rim Mine, NT [tailings]	Proposed	✓					-
Normetal Mine, QC [tailings]	?		✓				HDPE^2
Polaris Mine, NU [demolition debris]	2004?				✓		
Port Radium Mine, NT [tailings]	2007	✓	✓		✓		GCL^1
Port Radium Mine, NT [waste rock]	2007		✓		✓		-
Port Radium Mine, NT [waste rock]	1960/80		✓		✓		-
Potash Corp. of SK, SK [tailings]	Trial/91		✓				-
Quirke Mine, ON [tailings]	?	✓					-
Rabbit Lake, SK [waste rock]	Proposed		✓				-
Raglan Mine, QC [tailings]	?					✓	-
Rankin Inlet Mine, ON [tailings]	?					✓	-
Ranstad Mine, Sweden [tailings]	?		✓				-
Rayrock Mine, NT, [tailings]	1996				✓		-
Red Dog Mine, Alaska [tailings]	Proposed	✓					-
Red Dog Mine, Alaska [waste rock]	Proposed		✓	✓			
Red Dog Mine, Alaska [waste rock]	Trial/07		✓	✓			
Skorovas Mine, Norway [waste rock]	?	✓					-
Solbec Mine, QC [tailings]	1994	✓					-
Stanrock Mine, ON [tailings]	?		✓		✓		-
Stekenjok TSF, Sweden [tailings]	1990/91	✓					-
Sullivan Mine, BC [tailings]	Trial/94		✓	✓			-
Sullivan Mine, BC [tailings]	96		✓	✓			-
Suncor, AB [coke]	Trial/06			✓			-
Suncor, AB [tailings]	Pre & post-2000			✓			-
Suncor, AB [saline sodic overburden]	Pre & post-2000			✓			-
Syncrude, AB [coke]	Trial/05			✓			-
Syncrude, AB [sulphur]	Trial/06		✓	✓		✓	Bituminous

Site, Location [Waste Type]	Year Completed	Type of Cover					Non-Soil Components
		Water Cover	Barrier Cover	Store-and-Release Cover	Isolation Cover	Insulation Cover	
Syncrude, AB [tailings]	Pre & post-2000			✓			-
Syncrude, AB [saline sodic overburden]	200?			✓			-
Syncrude, AB [saline sodic overburden]	Trial/1999			✓			-
Terra Mine, NT [tailings]	Proposed	✓					-
Venus Mine, YT [tailings]	1998	✓	✓				Geotextile
Waite Amulet Mine, QC [tailings]	Trial/1990		✓				-
Whistle Mine, ON [waste rock]	Trial/2000		✓				Bentonite/ GCL[1]
Whistle Mine, ON [waste rock]	2004/05		✓				-

1. GCL = Geosynthetic Clay Liner
2. HDPE = High Density Polyethylene
3. BGM = Bituminous Geo-Membrane

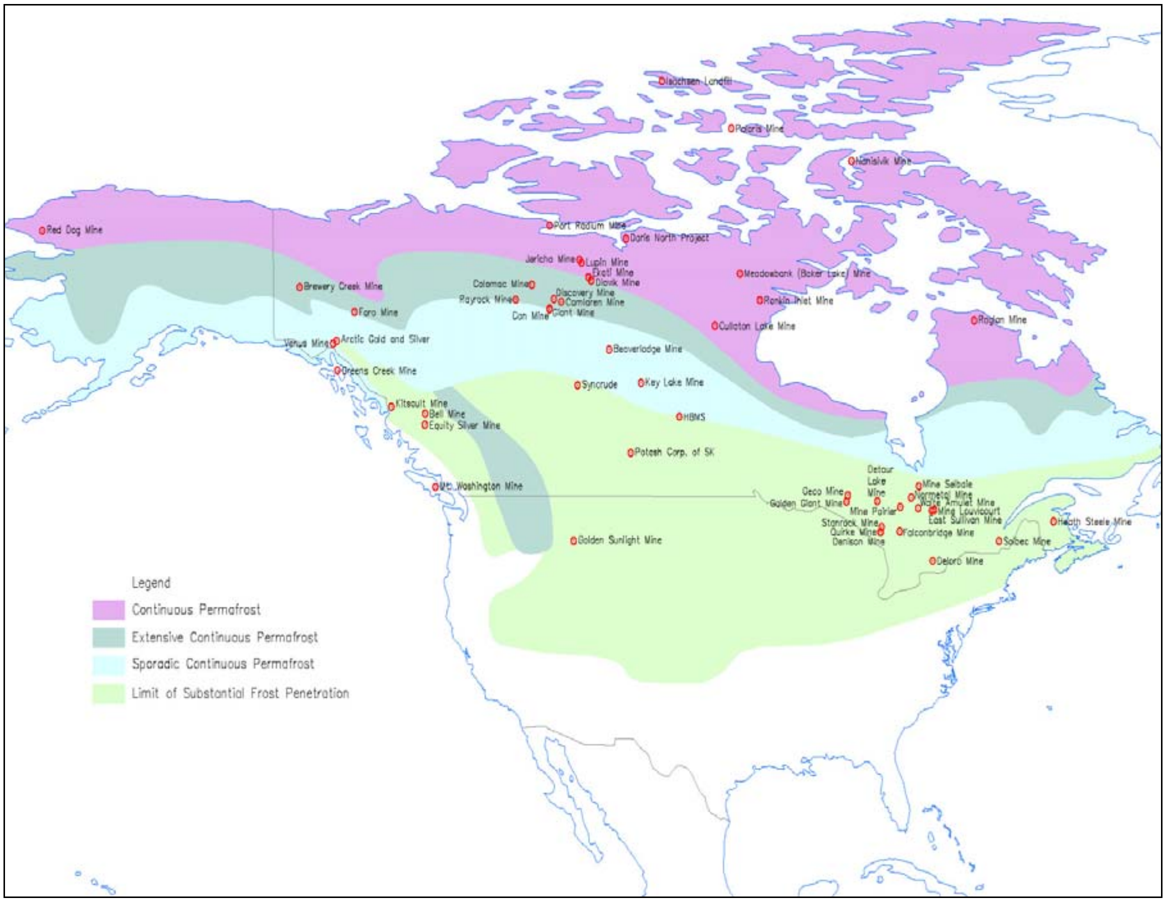

Figure 8: Constructed or Planned Mine Waste Covers in North American Cold Regions

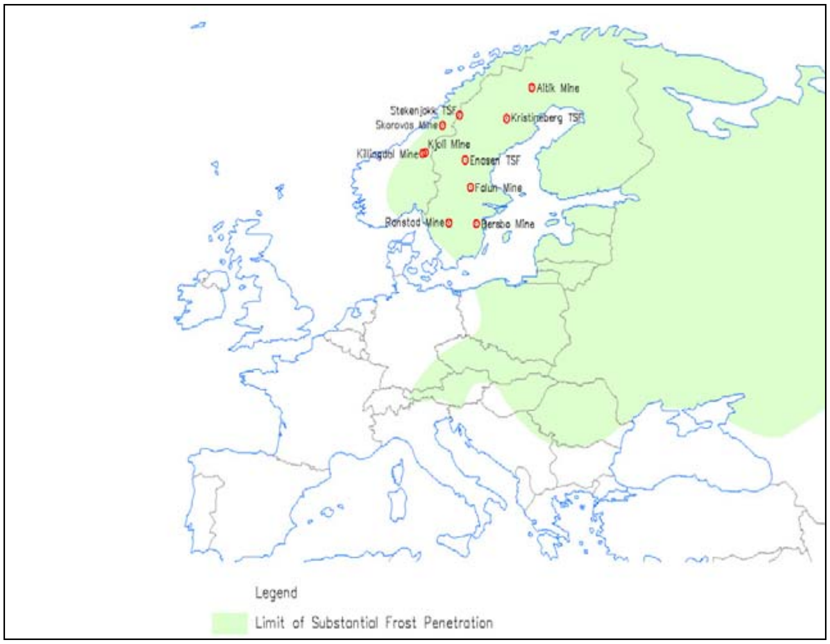

Figure 9: Constructed or Planned Mine Waste Covers in European Cold Regions

3.2 Cover Selection and Design Considerations

3.2.1 Cover Types

Table 4 illustrates the diversity of covers used in cold regions, clearly demonstrating that no one cover type dominates cold regions design. The cover types have been grouped into five categories:

- Isolation covers, which are intended only to prevent direct contact of animals and vegetation with the underlying material;
- Barrier covers, which incorporate at least one low permeability soil or geosynthetic layer to limit the infiltration of water and, in some case, the ingress of oxygen;
- Store-and-release covers, which make use of a generally thick layer of soil to store water until it can be taken up and evapo-transpired by plants;
- Water covers, which make use of a pond to completely cover the underlying waste, typically to prevent oxidation of potentially acid generating materials; and
- Insulation covers, which take advantage of the climate to freeze in, or insulate the underlying waste.

A detailed discussion of the first four cover types is outside the scope of this report. More detail related to the first four cover types can be found in MEND 2.21.4 (2004) and MEND 2.21.5 (2007).

Insulation covers are unique to cold climates and are a relatively new technology specifically developed to take advantage of cold regions conditions. They are used for two related purposes; to ensure that previously frozen underlying mine waste remains frozen, or to facilitate the aggradation of regional permafrost into unfrozen mine waste.

In both cases the design objective is adequate insulation from the seasonal surface warming. This is accomplished by providing an adequately thick layer of cover material. Finer-grained materials are preferred as they would tend to remain saturated and thereby provide more insulation per unit depth. However, fine-grained materials are not always available, and sandy esker materials have been used (e.g. MEND 2.21.4, 2004).

The use of insulation covers for mine wastes is not without controversy. From an acid mine drainage (AMD) perspective there is not yet consensus as to the temperature at which oxidation of mine wastes will cease. Meldrum *et al*. (2001) noted that the oxidation of tailings from Rankin Inlet was slowed significantly at -2°C and was not measurable at -10°C. Kyhn and Elberling (2001) noted that the critical temperature to limit sulphide oxidation may be near -5°C, rather than 0°C. A review of the effects of cold temperatures on acid mine drainage was presented in MEND 1.61.6 (2006), and is summarized in Section 3.2.2 below.

A second concern is the influence of global warming. It is clear that the level of insulation needed at a particular site could change if the local climate changes. However, the relationship between air temperature and soil temperature is very complex, for reasons discussed in the preceding sections of this report. Reduction in winter snow cover, for example, could lead to colder soil temperatures even when annual average air temperatures increase. The effects of climate change on particular insulation covers therefore needs to be evaluated on a site specific basis.

3.2.2 Cold Regions Effects on Mine Wastes

The design of cover systems includes consideration of several common factors, regardless of the location. These include availability of soil materials, costs of natural and synthetic materials, and construction constraints. Other reports present a full discussion of these considerations (e.g. MEND 2.21.4, 2004 and MEND 2.21.5, 2007). The following sections focus on cover design considerations that are particular to cold regions.

Permafrost Degradation below Mine Waste Facilities

Construction of a large mine waste facility in a cold region can substantially alter the ground thermal regime. Placing pools of tailings water or piles of oxidizing and heat generating waste rock onto a permafrost surface can lead to permafrost degradation. The resulting concerns of importance to cover designers can include settlement of structures, movement of the waste itself, and changes to seepage.

The tailings dams at the United Keno Hill Mine in the Yukon are an example of the first effect. Subsidence of the dam crest has continued decades after construction, and is complicating the design of closure measures. Permafrost degradation below the Lucky waste rock pile at the Brewery Creek Mine, near Dawson, Yukon, has led to movement of the dump crest and requirements to repair the cover two years after closure. Degradation of permafrost below the tailings impoundment at the Red Dog Mine in Alaska led to an increase in the width of the talik associated with the creek that previously ran through the valley. A multi-year investigation of groundwater and seepage flows was needed to show that the use of a water cover on the tailings would not lead to unacceptable long-term seepage rates.

It is clearly important that designers of cold regions covers familiarize themselves with the historical and current thermal regime of the site, the retaining structures, and the mine waste.

Ice Entrainment within Mine Waste

Ice entrainment in tailings is a common occurrence in cold regions, and the presence of this ice has the potential to affect cover design and long-term performance. For example, melting of entrained ice has created thermokarst topography on the surfaces of the Spruce Lake tailings impoundment at the Colomac Mine and on the Original and Secondary Impoundments at the Faro Mine. The differential settlement ranges from a few centimetres to more than 3 m in areas, significant enough to have profound effects on the construction and performance of most types of cover.

BGC (2003) investigated the occurrence of ice entrainment in tailings at eight sites in Northern Canada. At each of those sites, the original cause of ice entrainment was ice formation during tailings deposition. At the Con Mine, ice entrainment appeared to be limited seasonally, with clear evidence of settlement each summer as ice build-up from the previous winters deposition melts. At the Discovery, Giant, Colomac, Faro, Ekati, Lupin and Nanisivik Mines, ice was present in the tailings to various degrees, and there was evidence of both intermediate and long-term ice entrainment.

Entrained ice occupies volume that could otherwise contain tailings. Prevention or control of ice entrainment in tailings facilities is therefore of critical importance to mine operators. The deposition plans for sub-aerial tailings at the Diavik and Ekati Mines allows seasonal ice entrainment. However, the beach thicknesses that can freeze in any given winter season is strictly controlled by continuously moving the deposition points, such that during the subsequent summer, all entrained ice in that frozen beach can melt before tailings is once again deposited over those areas. In determining the allowable seasonal beach thicknesses the designers have taken into account the thermal properties of the tailings. This approach does not appear to be 100% successful, as some long-term ice entrainment is still apparent in these tailings facilities.

Several tailings facilities in northern Saskatchewan have lost volume to entrained ice. At the Rabbit Lake Mine, operators inject tailings deep into the In-Pit Tailings Management Facility (TMF) in order to melt ice accumulated during previous tailings deposition. At the Key Lake Mine, options to thaw ice in the Above Ground TMF are being considered as precursors to the construction of closure covers, and subaqueous deposition is used in the Deilmann TMF to avoid ice entrainment.

Ice entrainment could also occur in waste rock piles. Thawing of snow and ice entrained during winter construction of the Grum waste rock pile at the Anvil Range Mining Complex has created surface topography very similar to that seen on tailings ponds, with local differential settlements of up to 1 m.

Evidence of how the thawing of ice and snow entrained during cover construction can affect covers was seen at the Discovery Mine. During winter construction of a Geosynthetic Clay Liner (GCL) on the delta tailings deposit at that site, ice and snow collected in surface depressions and was entrained below the GCL. Subsequent thawing resulted in stress on the GCL and the separation of overlaps between some of the GCL panels. A gravel cover placed over Deloro tailings underwent significant settlement soon after construction, which required remedial work. The settlement was predominantly associated with inadequate snow clearing prior to cover placement.

Other Frozen Ground Features within Mine Waste

Small scale evidence of other ice entrainment features have been observed in cold regions mine wastes, especially tailings ponds during sub-aerial deposition. However, other than the thermokarst topography discussed above, there are no records of large scale features being observed.

From a theoretical point of view, the grain size distribution of tailings and the availability of moisture make it conceivable that tailings deposit could be affected by other ice, such as:

- Growth of massive ice lenses and frost heave processes.
- Formation of pingos and palsas, provided the appropriate drainage conditions exist, which may be the case in some water covered tailings.
- Desiccation cracks are common in fine or plastic tailings. These cracks may lead to the formation of ice wedges and associated patterned ground.

The coarse grain size and generally drier condition of waste rock makes the above features unlikely. Barsch (1996) reports that ice build-up has led to formation of rock glaciers in mine waste rock piles; however, he does not give details.

Convective Cooling of Mine Waste

The grain size distribution of mine waste rock indicates that it should be susceptible to convective cooling. There has been no systematic study of this possibility. However, anecdotal observations suggest that it occurs. Observations of year-round ice within the toe of coarse waste rock piles at the Colomac Mine are thought to indicate the effects of convective cooling. Convective cooling has also been proposed as an explanation for the unexpected freezing of waste rock test piles constructed at the Key Lake Mine in the mid-1990’s. If convective cooling does occur in waste rock, it could enhance other frozen ground processes that could be detrimental to cover performance, such as the formation of rock glaciers. On the positive side, convective cooling could inhibit permafrost degradation and, possibly, oxidation reactions.

The fine grain sizes of tailings would prevent any significant convective cooling within tailings deposits. However, many tailings dams are constructed from, or buttressed with, coarse rock fill, which would be subject to convective cooling.

Convective cooling could potentially be exploited as a cover technology. For example, the tailings cover for the proposed Meadowbank Mine is intended to be a coarse rock that will promote permafrost aggradation into the tailings via convective cooling. It is not known how effective convective cooling would be for a large flat surface area such as a cover, and therefore the success of this approach has been questioned.

Geochemical Weathering in Cold Regions

MEND 1.61.6 (2006) provides an update of cold temperature effects on geochemical weathering, specifically focussed towards evaluating opportunities to exploit cold temperatures for control of AMD. The study covered eight mechanisms expected to occur differently at low temperatures, or that were considered unique to low temperature conditions: (1) oxidation rates of iron sulphide minerals; (2) oxidation of other sulphide minerals; (3) activity of different types of bacteria;
(4) solubility and reactivity of acid buffering minerals including carbonates and silicates;
(5) formation and solubility of secondary minerals (weathering products); (6) freeze concentration;
(7) physical exposure of minerals due to freeze-thaw processes; and (8) solubility of oxygen in water used to flood reactive wastes.

MEND 1.61.6 (2006) concluded that limited research is available on the effect of low temperatures on the geochemical performance of mine waste, and recommends that more research be carried out in this field to determine if cold regions hold opportunities to control AMD. The implication for cover designers is that cold conditions alone cannot be relied upon to control AMD, and the design objectives related to control of AMD by covers in temperate regions will also apply to covers in cold regions.

3.3 Frozen Ground Effects on Cover Performance

Section 2.2 above surveys the phenomena that are known to affect cold regions soils in general. As noted in Section 3.1, there has been no systematic analysis of these phenomena in mine waste covers. The following sections discuss the few “frozen ground” effects that were studied or observed in cover systems, and briefly list others that might be expected to occur.

3.3.1 Freeze-Thaw Effects on Permeability

One frozen ground phenomenon that has been well studied is the effect of freeze-thaw cycles on low permeability layers. Most of the literature indicates that freeze-thaw cycles lead to significant increases in hydraulic conductivity (Chamberlain *et al*., 1997; Benson *et al*., 1995; Benson and Othman, 1993; Suter *et al*., 1993; Yuen *et al*., 1998; Chapuis, 2002; Konrad and Samson, 2000b; Viklander, 1998b). However, recent research has led to important limitations on the general findings (Eigenbrod, 2003).

Benson *et al*. (1995) reported that subjecting clay to repeated freeze-thaw cycles resulted in increased hydraulic conductivity by a factor of 50 to 300, while Othman *et al*. (1994) reported increases of three orders of magnitude. Benson and Othman (1993) observed that a sample of compacted clay subjected to freeze-thaw cycles experienced increases in hydraulic conductivity of 1.5 to 2 orders of magnitude above the freezing plane. The hydraulic conductivity of the sample 150 mm below the freezing front also changed due to desiccation with moisture re-distribution upon freezing. Othman and Benson (1993) examined three compacted clays and found that one freeze-thaw cycle was enough to increase hydraulic conductivity, and the majority of change occurred after three to five freeze-thaw cycles. Konrad and Samson (2000a) reported a similar finding, noting that hydraulic conductivity of silt-kaolin mixtures increased over one freeze-thaw cycle, despite a decrease in porosity resulting from freeze-induced consolidation.

The above studies seem to agree that the increased hydraulic conductivity of clay soils was caused by the formation of cracks during freezing, and that the largest changes occurred when the rates of freezing were high. The increase in hydraulic conductivity was also found to be inversely proportional to temperature, with greatest increase in hydraulic conductivity occurring in samples subjected to the lowest temperatures.

Viklander (1998b) observed that dense till samples increased in volume on freezing, experiencing an increase in hydraulic conductivity, while loose samples decreased in volume and experienced a decrease in hydraulic conductivity. Molding water content did not affect the observed increase in hydraulic conductivity, but an increase in compactive effort resulted in a somewhat smaller increase in hydraulic conductivity (Othman and Benson 1993).

Field evidence that freeze-thaw cycles do not necessarily lead to increases in hydraulic conductivity can be found in the papers by Benson and Othman (1993) and Chamberlain *et al.* (1997). The findings of 50 to 300 times increases in conductivity reported by Benson and Othman (1993) were from laboratory tests on samples taken from the upper layers of clay covers; freezing did not extend into the lower layers and, as a result, there was no overall increase in the field-measured vertical hydraulic conductivity. Chamberlain *et al.* (1997) reported increased hydraulic conductivities for natural clay soils, but also reported that field tests on sand-bentonite mixtures and geosynthetic clay liners showed no increases.

Eigenbrod (2003) reviewed the results of 28 freeze-thaw tests reported in the literature, as well as nine supplementary tests, to determine why some soils were much less affected by freeze-thaw cycles than others. Comparison of the freeze-thaw test results to soil index properties showed soils with either very low plasticity or very high plasticity do not experience significant changes in permeability during freeze thaw tests. Eigenbrod hypothesized that these exceptions were due to self-healing of freeze-thaw fractures during permeation of the samples. Three self-healing mechanisms were identified: (1) freezing and thawing of clay soils can lead to water contents that approach the plastic limit, so that even moderate overburden stresses cause the soil to deform and seal fractures; (2) in low-plasticity soils, particles that are eroded from the fracture walls during permeation can clog the fractures; and (3) in highly plastic and highly active soils, swelling of clay particles can seal the freeze-thaw fractures.

None of the papers cited above were specific to mine waste covers. There are reports of freeze-thaw effects on mine waste covers in the literature, but it is difficult to assess the strength of the evidence in some of these cases. Furthermore, there has been no systematic review that would allow the generality or limitations of the conclusions to be determined.

The till cover at the Equity Silver Mine in British Columbia has received considerable attention over the years, mainly as the water treatment plant had to be expanded to accommodate increased leachate. Different schools of thought exist as to the root cause for the increased leachate volumes. However, a recent review noted that “there was no evidence of cracks having developed in the cover from either freeze-thaw or wet-dry cycles” (Weeks and Wilson, 2005).

Adu-Wusu and Yanful (2007) report the findings of cover tests on the waste rock pile at the Whistle Mine in Ontario. The abstract for the paper states that “defects in the placement of the barrier layers, coupled with freeze-thaw effects, likely contributed to the unexpectedly high water percolation values observed”. However, the paper presents no evidence for a freeze-thaw effect. It does present ample evidence of variable construction quality, to the extent that it is questionable whether freeze-thaw effects would even be distinguishable. Other investigators working on the project point to wetting and drying effects as the most likely reason for higher than expected percolation rates (personal communication with B. Ayres).

Investigations of a cover placed on the Vangorda waste rock pile at the Anvil Range Mining Complex near Faro, Yukon, showed an apparent decrease in compaction between field values measured during construction in 1993 and those measured in 2004. Again however, the limitations of the construction quality data make it difficult to verify the significance of the apparent changes. In addition, there were no field measurements of hydraulic conductivity during or immediately after construction. More recent results, from well-instrumented cover trials at the same site, have shown no significant freeze-thaw effects after three years of infiltrometer testing.

Meiers *et al.* (2006) report the results of field cover trials on the SW30 overburden shale dump near Fort McMurray, Alberta. Guelph permeameter tests carried out over a period of five years showed one to two order of magnitude increases in the measured permeabilities of peat/mineral layers, glacial soil layers, and the underlying shale overburden. In this case, however, the covers were not intended to function as barriers and the increased permeabilities were actually seen as beneficial.

3.3.2 Frost Susceptibility

Since covers are engineered structures exposed to the atmosphere, they may be subject to frost action. Frost action can occur if: (1) the soil is frost-susceptible; (2) there is sufficient water available; and, (3) there is sufficient cooling to cause soil and water to freeze. If any one of these conditions can be eliminated, frost action will be less significant.

Frost-susceptibility is related to size distribution of soil particles. In general, coarse-grained soils such as sands and gravels do not heave, whereas clays, silts and very fine sands support the growth of ice lenses even when present in small proportions. The preferred cover soils are typically either clays (barrier covers), or well-graded materials with significant fines (store-and-release covers), which means that cover soils are inherently frost susceptible.

Water must be available in the unfrozen soil for movement to the freezing plane where the growth of ice lenses occurs. A high groundwater table with respect to the location of the ice lenses will therefore favour frost action. If proper drainage can be achieved, water can be prevented from reaching the freezing zone in frost-susceptible soils. Tailings impoundments often have high phreatic levels, therefore, covers over tailings impoundments are at risk from frost action. Store-and-release covers work on the principal of the cover layers holding on to moisture for release during the dry season. There is thus an inherent risk that excess moisture would be in storage upon freeze up, which could lead to frost action. The common cover practice of maintaining soil layers at high degrees of saturation in order to reduce oxygen ingress is therefore also counterproductive towards limiting frost action.

Arguably, the only area where cover practitioners would have any significant control over frost action would be managing the depth of freezing. Depth of freezing is largely determined by the rate of heat loss from the soil surface. Besides the thermal properties of the soil, this heat loss depends upon such climatic variables as solar radiation, snow cover, wind, and air temperature, which is the most significant. If loss of heat can be prevented or reduced, frost-susceptible soils may not experience freezing temperatures. Although this principle is simple, it has significant consequences on cover design. For example, the need for an insulating cover implies that a store-and-release cover could not be used in cold regions, unless the insulating layer itself acts as a store-and-release layer. Also, depending on the type of insulation layer, infiltration may be significantly increased, and thus the burden on the underlying barrier layer may be greater.

3.3.3 Migration of Fines through Covers

Fine tailings and cover materials have been observed to emerge upwards through covers at two cold regions sites. The term “boils” has been used to describe the resulting mounds of fine material. This term however has no scientific basis, and is not intended to imply a particular mechanism.

The Beaverlodge Mine tailings were covered with a shallow rock cover in 1984/85, and after approximately five years, inspectors noted boils on the rock surface. The entire area subsequently received an engineered cover in 1995, consisting of 0.3 m of fine-grained filter sand followed by 0.3 m of sand and gravel. However, boils continued to occur and in 2006/07 another two-layer cover, similar to that placed in 1995 was placed over the affected areas.

Apparently similar boils developed at the Discovery Mine tailings cover, which was constructed in 1998 to 2000. Two different covers were applied: (1) the lake tailings cover consisted of a GCL overlain by about 0.15 m of crushed blast rock (25 mm nominal size), and (2) the upland tailings cover consisted of 0.3 m silty clay overlain by 0.3 m of crushed rock (100 mm nominal size). Boils were observed on the lake tailings cover within a year after construction, but these were believed to be a result of snow entrainment in some areas (see Section 3.2.2 above), and insufficient rock cover in others. The lake tailings cover was repaired by placing an additional 0.2 m thick crushed rock (100 mm nominal size) layer on top in select areas, and no further boils have been noted. By 2004, however, boils were observed on the upland covers. The boils in this case consisted mostly of fine-grained silty clays that had been pushed up through the rock cover.

Extensive investigation into the boils at Beaverlodge concluded that the cause was high pore pressures within the tailings, and the high pore pressures were attributed to groundwater inflow from an upland source. The possible contributing influences of cold regions phenomena were considered, but no strong evidence was found. The use of a filter zone in the cover was found to be appropriate, but there was initially insufficient surcharge on the upper cover layer.

The cause of the boils in the upland covers at Discovery has not been conclusively determined. All of the boils were noted to occur in low-lying and generally wet areas, leading to an inference that the cause is similar to that observed at Beaverlodge. However, the soil layering and the observed effects are very similar to what would be expected from the cold regions phenomena known as “mudboils” or “soil diapirs”. Another possible explanation for at least some of the boils is local increases in pore pressures due to vehicle traffic associated with subsequent stages of the site remediation and/or exploration at neighbouring sites. However, no boils appeared under the Discovery airstrip, perhaps because it consisted of a finer material, and since repairs were carried out over the other areas there have been no further appearance of boils. The boils in the upland covers were repaired by removing the rock cover and installing a geosynthetic liner over the affected area, then replacing the rock. No further boils have been noted since the repairs.

It should be noted that the process by which natural mudboils form is the subject of considerable debate in the periglacial research community, with two hypotheses put forward as follows:

- When the natural moisture content of the underlying fine-grained material is near its liquid limit causing it to liquefy and flow in response to slight changes in moisture content or stress, and the stress cannot be relieved by down slope movement, mud may burst through a rigid surface layer creating or maintaining a mudboil.
- Where high density soils overlie lower density soils with high moisture content, a reverse density gradient may cause a mudboil. Saturation of the active layer may be sufficient to produce reverse density gradients, which when coupled with liquefaction, results in injection of the underlying sediments to the surface.

In the context of covers, the factors that might increase the risk of mudboil formation include:

- Covers on flat or very moderately sloped surfaces, that cannot allow much lateral internal flow (and stress release);

- When either the waste material itself (i.e. tailings), or one of the cover layers is near saturation and is liquefiable; and
- A supply of moisture to the fine liquefiable material.

All of the above risk factors are present in both the Beaverlodge and Discovery cases.

3.3.4 Other Potential Frozen Ground Effects

In addition to the cold regions phenomena discussed in the preceding sections, there are a number of other potential ways that cover performance can be affected by cold regions phenomena. Most of these cannot be supported through illustration in real case studies, but based on a basic understanding of cold regions phenomena it is at least theoretically possible to impact covers. These are:

- *Frost heaving:* Frost susceptible soils will undergo frost heave, and frost heaves could impact cover performance both with respect to final landform and the associated hydrological effects. It is therefore surprising that frost heaving does not appear to have been documented in any of the cover case histories. One possibility is that a significant portion of current cover studies are on waste rock sites where there is no source of water to allow the ice to grow. Another possibility is that the capillary break layers in some covers act to prevent water movement into frost susceptible layers. A third possibility is that the results of frost heaving have been observed, in the form of surface cracking or other localized disturbances, but not properly attributed to that mechanism.
- *Solifluction*: Covers on slopes less than 10^{o} could be subjected to solifluction, especially if the cover soils, or the underlying waste has a high degree of saturation. Solifluction cannot be predicted using conventional slope stability analysis; however, it has been observed in nature to occur at rates sufficiently fast that the phenomena could conceivably be observed in covers shortly after construction.
- *Boulder Fields*: In temperate climates, a well-graded cover soil such as a till, is arguably a better cover material than a silt, sand or clay. This is because the large grain size distribution offers the cover the best of both worlds in cover design; i.e. the material has sufficient fines to have an inherent low hydraulic conductivity, yet it has a sufficient coarse fraction to be self-armouring and erosion resistant. In cold regions, however, materials containing rocks and boulders, such as tills, have been subjected to frost action resulting in the rocks and boulders being segregated and accumulating at the surface. This is called a boulder field. Research has shown that open systems (i.e. where there was free access to moisture to drive the frost action) were more prone to this. Furthermore, in dense till, stones were shown to move down, while in loose till they move up.
- *Ploughing Boulders*: In some temperate climates large boulders have been placed at random locations on the final cover surface to create shelter and habitat for wildlife. In cold regions this practice may lead to ploughing boulders.

- *Soil Heterogeneity*: While not solely a cold regions phenomena, cover soil heterogeneity does lead to some interesting effects. Variable frost action has been monitored in highly heterogeneous soils, which may result in differential heave and settlement of covers. More homogeneous soils, if they are frost susceptible, may therefore help in controlling this effect. On the other hand, single layer covers subject to frost cracking may result in ice wedge and other patterned ground formation. In this case, heterogeneity introduced as multi-layer covers would help alleviate the problem.
- *Solute Concentration*: It has previously been mentioned that pore water salinity affects the freezing point of bulk water, increases the unfrozen water content of soil, and thus, the freezing point and hydraulic conductivity of the soil. However, it is also known that as water freezes solute concentration occurs, which in turn results in significant horizontal variability in freezing temperatures in a soil profile. This phenomenon may severely complicate the frost penetration, thaw development and frozen soil infiltration regimes in a cover profile. It may be a significant issue for mine waste covers, where upwards solute transport could be expected.

3.4 Hydrologic Effects on Cover Performance

3.4.1 Snow and Surface Water

The complexity of cold regions hydrology was discussed in Chapter 2. One of the most significant challenges facing cover practitioners is the inadequacy of numerical tools to predict cold regions hydrology. However, there are a few fundamentals that should not be forgotten when looking at cold regions covers. These are:

- The most important part of the hydrological year is the snowmelt season as it pertains to covers. This is when the bulk of infiltration and runoff will occur in typical cold regions applications.
- Cold regions runoff factors are significantly higher than those for temperate regions due to the presence of frozen ground. Therefore, surface water conveyance systems should be designed appropriately.
- The amount of snow cover on a cover surface to a large extent defines the site water balance. Appropriate cover landform design may be manipulated to locally effect snow accumulation to better suit cover performance.
- Rain on snow is a cold regions hydrological condition that could result in significant flood peaks, which are notably above normal statistical hydrological reoccurrence interval calculations. Again, the importance of the design of surface water conveyance systems for covers should be emphasised.
- Ground thaw and subsequent differential settlement can significantly alter surface hydrology.

A recent three-year study of water balances on the uncovered Grum and Vangorda waste rock piles at the Faro Mine in the Yukon led to interesting findings about the importance of snow pack ablation. Snow re-distribution was found to strongly affect local snow pack thickness across the dumps and along slope transects. The roughness of the dump surface was found to play a role in snow capture, with “bubble dumps” capturing more of the drifting snow than flat surfaces. Sublimation was estimated using the data from intensive site meteorological monitoring and found to account for less than about 3% of the snow pack (Janowicz *et al*., 2004; 2006; 2007a, b). These findings have not yet been extrapolated to covered dumps.

3.4.2 Soil Water and Groundwater

The hydraulic conductivity of a frozen soil with 0% saturation, is only slightly less than that of unfrozen soil. With increased saturation, the frozen soil’s hydraulic conductivity will decrease significantly. Ice saturated soils have been shown to have hydraulic conductivities of less than 1×10^{-5} cm/sec (McCauly *et al*., 2002).

Water will continue to flow via capillary action in soils even at temperatures below the bulk freezing point of water. Therefore, frozen soils are said to have an unfrozen water content for any given soil temperature. Increased pore water salinity will increase the unfrozen water content for a soil.

Complex cold regions covers that include interflow drains could be subjected to aufeis formation. Although case studies of aufeis formation on covers do not exist, in theory it is possible that there could be flow in these drains at a time when ground-temperatures are below freezing. Typically, these drains would emerge at the toe of the waste facility, and if this outflow is not properly designed, or is blocked for any reason, the confined water may emerge at an alternate location and create icing.

3.4.3 Cold Regions Hydrological Process Models

Several models are currently being investigated to model snowmelt and frozen ground infiltration processes. Boggild *et al*. (1999) compared snowmelt models (Hydrologiska Byråns Vattenbalansavdelning (HBV) and MIKE SHE) that predict runoff with varying degrees of accuracy for a Greenland Basin. Takata (2002) presented a model for infiltration that could be coupled with climate models. Lee *et al*. (2005) used the Snow Runoff Melt (SRM) model to examine differences in the snow map products produced by MODIS (Moderate Resolution Imaging Spectroradiometer) and NOHRSC (National Operational Hydrologic Remote Sensing Center).

Gray *et al*. (2001) presented a model for estimating snowmelt infiltration into frozen soils, as did Johnson and Lundun (1991) (reported in Gray *et al*. (2001)). Westerstrom and Singh (2000) examined runoff from snowmelt for different surfaces, while Zhao and Gray (1999) developed a general parametric correlation for estimating snowmelt infiltration into frozen mineral soils using results from the HAWTS numerical model. Zhao *et al*. (2002) examined influence of soil texture on snowmelt infiltration of frozen soils by field measurements and the HAWTS model, but found little difference in infiltration between soil types.

The Cold Regions Hydrological Model (CRHM), developed by a large multidisciplinary research group from various institutions in Canada is arguably one of the most advanced tools in development for predicting hydrological processes in cold regions. The CRHM incorporates hydrological processes of considerable uncertainty such as snow redistribution by wind, snow interception, sublimation, snowmelt, infiltration into frozen soils, hill slope water movement over permafrost, actual evaporation, and radiation exchange to complex surfaces. These processes are described and linked in the model using physically based algorithms (Pomeroy *et al.*, 2007). This model is continuously being updated, and the researchers hope to keep structuring it in a way that it can be used to effectively simulate hydrologic processes for a large array of cold regions landscapes.

3.5 Other Effects on Cover Performance

3.5.1 Vegetation

The issue of whether covers should be vegetated is always contentious. Even in temperate climate regions, agreement on this matter is seldom reached. Some cover types, such as store-and-release covers, rely on the presence of vegetation, whereas others rely on the integrity of the barrier layer, irrespective of the presence of vegetation. Due to concerns about root penetration through the barrier layer, which may lead to increased hydraulic conductivity and/or preferential flow through the cover, many barrier covers are therefore designed with the explicit understanding that vegetation is not allowed, or with certain shallow rooted species only. Another reason vegetation is often discouraged is the potential for roots to penetrate the underlying waste, which could entrain metal uptake by vegetation.

Another potential concern with vegetation is cracks associated with root holes (and animal burrows) located at the toe of a sloped cover system. Downslope movement of water infiltrating could result in aufeis formation, especially if there is a defined underdrain design.

In cold regions it may be possible to create a final cover landform that would be extremely hostile to the establishment of vegetation. This would be described as natural vegetation control. This could for example be done by creating a landform that will be exposed and wind-swept, allowing little shelter for seed germination, as well as providing limited microtopography and soils with little or no moisture retaining capacity. Use of cover soils of poor nutritional value will also be counterproductive towards establishment of vegetation.

Pragmatically even in cold regions nature is extremely resilient, and over the long term it may not be practical or feasible to prevent the natural establishment of vegetation. Therefore, appropriate attention should be given to how a cover could be designed to ensure performance, even if vegetation does naturally establish.

3.5.2 Animals

Animal activities that have been observed to affect cover performance in cold regions include the destruction of freshly planted saplings by beavers. Recent traditional knowledge discussions with First Nations hunters have identified examples of other animal activities that might affect cover performance. One is the tendency of caribou to follow a small number of distinct trails as they migrate across open terrain. This was hypothesized to be the cause of local erosion of a cover at a particular site. Another is the shaking of the ground that can occur when a large herd of caribou runs, which was hypothesized to cause local liquefaction and boils of covered tailings (INAC 2004).

Other areas of concerns that were raised for recent covers through traditional knowledge workshops include the assurance that if covered areas cross migration pathways, that the cover surface be designed to prevent harm to the animals, i.e. a rip-rap surface may be considered an obstacle. Likewise the covered areas may become hunting grounds for prey due to the altered landscape. There is also a concern that covered waste areas may attract animals due to the presence of salts.

3.6 Effects on Cover Construction

3.6.1 Logistics

It is not uncommon for mine sites to be located in remote parts of the world and this provides unique challenges to otherwise simple engineering tasks. Arguably the biggest logistical challenges exist where a mine can only be accessed by air, and this is made even worse if the site is prone to unpredictable weather. In cold regions, unpredictable weather is the norm, especially during shoulder seasons. Although there are always exceptions, mines are generally not considered economic if the only access is by air. Usually the cost of year-round access by road or sea is considered integral to the cost of development. In cold regions, especially areas subject to permafrost, construction of all-weather roads that would allow year-round site access is often prohibitively expensive; however, seasonal winter roads can be constructed to allow access for between 2 and 3 months each year.

This seasonal access provides large logistical challenges when it comes to constructing covers. All construction equipment and materials can only be brought in during that season. If construction cannot be completed in time to demobilize equipment before the winter roads are decommissioned for the season, equipment would have to remain on site until the following season. Other than the financial impact on cover construction, probably the biggest challenge is that the optimum construction fleet for any given task would be different than one would expect in a temperate region, or more accessible location. Cover design practitioners should be cognisant of this.

Another significant logistical challenge to overcome in remote cold regions is that the workforce is usually housed in a camp. The cost of transporting the workforce to and from their home, as well as feeding and maintaining their health while on site, substantially adds to the cost of construction. Also, components of cover construction that are already considered expensive, such as the use of geomembranes, become even more costly as crews of specialised workers need to be brought to the site.

3.6.2 Productivity

The productivity of workers exposed to extreme climatic conditions is less than those working under more favourable conditions. This is especially true of jobs where workers have to be outside, exposed to the elements during the harsh winter months.

Heavy construction equipment can operate at the same productivity under extreme cold climatic conditions as under temperate conditions. However, there are generally two conditions that require construction to be shut down: (1) white-out conditions (i.e. severe snowstorms); and, (2) very cold temperatures (generally when temperatures drop to below about -40^{o}C) as equipment is stopped since the metal becomes brittle.

At high latitudes daylight hours can be few, short and even non-existent during the winter months. This means that all work has to be done using artificial light. This adds to cost, but more importantly makes it more challenging to carry out tasks such as Quality Control and Quality Assurance on cover soils.

3.6.3 Soil Placement

Soils that contain any amount of moisture will freeze solid in cold regions, with finer grained soils, such as silts and clays, especially prone to freezing. Frozen soils cannot be used for engineered covers, primarily since adequate compaction cannot be done. Therefore, construction of soil covers in cold regions under winter conditions poses significant challenges. Also, development of a borrow source for the construction of covers under winter conditions is complicated because, depending on the *in-situ* moisture content of the soil, drilling and blasting techniques may be required. Not only does this add complexity, but the costs of blasting ice rich soils can be higher than rock, since a higher load factor is required.

Methods to successfully overcome these challenges have been developed and used; however, they usually result in greater cost than would be considered normal in temperate climate zones. For example, borrow development can be done during summer and a stockpile of soil created for placement in the winter. If the outer shell of the stockpile is sufficiently moisture controlled during placement and the stockpile is sufficiently large, a crust of frozen soils will develop around the stockpile such that the entire stockpile will not freeze. Careful removal of the frost layer and placement of the unfrozen material prior to freeze-up is required, and usually the stockpile will have to be insulated every day to avoid frost penetration at night.

The use of compaction to create a low permeability layer in a soil cover is common, and much work has been carried out to determine the moisture content for optimum compaction. As a rule for conventional civil engineering applications, it is advantageous to err on the side of *too moist* during compaction (i.e. wet of optimum moisture content). Cover design practitioners however prefer to err on the side of *too dry,* i.e. dryer than optimum moisture content. The reason is that the more moisture contained in the compacted layer the more prone it would be to cracking when subjected to repeated wet-dry cycles. The same logic has been applied to covers in cold regions subjected to repeated freeze-thaw cycles. Chapuis (2002) found that for optimum performance, clay liners should be placed at water contents near their plastic limits. For cold regions applications, Eigenbrod *et al*. (1996) demonstrated that clay soils, when exposed to freeze-thaw, will approach water contents close to their plastic limits. Irrespective of the technical requirements, moisture conditioning of cover soils under winter conditions is extremely difficult and for that reason is seldom done.

In temperate climates, one of the biggest challenges with respect to moisture control is rainfall. The usual practice is that material wetted by rainfall gets removed and allowed to dry. In cold regions, there is an added complexity presented by snowfall. Snowfall can theoretically be removed with no detrimental effect on the moisture content of the material. However, depending on the frequency of snowfall events, and the surface topography of the borrow site, significant amounts of snow is often included in the matrix of soil being used as cover. This can negatively affect compaction, but more importantly can result in ice lens formation within soil cover layers.

One of the standard engineering specifications used for soil cover construction in cold regions is the requirement to clear snow from the surface prior to cover placement. The rationale for this is obvious; however, often, this specification is not followed, especially during the shoulder seasons when daily snowfall is experienced, and if adequate construction QC is not carried out. The result is a layer of compact snow separating the placed cover layers. This layer of compact snow can lead to differential settlement as well as ice lens formation under the right conditions. Differential cover settlement resulting from inadequate snow clearing was observed at the Deloro Mine site tailings cover.

3.6.4 Trafficability

Construction of covers over soft unconsolidated tailings is always a large challenge. In temperate climates this problem can be overcome using a multitude of methods, including; dewatering by means of wick drains or other such techniques, using low ground pressure construction equipment, constructing a “trafficability” layer in advance of the cover, and delaying cover construction sufficiently long that natural consolidation can occur.

Cold regions, more specifically areas where substantial ground frost occurs seasonally, does offer a unique opportunity for accessing tailings surfaces and constructing the cover on a hard frozen surface. The minimum frost thickness required to make use of this advantage will vary depending on the construction fleet size and construction methodology. Reliable methods exist to estimate the required frost thickness for this requirement.

3.6.5 Use of Geosynthetics

Geosynthetics have been in use in engineering applications for a long time. They are available in various product names and include geotextiles, geosynthetic clay liners (GCL), plastic liners, bituminous liners and geonets (or geodrains). For cover applications, it is generally more economical to use natural soil materials, unless suitable natural soils are not readily available, in which case geosynthetics are considered advantageous. The second most prominent reason for using geosynthetics, especially liners, is the greater performance capabilities that these materials present.

A major concern with incorporating geosynthetics in cover design is the life of these materials. It is generally understood that geosynthetics have a finite lifetime, and therefore their use may imply replacing of the cover at specified intervals.

Manufacturer stated design life of geosynthetic products appear to be intentionally vague. Most manufacturers do not provide a design life but state that its life expectancy depends on how, where, and for what application the material was deployed. Where design life is stated, it is usually between 20 and 50 years, but manufacturers often add that the real expected life could be well in excess of 100 years. In reality, the synthetic materials with which these geosynthetics are manufactured are sufficiently resilient. The design life is arguably governed by exposure to ultraviolet rays (i.e. sunlight), chemical degradation, animal and/or root penetration, and extreme natural disasters (i.e. an earthquake).

There are generally strict specifications for handling, transporting and storing geosynthetics, all of which are designed to ensure the product is in optimal condition immediately prior to placement. In cold climates, these specifications are of even greater importance for two reasons. Firstly, if rolls of geotextile, GCL or liner are left exposed to the elements and become sufficiently wet during summer months, they will become solid blocks of ice, which makes winter deployment impossible. Thawing of these rolls must then be done inside a heated building and can take a long time. Secondly, some products, especially liners, have specified temperatures below which they cannot be installed. This is because the materials become brittle, and moisture condenses on the sheet reducing the quality of seam welding.

Geotextile

Geotextiles have been extensively used in cold regions and there are no known restrictions or limitations associated with the use of geotextiles in cold regions. The most common use of geotextiles with soil covers is as protective layers for liners where suitable puncture resistant natural soils are not available. Geotextiles are also used as separation and/or filter layers where suitable natural materials are not available. In an attempt to contain frost heave, Henry and Holtz (2001) carried out experiments using geotextiles as capillary barriers to limit the water supply to frost susceptible soil. They concluded that geotextiles containing soil fines and moistened to 30-40% saturation failed as capillary breaks and thus did not reduce frost heave.

Geosynthetic Clay Liner (GCL)

In areas where low infiltration and/or barrier covers are required, and where natural low permeability soils are not freely available, geosynthetic clay liners (GCL) are often used. GCLs are relatively easy to place, and are more forgiving towards less than perfect installation conditions and poor QA/QC than conventional liners.

Since a GCL consists of a thin layer of bentonite clay sandwiched between two geotextiles (although one layer could be a conventional liner), the active seal is created by the integrity and low hydraulic conductivity of the bentonite. In temperate climates GCLs are considered to perform best if they remain hydrated. However, if the GCL is placed under a suitable confining overburden layer, a GCL has the ability to “self-heal” when cracks appear as a result of wet-dry cycles. The net effect of water permeability under these conditions is likely small; however, the effect on air permeability (i.e. covers that are intended to act as oxygen reducing covers), could be significant, since cracks could be widely spread and exposed for entire seasons.

As stated previously, compacted clay subjected to freeze-thaw cycles can undergo significant increase in hydraulic conductivity. Therefore, the integrity of a GCL subject to freeze-thaw cycles could be questioned. This was investigated by Chamberlain *et al*. (1997), Hewitt and Daniel (1997) and Kraus *et al*. (1997), both in laboratory and field applications and they concluded that GCLs can withstand freeze-thaw cycling without significant increase in hydraulic conductivity.

There are no limiting temperatures at which a GCL can be placed; however, if there is any appreciable moisture in the GCL prior to, or during deployment, the bentonite can become rigid and the risk of geotextile punctures increase.

In contrast to geotextiles, which are generally grey or black in colour, GCLs are often light grey or white. These light coloured products can be very difficult to see in flat light conditions often encountered in cold regions during winter season. This may result in traffic inadvertently passing over unprotected liners, causing costly and time-consuming repairs. Cover practitioners may therefore consider specifying darker coloured GCLs to help alleviate this problem.

Polyethylene and Polyvinyl Chloride Liners

Polyethylene (High Density – HDPE and Low Density – LDPE) and Polyvinyl Chloride (PVC) liners are used in barrier cover applications, when infiltration or oxygen reduction must be reduced commonly to a very low value. These liners are available in a wide range of products and have been successfully applied in landfill cover applications for many decades. Their use in mine waste covers is not as common, mostly due to the large surface area coverage required.

In terms of cold regions applications, most liner manufacturers have products specifically developed for use in cold regions. These liners have compounds that make the material less brittle and thus easier to handle and install during winter. It is possible to use liners that do not have a cold weather rating in cold regions, provided it is installed during summer under appropriate conditions. Once in place, and as long as the liner is not subject to movement (i.e. significant differential settlement), the fact that the material becomes brittle does not come into play.

Manufacturers also have strict specifications about temperatures under which seaming is done in the cold. The coldest temperatures under which this can occur is product specific but range between -10^{o}C and -20^{o}C. Specialist liner installation contractors working exclusively in cold regions have developed techniques to overcome these limitations, and successful field seaming is routinely done at temperatures below -40°C.

PE and PVC liners are extremely slippery under the best of conditions, and in cold regions with a light dusting of snow, these liners can be extremely hazardous. For that reason, the installation specialists usually recommend that textured liners be specified. The liner is installed with the textured side on top. This provides traction for the workers and allows safer construction. These textured liners typically cost more than untextured liners, and although this is not their intended use it is considered “Best Practice” to specify textured liner for use in cold regions cover applications.

Bitumen Liners

Bitumen impregnated geotextiles were the precursors to the modern bituminous liners that are used today. These liners are true infiltration barriers and most commonly have been used for the lining of water conveyance systems. There are no known large scale applications of bituminous liners for mine waste facilities in cold regions; however, one supplier has covered a small waste pile containing aluminium waste at a site in Quebec, and trials are being carried out at Syncrude over sulphur waste.

Bituminous liners are manufactured specifically for use in cold regions, again with the emphasis on making the material less brittle. Just as with PE and PVC liners the manufactures guarantee their product to perform under very cold temperatures; however, they recommend that installation be carried out at temperatures above -20°C. Techniques to successfully overcome this limitation have been developed by specialist installers of these products.

Drainage Nets (Geodrains)

Drainage nets (i.e. geodrains consisting of two geotextiles sandwiching a drainage net) are an elegant and simple, albeit expensive way to direct subsurface flow in a cover system. The products are generally not sensitive to cold regions application, and providing the system drains freely, the drain performance should not be different than in temperate regions. There are few actual covers in cold regions that include these drains and no information has been reported on their success or failure.

From a theoretical point of view it is conceivable that these drains can ice over, resulting in ice lens formation and associated frost heave effects on the overlying cover.

Henry and Holtz (2001) evaluated whether drainage nets could be used as effective capillary barriers to limit the upwards flow of water, and thus prevent frost heave. Laboratory experiments suggest that if the geonets contain fines, frost heave is reduced, provided the water level was below the geodrain. When the geodrains did successfully reduce frost heave, the suction of the cover soils was about 1.8 m; however, when the suction in the cover soils was reduced to 0.8 m or less the geodrain no longer acted as a capillary break. This meant that when the geodrains failed as capillary breaks they were not saturated, but flow most likely occurred from one geotextile to the other in films adhered to the net material. The geotextiles did not have to be saturated to transmit sufficient water to sustain frost heave. Henry and Holtz (2001) recommended that if capillary barriers are to be considered for the purpose of frost heave control, they should be tilted to divert infiltrating water away when the cover soil is not frozen. This will help keep the cover soil from becoming saturated and may help drain water during spring thaw.

Ground Temperature Control

Control of the ground temperature could be appropriate in some cover construction projects. Both active and passive techniques exist for controlling ground temperature. Active techniques include forced ventilation (via vent pipes or piles), or artificial refrigeration (Mageau and Nixon, 2004). Passive techniques (i.e. requiring no power, and no moving mechanical parts) include natural convection devices, thermal barriers, thermal sinks, elevated construction modes, and ground surface modifications (Long and Zarling, 2004).

As previously noted, the radiation balance in high latitude regions are often negative, and although nothing can be done to control the seasonal day/night ratio, cover surfaces can be engineered to alter this radiation balance to some degree. The following are strategies to control the ground temperature of a cover:

- The surface color of the cover; light covers will reflect more incoming radiation than dark colors.
- Create landforms that naturally shed snowfall; raised landforms will result in increased wind clearing and strategic placement of ridges may curtail snow drifting. Less snow cover reduces ground insulation, and promotes more rapid freezing.
- Likewise, landforms can be created that promote snowfall; More snowfall increases ground insulation, and this could reduce frost penetration, especially in non-permafrost cold regions. Where the cover must act to insulate against thaw (i.e. insulating cover), promoting a good snow cover will ensure less heat loss from the system.
- Ground cover in the form of vegetation or organics (i.e. peat or sodding) can be used to promote rapid cooling in the summer; however, during winter months vegetation can trap snow and reduce winter cooling.

If the available cover soils are specifically frost susceptible, then frost penetration can be manipulated using artificial or imported products into the cover design. Benson *et al*. (1996) investigated the use of insulation for protection of landfill liners, and concluded that tire chips, encapsulated fibreglass, extruded polystyrene, and polyurea foam were effective. Feklistov and Rusakov (1996) also advocated the use of urea foams for the preservation of permafrost in construction projects.

There are empirical tools that can be used to determine the minimum thickness of a frost protection layer (Smith and Rager, 2002). Generally, finer grained and more saturated soils will be better insulators than coarser dry soils, and as a result, coarse, dry soil frost protection layers have to be thicker. Convective cooling of the surface can be promoted with the use of coarse cover materials, as described previously.

4 Ongoing and Recommended Research

4.1 Current Cold Regions Cover Studies

The fundamental processes relating to many cold regions phenomena are poorly understood, especially as they pertain to covers; therefore, the most reliable methods to advance the state of knowledge is to carry out field trials (experimental and full-scale). Field trials allow for measurement and monitoring of the performance of the covers subjected to actual conditions experienced at the site. Currently the authors are involved in a number of field trials specifically looking at how cold regions phenomena would affect covers. These include:

- *Colomac Tailings Cover:* Two waste rock cover test plots were constructed on the tailings surface to monitor cover settlement, as well as to determine whether inclusion of a geotextile at the cover interface would resist mudboil formation. Useful settlement data was collected for two seasons, after which the testing was ceased. No mudboil formation occurred during this time. The final tailings cover was subsequently constructed without a filter layer.
- *Faro Mine Tailings Cover*: Similar trials to those at Colomac Mine; however, five seasons of good data are available to date, and will continue to be collected for at least one more season. Valuable tailings consolidation and settlement data have been collected, and some unique seasonal variations are starting to emerge, suggesting cover volume change associated with seasonal freeze-thaw cycles. Mudboil formation data are also being collected, and detailed geochemical testing will be carried out at completion of the tests to determine if there has been any solute movement within the cover. Valuable information was also obtained during construction of these trials.
- *Giant Mine Tailings Cover*: Multi-layer cover test plots were constructed in 2007. These trials are designed to gather information on cover constructability; cover settlement, the benefits and usefulness of capillary breaks to prevent upwards migration of tailings solids and solutes, the benefits of using geotextile as filter layers, and the store-and-release properties of a local silt soil cover. Data to be collected as part of these trials will include settlement data, thermal data and cover moisture content profiles. It is expected that these test plots will be maintained for 3 to 5 years.
- *Faro Mine Waste Rock Covers*: Eight test-cover trials have been constructed, including two complete large-scale lysimeters. These covers represent different cover variants, including different soil types and slopes. The test covers have an extensive array of instrumentation specifically designed to monitor the cover water balance. In addition the trials are designed to test physical degradation of the cover material over time. Three seasons of data are available to date, and it is expected that monitoring will continue for at least 2 to 5 more years.
- *Red Dog Mine Waste Rock Covers*: In 2007, Teck Cominco Alaska, working with O’Kane Consultants Inc., initiated cover trials on four lysimeters that had initially been constructed for geochemical tests. Previous field trials of waste rock compaction and modeling of long-term

cover performance were used as the basis for the trial designs. The construction of a full-scale test cover on the Oxide stockpile is scheduled for 2008.

4.2 Research Needs

In order to further the state of knowledge in cover design and performance for cold regions, research of the following topics are recommended:

- *Fundamental cold regions phenomena*: Fundamental research into classifying cold regions phenomena into processes and features would be useful to avoid confusion and arguments about definition. It would be beneficial if a comprehensive table such as that presented by Washburn (1973) (see Table 1 of this report) could be formulated specifically for use by cover practitioners. This table would list all known cold regions phenomena both by process and feature, complete with a definition of the terminology. Further, a discussion of how these phenomena may relate to covers should be included. It is anticipated that such a research project would consist of primarily a desk study carried out by a team of periglacial researchers, cold regions engineering researchers as well as cover practitioners. The deliverable could be a booklet style reference document that can be consulted by cover practitioners, industry and regulators. This booklet would identify specific processes that are poorly understood, which could trigger specific additional research projects.
- *Establish and maintain a database of cold regions covers*: Although cover design is site specific, cover practitioners do give considerable weight to precedence. As shown in Table 4 of this report, there is a large and growing database of cold regions covers from which to draw information; however, useful data from these case studies are difficult to obtain. It would be of considerable value if a database could be developed that compiles and stores relevant information about cold regions covers, which can be accessed by interested parties. In order to make this database functional a standard template should be developed to ensure that all relevant data about the covers are collected. This project would consist of a desk study consisting of a team of cover practitioners. The deliverable of this project would be a complete database of cold regions covers, universally accessible, as well as recommendations on how such a database could be continuously updated.
- *Development of appropriate cold regions surface flux boundary modeling tools*: Research is needed to bridge the gap between current soil flux boundary numerical models in use (e.g. SVFlux, and VadoseW) and true cold regions hydrological models such as the CRHM model. This project should consist of a team of cold regions hydrologists and cover practitioners familiar with codes currently is use. The deliverable should ultimately be the development of comprehensive cold regions surface flux boundary numerical models; however, more than likely an appropriate theoretical base would be the first step. Data gleaned from current cold regions trial covers, such as those at the Faro Mine could ultimately be used as field calibration data to assist in development of these models.
- *Tracking long-term full-scale cover performance*: Consideration should be given to going back to sites where covers have been constructed for some time and establishing formal performance

monitoring protocols to target specific cold regions phenomena. For example at the Discovery- and Beaverlodge Mines there may be an additional opportunity to investigate mudboils. Likewise at Discovery, there may be opportunity to investigate the influence that the presence of vegetation will have on the cover water balance. Sites such as Nanisivik and Lupin may offer opportunities to study ground temperature control effects. The objective would be to validate cover performance with specific goals. In all cases such research should involve teams of cover practitioners and appropriate discipline dependant experts. Carrying out the first three research projects listed here may help focus these opportunistic research opportunities. Back analysis of actual cold regions cover observations in relation to cold regions phenomena would be invaluable.

- *Development of "Best Practice" guidelines*: Perhaps the long-term goal would be to develop "Best Practice" guidelines for cold regions covers. Arguably, given the current state of knowledge it may be premature to initiate such a document at this time. Unfortunately, cover practitioners, industry and regulators cannot stop using covers until all the answers are available, and the very real questions about how should cold regions covers be designed, constructed, maintained and monitored require immediate answers. Furthermore, it is not only the technical know-how that is of importance, but also issues such as appropriate ways to finance and pay for covers, their maintenance, monitoring and possibly replacement and repair. Therefore consideration should be given to developing a "Living Best Practice" guideline document for cold regions covers. Such a document should be compiled by a group consisting of members of the industry, regulators and cover practitioners.
- *Co-ordination of existing cover trials and monitored full-scale covers*: As previously documented there are a few ongoing cover trials on both tailings and waste rock, specifically focussed towards evaluating cold regions phenomena. In addition, there are others with which the authors of this report are not intimately familiar such as the Diavik Mine waste rock pile trials and potential ongoing vegetation trials at Discovery Mine, as well as other cold regions countries such as Russia, Sweden and Denmark. Furthermore, there are many cold regions covers where performance monitoring is ongoing, such as at Nanisivik Mine, Lupin Mine and Culluton Lake to name a few. It would be beneficial if there were collaboration and co-ordination of these current research programs and regulatory monitoring programs to maximize the deliverables from these programs. Possibly a small technical working group could be established with representation from each cover trial program and/or regulatory group. This group could meet and exchange ideas on a regular basis to foster sharing of data, hypotheses, etc.

5 Conclusions

This report has highlighted the current state of knowledge in cold regions covers, and has attempted to demonstrate how cold regions cover design and performance is different from the broader experience with covers in temperate regions. Some basic principles that can be highlighted are as follows:

- Although cover performance data from cold regions are scarce, there is enough information to demonstrate clearly that designing covers with only temperate climate technology in cold regions should not be considered best practice.
- Cold regions cover design practitioners must familiarize themselves with the fundamental research into cold regions phenomena carried out by the periglacial research community, and consider that research during cover design and performance predictions.
- Owners and operators of mine waste facilities that have identified covers as a temporary or permanent closure and/or a remediation technique should be aware that the technology of covers for use in cold regions is in its infancy. Greater emphasis should be placed on developing field trials, and should include sufficient monitoring to ensure that performance can be evaluated prior to making a final selection. A mechanism to report and distribute this information should also be put in place.

This report should allow cover practitioners, industry and regulators to have a fresh look at how their existing cold regions covers are performing. It is hoped that some of the cold regions phenomena discussed in this report could be identified at existing cold region covers and, through collaboration, the knowledge base and understanding of cold regions covers can be expanded and illustrated through specific case studies.

References

References cited in this report were listed; however, in the process of preparing this report a large number of other relevant reference documents pertaining to cold regions phenomena were consulted. Since this document aims to provide a platform from which to initiate further research into the use of covers in cold regions, this extended reference list is also provided.

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Glossary

This glossary has for the most part been extracted from the International Permafrost Association (IPA) Multi-Language Glossary of Permafrost and Related Ground Ice Terms, and associated Illustrations, compiled and edited by Robert O. van Everdingen (1998; revised 2005). Only the main description of each term is provided here. The reader should consult the primary reference source for more detailed comments.

Active air-cooled thermal pile: A foundation pile on which a cold air refrigeration system has been installed to remove heat from the ground.

Active construction methods in permafrost: Special design and construction methods used for engineering works in permafrost areas where *permafrost degradation* cannot be prevented.

Active ice wedge: An *ice wedge* that is growing as a result of repeated (but not necessarily annual) winter cracking.

Active layer: The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

Active-layer failure: A general term referring to several forms of slope failures or failure mechanisms commonly occurring in the active layer overlying permafrost.

Active-layer thickness: The thickness of the layer of the ground that is subject to annual thawing and freeing in areas underlain by permafrost.

Active liquid refrigerant pile: A foundation pile on which a liquid coolant refrigeration system has been installed to remove heat from the ground.

Active rock glacier: A mass of rock fragments and finer material, on a slope, that contains either an ice core or interstitial ice, and shows evidence of present movement.

Active thermokarst: The process by which characteristic landforms are currently developing as a result of thawing of *ice-rich permafrost* or melting of *massive ice*.

Adfreeze/adfreezing: The process by which two objects are bonded together by ice formed between them.

Adfreeze strength: The tensile or shear strength which has to be overcome to separate two objects that are bonded together by ice.

Aggradational ice: The additional *ground ice* formed as a direct result of *permafrost aggradation*

Air freezing index: The cumulative number of *degree-days* below 0°C for the air temperature during a given time period.

Air thawing index: The cumulative number of *degree-days* above 0°C for the air temperature during a given period.

Alas/alas: A large depression of the ground surface produced by thawing of a large area of very thick and exceedingly *ice-rich permafrost*.

Albedo: Albedo is a measure of the reflecting power of a surface, expressed as the fraction of the incoming solar radiation reflected by the surface.

Altitudinal limit of permafrost: The lowest altitude at which *mountain permafrost* occurs in a given highland area outside the general *permafrost region*.

Altitudinal zonation of permafrost: The vertical subdivision of an area of *mountain permafrost* into *permafrost zones*, based on the proportion of the ground that is perennially cryotic.

Anti-syngenetic ice wedge: An ice wedge that grows progressively downwards into a receding slope, in a direction normal to the surface (see Figure 17i).

Apparent heat capacity: The amount of heat required to raise the temperature of a unit mass of *frozen ground* by one degree.

Approximate freezing index: The cumulative number of *degree-days* below 0°C for a given time period, calculated from the mean monthly temperatures for a specific station without making corrections for positive *degree-days* in spring and fall.

Approximate thawing index: The cumulative number of *degree-days* above 0°C for a given time period, calculated from the mean monthly temperatures for a specific station without making corrections for negative *degree-days* in spring and fall.

Artificial ground freezing: The process of inducing or maintaining a frozen condition in earth materials by artificial means.

Banded cryogenic fabric: A distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which soil particles form sub-horizontal layers.

Barrens: Areas of discontinuous vegetation cover in the polar semi-desert of the High Arctic.

Basal cryopeg: A layer of *unfrozen ground* that is perennially cryotic ($T < 0°C$), forming the basal portion of the permafrost.

Basal cryostructure: The cryostructure of a frozen deposit of boulders that is saturated with ice.

Basal-layered cryostructure: The cryostructure of a frozen layered deposit of gravel and boulders that is saturated with ice.

Beaded stream: A stream characterized by narrow reaches linking pools or small lakes.

Block field: A surficial layer of angular shattered rocks formed in either modern or Pleistocene *periglacial* environments.

Bottom temperature of snow cover (BTS): Temperature measured at the base of the snow cover during mid- to latewinter (February/March).

BTS method: Method to predict the presence or absence of permafrost in a mountain area, using measurements of the *bottom temperature of snow cover* in mid to late-winter.

Buried ice: Ice formed or deposited on the ground surface and later covered by sediments.

Cave ice: Ice formed in a closed or open cave.

Closed-cavity ice: Ice formed in a closed space, cavity or cave in permafrost.

Closed-system freezing: Freezing that occurs under conditions that preclude the gain or loss of any water by the system.

Closed-system pingo: A *pingo* formed by doming of *frozen ground* due to freezing of injected water supplied by expulsion of *pore water* during *permafrost aggradation* in the *closed talik* under a former water body.

Closed talik: A layer or body of *unfrozen ground* occupying a depression in the *permafrost table* below a lake or river.

Coefficient of compressibility: The volume change per unit volume of a substance per unit increase in effective compressive stress, under isothermal conditions.

Collapse scar: That portion of a *peatland* where the whole or part of a *palsa* or *peat plateau* has thawed and collapsed to the level of the surrounding *peatland.*

Composite wedge: A wedge showing evidence of both primary and secondary filling.

Conglomeric cryogenic fabric: Distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which coarser soil particles form compound arrangements.

Construction methods in permafrost: Special design and construction procedures required when engineering works are undertaken in permafrost areas.

Continuous permafrost: Permafrost occurring everywhere beneath the exposed land surface throughout a geographic region with the exception of widely scattered sites, such as newly deposited unconsolidated sediments, where the climate has just begun to impose its influence on the *thermal regime of the ground*, causing the development of continuous permafrost.

Continuous permafrost zone: The major subdivision of a *permafrost region* in which permafrost occurs everywhere beneath the exposed land surface with the exception of widely scattered sites.

Creep of frozen ground: The slow deformation (or time-dependent shear strain) that results from long-term application of a stress too small to produce failure in the frozen material.

Creep strength: The failure strength of a material at a given strain rate or after a given period under deviatoric stress.

Crust-like cryostructure: The cryostructure of a frozen deposit of angular blocks that are coated with ice, whereas large spaces between the blocks are not filled with ice.

Cryofront: The boundary between *cryotic* and *non-cryotic ground* as indicated by the position of the 0°C isotherm in the ground.

Cryogenesis: The combination of thermophysical, physico-chemical and physic-mechanical processes occurring in freezing, frozen and thawing earth materials.

Cryogenic aquiclude: A layer of ground which, because of its frozen state, has a low enough permeability to act as a confining bed for an aquifer.

Cryogenic fabric: The distinct soil micro-morphology resulting from the effects of freezing and thawing processes.

Cryogenic temperature: In international materials science, this term refers to temperatures generally below -50°C, but usually to temperatures within a few degrees of absolute zero (-273°C).

Cryolithology: The study of the genesis, structure and lithology of frozen earth materials.

Cryopedology: The study of soils at temperatures below 0°C, with particular reference to soils subject to intensive *frost action*, and to soils overlying permafrost.

Cryopeg: A layer of *unfrozen ground* that is perennially cryotic (forming part of the permafrost), in which freezing is prevented by *freezing-point depression* due to the dissolved-solids content of the *pore water*.

Cryoplanation: The process through which *cryoplanation terraces* form.

Cryoplanation terrace: A step-like or table-like bench cut in bedrock in cold climate regions.

Cryosol: Soil formed in either mineral or organic materials having permafrost either within 1 m below the surface or, if the soil is strongly cryoturbated, within 2 m below the surface, and having a *mean annual ground temperature* below 0°C.

Cryosphere: That part of the earth's crust, hydrosphere and atmosphere subject to temperatures below 0°C for at least part of each year.

Cryostructure: The structural characteristics of frozen earth materials (see Figure 9).

Cryosuction: Suction developed in freezing or partially frozen fine-grained materials as a result of temperature-dependent differences in *unfrozen water content*.

Cryotexture: The textural characteristics of frozen, fine-grained organic and mineral earth materials cemented together with ice.

Cryotic ground: Soil or rock at temperatures of 0°C or lower.

Cryoturbate: A body of earth material moved or disturbed by *frost action*.

Cryoturbation: (1) (Singular) A collective term used to describe all soil movements due to *frost action*. (2) (Plural) Irregular structures formed in earth materials by deep *frost penetration* and *frost action* processes, and characterized by folded, broken and dislocated beds and lenses of unconsolidated deposits, included organic horizons and even bedrock.

Debris flow: A sudden and destructive variety of landslide, in which loose material on a slope, with more than 50 percent of particles larger than sand size, is mobilized by saturation and flows down a channel or canyon.

Deformability: The ability of a material to change its shape or size under the influence of an external or internal agency, such as stress, temperature, or pore pressure.

Degree-day (C or F): A derived unit of measurement used to express the departure of the mean temperature for a day from a given reference (or base) temperature.

Degree of saturation: 1. The total degree of saturation of frozen soil is the ratio of the volume of ice and unfrozen water in the soil pores to the volume of the pores. 2. The degree of saturation of frozen soil by ice is the ratio of the volume of ice in the soil pores to the volume of the pores.

Delayed strength: The failure strength of a material at a given strain rate or after a given period under deviatoric stress.

Density of frozen ground: The mass of a unit volume of frozen soil or rock.

Depth of seasonal frost penetration: The maximum thickness of the *seasonally frozen layer*.

Depth of thaw: The minimum distance between the ground surface and *frozen ground* at any time during the thawing season in an area subject to seasonal freezing and thawing.

Depth of zero annual amplitude: The distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature.

Desiccation crack: Crack or fissure developed in fine-grained soil material as a result of shrinkage during drying.

Desiccation polygon: Closed, multi-sided *patterned-ground* feature formed by *desiccation cracks* in fine-grained soil material. Usually less than 2 m in diameter.

Design depth of frost penetration: 1. (North-American usage) The mean of the three largest *depths of seasonal frost penetration* measured during the past thirty years, or the largest *depth of seasonal frost penetration* beneath a snow-free soil surface measured during the past ten years. 2. (Russian usage) The mean of the *depths of seasonal frost penetration* measured during at least the last ten years with the ground surface free of snow and the groundwater level below the *depth of seasonal frost penetration*.

Design freezing index: The cumulative number of *degree-days* below 0°C, calculated by taking the average of the *seasonal freezing indices* for the three coldest winters in the most recent 30 years of record.

Design thawing index: The cumulative number of *degree-days* above 0°C, calculated by taking the average of the *seasonal thawing indices* for the three warmest summers in the most recent 30 years of record.

Detachment failure: A slope failure in which the thawed or thawing portion of the *active layer* detaches from the underlying frozen material.

Dielectric constant: The dielectric constant of a soil is a measure of the ability of the soil to store electrical energy in the presence of an electrostatic field.

Dilation crack: A tensile fracture in a frozen material due to surface extension caused by doming.

Dilation crack ice: Ice that forms in *dilation cracks*.

Discontinuous permafrost: Permafrost occurring in some areas beneath the exposed land surface throughout a geographic region where other areas are free of permafrost.

Discontinuous permafrost zone: The major subdivision of a *permafrost region* in which permafrost occurs in some areas beneath the exposed land surface, whereas other areas are free of permafrost.

Disequilibrium permafrost: Permafrost that is not in thermal equilibrium with the existing *mean annual surface* or sea-bottom *temperature* and the *geothermal heat flux*.

Drunken forest: Trees leaning in random directions.

Dry density: The mass of a unit volume of dried material (e.g. soil).

Dry frozen ground: Frozen ground with a very low *total water content* consisting almost completely of *interfacial water*, and not cemented by ice.

Dry permafrost: Permafrost containing neither *free water* nor ice.

Dynamic modulus of elasticity: The ratio of stress to strain for a material under dynamic loading conditions.

Dynamic Poisson's ratio: The absolute value of the ratio between the linear strain changes, perpendicular to and in the direction of a given uniaxial stress change, respectively, under dynamic loading conditions.

Earth hummock: A hummock having a core of silty and clayey mineral soil which may show evidence of *cryoturbation*.

Electrical conductivity: The inverse of electrical resistivity.

Electrical properties of frozen ground: The *dielectric constant* (or *relative permittivity*), *electrical conductivity* and *electrical resistivity* are the major electrical properties governing the flow of electric current through frozen ground.

Electrical resistivity: The property of a material that determines the electrical current flowing through a centimetre cube of the material when an electrical potential is applied to opposite faces of the cube.

Epigenetic ice: *Ground ice* developed in *epigenetic permafrost*, or in previously formed *syngenetic permafrost*.

Epigenetic ice wedge: An *ice wedge* developed in *epigenetic permafrost*, or in previously formed *syngenetic permafrost*.

Epigenetic permafrost: Permafrost that formed through lowering of the *permafrost base* in previously deposited sediment or other earth material.

Equilibrium permafrost: Permafrost that is in thermal equilibrium with the existing *mean annual surface* or sea-bottom *temperature* and with the *geothermal heat flux*.

Excess ice: The volume of ice in the ground which exceeds the total pore volume that the ground would have under natural unfrozen conditions.

Extensive discontinuous permafrost: 1. (North-American usage) Permafrost underlying 65 to 90 percent of them area of exposed land surface. 2. (Russian usage) Permafrost underlying 70 to 80 percent of the area of exposed land surface.

Fabric: Soil micro-morphology.

Fragmic cryogenic fabric: A distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which soil particles form discrete units that are densely packed.

Fragmoidal cryogenic fabric: A distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which soil particles form discrete units that are coalescing.

Free water: Free water is that portion of the *pore water* that is free to move between interconnected pores under the influence of gravity.

Freeze-thaw cycle: Freezing of a material followed by thawing.

Freezeback: Refreezing of thawed materials.

Freezing (of ground): The changing of phase from water to ice in soil or rock.

Freezing front: The advancing boundary between *frozen* (or *partially frozen*) *ground* and *unfrozen ground.*

Freezing index: The cumulative number of *degree-days* below 0°C for a given time period.

Freezing point: 1. The temperature at which a pure liquid solidifies under atmospheric pressure. 2. The temperature at which a ground material starts to freeze.

Freezing-point depression: The number of degrees by which the freezing point of an earth material is depressed below 0°C.

Freezing pressure: The positive pressure developed at ice-water interfaces in a soil as it freezes.

Friable permafrost: *Permafrost* in which the soil particles are not held together by ice.

Frost: The occurrence of air temperatures below 0°C.

Frost action: The process of alternate freezing and thawing of moisture in soil, rock and other materials, and the resulting effects on materials and on structures placed on, or in, the ground.

Frost blister: A seasonal *frost mound* produced through doming of *seasonally frozen ground* by a subsurface accumulation of water under elevated hydraulic potential during progressive *freezing* of the *active layer.*

Frost boil: A small mound of soil material, presumed to have been formed by *frost action*.

Frost bulb: A more or less symmetrical zone of *frozen ground* formed around a buried chilled pipeline or beneath or around a structure maintained at temperatures below 0°C.

Frost creep: The net down slope displacement that occurs when a soil, during a freeze-thaw cycle, expands normal to the ground surface and settles in a nearly vertical direction.

Frost heave: The upward or outward movement of the ground surface (or objects on, or in, the ground) caused by the formation of ice in the soil.

Frost-heave extent: The difference between the elevations of the ground surface before and after the occurrence of *frost heave*.

Frost jacking: Cumulative upward displacement of objects embedded in the ground, caused by *frost action*.

Frost mound: Any mound-shaped landform produced by ground freezing combined with accumulation of *ground ice* due to groundwater movement or the migration of soil moisture.

Frost penetration: The movement of the *freezing front* into the ground during freezing.

Frost phenomena: Effects on earth materials and on structures placed in or on the ground, resulting from *frost action*.

Frost shattering: The mechanical disintegration of rock by the pressure of the freezing of water in pores and along grain boundaries.

Frost sorting: The differential movement of soil particles of different size ranges as a result of *frost action*.

Frost-stable ground: Ground (soil or rock) in which little or no *segregated ice* forms during *seasonal freezing*.

Frost-stable soil: Soil in which little or no *segregated ice* forms during *seasonal freezing*.

Frost-susceptible ground: Ground (soil or rock) in which *segregated ice* will form (causing *frost heave*) under the required conditions of moisture supply and temperature.

Frost-susceptible soil: Soil in which *segregated ice* will form (causing *frost heave*) under the required conditions of moisture supply and temperature.

Frost weathering: The disintegration and break-up of soil or rock by the combined action of *frost shattering*, *frost wedging* and hydration shattering.

Frost wedging: The mechanical disintegration, splitting or break-up of rock by the pressure of the freezing of water in cracks, crevices, pores, joints or bedding planes.

Frozen fringe: The zone in a freezing, *frost-susceptible* soil between the warmest isotherm at which ice exists in pores and the isotherm at which the warmest *ice lens* is growing.

Frozen ground: Soil or rock in which part or all of the *pore water* has turned into ice.

Gas hydrate: A special form of solid clathrate compound in which crystal lattice cages or chambers, consisting of host molecules, enclose guest molecules.

Gelifluction: The slow down slope flow of unfrozen earth materials on a frozen substrate.

Geocryology: The study of earth materials having a temperature below 0°C.

Geothermal gradient: The rate of temperature increase with depth in the subsurface.

Geothermal heat flux: The amount of heat moving steadily outward from the interior of the earth through a unit area in unit time.

Granic cryogenic fabric: A distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which soil particles form discrete loosely packed units.

Granoidic cryogenic fabric: A distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which soil particles form more or less discrete loosely packed units.

Gravimetric (total) water content: The ratio of the mass of the water and ice in a sample to the dry mass of the sample, commonly expressed as a percentage.

Ground ice: A general term referring to all types of ice contained in freezing and *frozen ground*.

Hard frozen ground: *Frozen ground* (soil or rock) which is firmly cemented by ice.

Heat capacity: The amount of heat required to raise the temperature of a unit mass of a substance by one degree.

Heaving pressure: Upward pressure developed during freezing of the ground.

High-centre polygon: An *ice-wedge polygon* in which melting of the surrounding *ice wedges* has left the central area in a relatively elevated position.

Hydraulic conductivity: The volume of fluid passing through a unit cross section in unit time under the action of a unit hydraulic potential gradient.

Hydraulic diffusivity: The ratio of the *hydraulic conductivity* and the storage capacity of a groundwater aquifer.

Hydraulic thawing: Artificial thawing (and removal) of *frozen ground* by the use of a stream or jet of water under high pressure.

Hydrochemical talik: A layer or body of *cryotic* (but *unfrozen*) *ground* in a permafrost area, maintained by moving mineralized groundwater.

Hydrothermal talik: A layer or body of *noncryotic unfrozen ground* in a permafrost area, maintained by moving groundwater.

Ice: Water in the solid state.

Ice-bearing permafrost: Permafrost that contains ice.

Ice-bonded permafrost: *Ice-bearing permafrost* in which the soil particles are cemented together by ice.

Ice content: The amount of ice contained in frozen or partially frozen soil or rock.

Ice-cored topography: Topography that is due almost solely to differences in the amount of *excess ice* underlying its surface.

Ice lens: A dominantly horizontal, lens-shaped body of ice of any dimension.

Ice-nucleation temperature: The temperature at which ice first forms during freezing of a soil/water system that does not initially contain ice.

Ice-rich permafrost: Permafrost containing *excess ice*.

Ice segregation: The formation of discrete layers or lenses of *segregated ice* in freezing mineral or organic soils, as a result of the migration (and subsequent freezing) of *pore water*.

Ice vein: An ice-filled crack or fissure in the ground.

Ice wedge: A massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice.

Ice-wedge cast: A filling of sediment in the space formerly occupied by an *ice wedge*.

Ice-wedge polygon: A *polygon* outlined by *ice wedges* underlying its boundaries.

Icing: A sheet-like mass of layered ice formed on the ground surface, or on river or lake ice, by freezing of successive flows of water that may seep from the ground, flow from a spring or emerge from below river or lake ice through fractures.

Icing blister: A seasonal *frost mound* consisting of ice only and formed at least in part through lifting of one or more layers of an *icing* by injected water.

Icing glade: An area kept clear of trees and shrubs by the annual occurrence of *icings*.

Icing mound: A seasonal *frost mound* consisting exclusively of thinly layered ice, formed by freezing of successive flows of water issuing from the ground or from below river ice.

Inactive ice wedge: An *ice wedge* that is no longer growing.

Inactive rock glacier: A mass of rock fragments and finer material, on a slope, that contains either an ice core or interstitial ice, and shows evidence of past, but not present, movement.

Interfacial water: Interfacial water forms transition layers at mineral/water and mineral/water/ice interfaces in *frozen ground*.

Intermediate discontinuous permafrost: 1. (North-American usage) Permafrost underlying 35 to 65 percent of the area of exposed land surface. 2. (Russian usage) Permafrost underlying 40 to 60 percent of the area of exposed land surface.

Intrapermafrost water: Water occurring in unfrozen zones (*taliks* and *cryopegs*) within permafrost.

Intrusive ice: Ice formed from water injected into soils or rocks.

Isoband cryogenic fabric: A distinct soil micromorphology, resulting from the effects of freezing and thawing processes, in which soil particles form subhorizontal layers of similar thickness.

Isolated cryopeg: A body of *unfrozen ground*, that is perennially cryotic (T < 0°C) and entirely surrounded by perennially *frozen ground*.

Isolated patches of permafrost: Permafrost underlying less than 10 percent of the exposed land surface.

Isolated talik: A layer or body of *unfrozen ground* entirely surrounded by perennially *frozen ground*.

Kurum: A general term for all types of coarse clastic formations on slopes of 2-3 to 40 degrees, moving downslope mainly due to creep.

Lake talik: A layer or body of *unfrozen ground* occupying a depression in the *permafrost table* beneath a lake.

Latent heat (of fusion): The amount of heat required to melt all the ice (or freeze all the *pore water*) in a unit mass of soil or rock.

Lateral talik: A layer or body of *unfrozen ground*, overlain and underlain by perennially *frozen ground*.

Latitudinal limit of permafrost: The southernmost (northernmost) latitude at which permafrost occurs in a lowland region in the northern (southern) hemisphere.

Latitudinal zonation of permafrost: The subdivision of a *permafrost region* into *permafrost zones*, based on the percentage of the area that is underlain by permafrost.

Layered cryostructure: The cryostructure of frozen silt or loam in which ice layers alternate with mineral layers that have a *massive cryostructure* (see Figure 9e).

Lens ice: *Ground ice* occurring as *ice lenses*.

Lens-type cryostructure: The cryostructure of frozen silt or loam containing numerous *ice lenses.*

Long-term strength: The failure strength of a material after a long period of creep deformation.

Low-centre polygon: An *ice-wedge polygon* in which thawing of *ice-rich permafrost* has left the central area in a relatively depressed position.

Macro-scale polygons: Macro-scale polygons are closed, multi-sided, roughly equidimensional patterned-ground features, typically 15 to 30 m across, commonly resulting from thermal contraction cracking of the ground.

Marine cryopeg: A layer or body of *unfrozen ground*, that is perennially cryotic (T < 0°C), forming part of coastal or *subsea permafrost.*

Mass wasting: Downslope movement of soil or rock on, or near, the earth's surface under the influence of gravity.

Massive-agglomerate cryostructure: The cryostructure of frozen silt or loam in which ice veins form an irregular three-dimensional network.

Massive cryostructure: The cryostructure of frozen sand in which all mineral particles are bonded together by ice, and all pore spaces completely filled with ice.

Massive ice: A comprehensive term used to describe large masses of *ground ice*, including *ice wedges, pingo ice, buried ice* and large *ice lenses.*

Massive-porous cryostructure: The cryostructure of frozen sand and gravel in which all mineral particles are bonded together with ice, but larger pore spaces are not completely filled with ice.

Mean annual ground-surface temperature (MAGST): Mean annual temperature of the surface of the ground.

Mean annual ground temperature (MAGT): Mean annual temperature of the ground at a particular depth.

Mechanical properties of frozen ground: The properties of *frozen ground* governing its *deformability* and strength.

Mechanical strength: The failure strength of a material under given loading conditions.

Micro-scale polygon: Micro-scale polygons are closed, multi-sided, roughly equidimensional patterned-ground features, less than 2 m in diameter, usually caused by desiccation cracking of fine-grained soil materials.

Minerogenic palsa: A *palsa* in which the frozen core extends below the peat into underlying mineral material.

Mountain permafrost: Permafrost existing at high altitudes in high, middle, and low latitudes.

Mud circle: A type of non-sorted circle developed in fine-grained materials.

Multiple retrogressive slide: A type of mass movement associated with shear failure in unfrozen sediments underlying permafrost, leading to detachment of blocks of *frozen ground* that move down slope.

n-factor: The ratio of the *surface freezing* or *thawing index* to the *air freezing* or *thawing index*.

Needle ice: Thin, elongated ice crystals that form perpendicular to the ground surface.

Non-cryotic ground: Soil or rock at temperatures above 0°C.

Non-sorted circle: A non-sorted circle is a *patterned ground* form that is equi-dimensional in several directions, with a dominantly circular outline which lacks a border of stones.

Non-sorted net: A non-sorted net is a type of *patterned ground* with cells that are equi-dimensional in several directions, neither dominantly circular nor polygonal, and lacking borders of stones.

Non-sorted polygon: A non-sorted polygon is a *patterned ground* form that is equi-dimensional in several directions, with a dominantly polygonal outline which lacks a border of stones.

Non-sorted step: A non-sorted step is a *patterned ground* feature with a step-like form and a down slope border of vegetation embanking an area of relatively bare ground upslope.

Non-sorted stripe: Non-sorted stripes form *patterned ground* with a striped and non-sorted appearance, due to parallel strips of vegetation-covered ground and intervening strips of relatively bare ground, oriented down the steepest available slope.

Onshore permafrost: Permafrost occurring beneath exposed land surfaces.

Open-cavity ice: Ice formed in an open cavity or crack in the ground by reverse sublimation of water vapour.

Open-system freezing: Freezing that occurs under conditions that allow gain or loss of water by the system.

Open-system pingo: A *pingo* formed by doming of *frozen ground* due to freezing of injected water supplied by groundwater moving dow nslope through *taliks* to the site of the *pingo*, where it moves towards the surface.

Open talik: A body of *unfrozen ground* that penetrates the permafrost completely, connecting *suprapermafrost* and *subpermafrost water*.

Orbiculic cryogenic fabric: A distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which coarser soil particles form circular to ellipsoidal patterns.

Organic cryosol: An organic soil having a surface layer containing more than 17% organic carbon by weight, with permafrost within 1 m below the surface.

Oriented lake: One of a group of lakes possessing a common, preferred, long-axis orientation.

Palsa: A peaty permafrost mound possessing a core of alternating layers of *segregated ice* and *peat* or mineral soil material.

Palsa bog: A poorly-drained lowland underlain by organic-rich sediments, which contains perennially frozen peat bodies (*peat plateaux*) and occasionally *palsas*.

Partially-bonded permafrost: *Ice-bearing permafrost* in which some of the soil particles are not held together by ice.

Passive construction methods in permafrost: Special design and construction methods used for engineering works in permafrost areas where preservation of the frozen condition is feasible.

Passive single-phase thermal pile: A foundation pile provided with a single-phase natural convection cooling system to remove heat from the ground.

Passive two-phase thermal pile: A foundation pile provided with a two-phase natural convection cooling system to remove heat from the ground.

Patterned ground: A general term for any ground surface exhibiting a discernibly ordered, more or less symmetrical, morphological pattern of ground and, where present, vegetation.

Peat: A deposit consisting of decayed or partially decayed humified plant remains.

Peat hummock: A hummock consisting of *peat*.

Peat plateau: A generally flat-topped expanse of *peat*, elevated above the general surface of a *peatland*, and containing *segregated ice* that may or may not extend downward into the underlying mineral soil.

Peatland: Peat-covered terrain.

Pereletok: A layer of *frozen ground* which forms as part of the *seasonally frozen ground* (in areas free of permafrost or with a lowered *permafrost table*), remains frozen throughout one or several summers, and then thaws.

Periglacial: The conditions, processes and landforms associated with cold, non-glacial environments.

Periglacial phenomena: Landforms and soil characteristics produced by *periglacial processes*.

Periglacial processes: Processes associated with *frost action* in cold, non-glacial environments.

Permacrete: An artificial mixture of frozen soil materials cemented by *pore ice*, which forms a concrete-like construction material used in cold regions.

Permafrost: Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

Permafrost aggradation: A naturally or artificially caused increase in the thickness and/or areal extent of permafrost.

Permafrost base: The lower boundary surface of permafrost, above which temperatures are perennially below 0°C (cryotic) and below which temperatures are perennially above 0°C (non-cryotic).

Permafrost boundary: 1. The geographical boundary between the *continuous* and *discontinuous permafrost zones*. 2. The margin of a discrete body of permafrost.

Permafrost degradation: A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost.

Permafrost limit: Outermost (latitudinal) or lowest (altitudinal) limit of the occurrence of permafrost.

Permafrost region: A region in which the temperature of some or all of the ground below the seasonally freezing and thawing layer remains continuously at or below 0°C for at least two consecutive years.

Permafrost table: The upper boundary surface of permafrost.

Permafrost thickness: The vertical distance between the *permafrost table* and the *permafrost base*.

Permafrost zone: A major subdivision of a *permafrost region*.

Pingo: A perennial *frost mound* consisting of a core of *massive ice*, produced primarily by injection of water, and covered with soil and vegetation.

Pingo ice: *Massive ice* forming the core of a *pingo*.

Pingo remnant: A collapsed *pingo*.

Pingo scar: A *pingo remnant* in a contemporary non-permafrost environment.

Planetary permafrost: Permafrost occurring on other planetary bodies (planets, moons, asteroids).

Plastic frozen ground: Fine-grained soil in which only a portion of the *pore water* has turned into ice.

Poisson's ratio: The absolute value of the ratio between linear strain changes, perpendicular to and in the direction of a given uniaxial stress change, respectively.

Polygon: Polygons are closed, multi-sided, roughly equi-dimensional *patterned ground* features, bounded by more or less straight sides; some of the sides may be irregular.

Polygon trough: The narrow depression surrounding a *high-centre polygon*.

Polygonal pattern: A pattern consisting of numerous multi-sided, roughly equi-dimensional figures bounded by more or less straight sides.

Polygonal peat plateau: A *peat plateau* with *ice-wedge polygons*.

Poorly-bonded permafrost: *Ice-bearing permafrost* in which few of the soil particles are held together by ice.

Pore ice: Ice occurring in the pores of soils and rocks.

Pore water: Water occurring in the pores of soils and rocks.

Pressure-melting: Lowering the melting point of ice by applying pressure.

Relative permittivity: The relative permittivity of a soil is the ratio of the permittivity of the soil to the permittivity of a vacuum.

Relict active layer: A layer of ground, now perennially frozen, lying immediately below the modern *active layer*. Its thickness indicates the greater annual *depth of thaw* that occurred during a previous period.

Relict ice: Ice formed in, and remaining from, the geologically recent past.

Relict permafrost: Permafrost existing in areas where permafrost cannot form under present climatic conditions.

Residual stress: The effective stress generated in a thawing soil if no volume change is permitted during thaw.

Residual thaw layer: A layer of *thawed ground* between the *seasonally frozen ground* and the *permafrost table*.

Reticulate-blocky cryostructure: The cryostructure in which horizontal and vertical *ice veins* form a three dimensional, irregular rectangular lattice.

Reticulate cryostructure: The cryostructure in which horizontal and vertical *ice veins* form a three dimensional, rectangular or square lattice.

Reticulate ice: A network of horizontal and vertical *ice veins* forming a three dimensional, often rectangular or square lattice.

Retrogressive thaw slump: A slope failure resulting from thawing of *ice-rich permafrost.*

River talik: A layer or body of *unfrozen ground* occupying a depression in the *permafrost table* beneath a river.

Rock glacier: A mass of rock fragments and finer material, on a slope, that contains either interstitial ice or an ice core and shows evidence of past or present movement.

Saline permafrost: Permafrost in which part or all of the *total water content* is unfrozen because of *freezing-point depression* due to the dissolved-solids content of the *pore water*.

Salinity: 1. A general property of aqueous solutions caused by the alkali, alkaline earth, and metal salts of strong acids (Cl, SO_4 and NO_3) that are not hydrolyzed. 2. In soil science, the ratio of the weight of salt in a soil sample to the total weight of the sample.

Sand wedge: A wedge-shaped body of sand produced by filling of a *thermal contraction crack* with sand either blown in from above or washed down the walls of the crack.

Sand-wedge polygon: A *polygon* outlined by *sand wedges* underlying its boundaries.

Seasonal freezing index: The cumulative number of *degree-days* below 0°C, calculated as the arithmetic sum of all the negative and positive mean daily air temperatures (°C) for a specific station during the time period between the highest point in the fall and the lowest point the next spring on the cumulative *degree-day* time curve.

Seasonal frost: The occurrence of ground temperatures below 0°C for only part of the year.

Seasonal thawing index: The cumulative number of *degree-days* above 0°C, calculated as the arithmetic sum of all the positive and negative mean daily air temperatures (°C) for a specific station during the time period between the lowest point in the spring and the highest point the next fall on the cumulative *degree-day* time curve.

Seasonally-active permafrost: The uppermost layer of the permafrost which undergoes seasonal phase changes due to a lowered thawing temperature.

Seasonally frozen ground: Ground that freezes and thaws annually.

Seasonally frozen layer (SFL): "Active layer" in areas without permafrost.

Seasonally thawed ground: Ground that thaws and refreezes annually.

Seasonally thawed layer (STL): The *active layer* in permafrost areas.

Segregated ice: Ice in discrete layers or *ice lenses*, formed by *ice segregation*.

Segregation potential: The ratio of the rate of moisture migration to the temperature gradient in a frozen soil near the 0°C isotherm.

Short-term strength: The failure strength of a material under a short-term loading (e.g. up to about 10 minutes in a uniaxial compression test).

Single-phase thermosyphon: A passive heat transfer device, filled with either a liquid or a gas, installed to remove heat from the ground.

Snow: Ice crystals precipitated from the atmosphere, mainly in complex hexagon (plate, column or needle) form, often agglomerated into snowflakes.

Snowcover: The accumulation of fallen snow covering the ground.

Snowdrift: An accumulation of wind-blown snow, commonly considerably thicker than the surrounding *snowcover*.

Snowline: The lower boundary of a highland region in which snow never melts.

Snowmelt: Melting of the *snowcover*, and also the period during which melting of the *snowcover* occurs at the end of the winter.

Snowpatch: Relatively small area of *snowcover* remaining after the main *snowmelt* period.

Soil wedge: A wedge-shaped body of soil that is different in structure and texture from the surrounding soil.

Solifluction: Slow down slope flow of saturated unfrozen earth.

Solifluction apron: A fan-like deposit at the base of a slope, produced by *solifluction*.

Solifluction features: Geomorphological features of varying scale produced by the process of *solifluction.*

Solifluction lobe: An isolated, tongue-shaped *solifluction feature*, up to 25 m wide and 150 m or more long, formed by more rapid *solifluction* on certain sections of a slope showing variations in gradient.

Solifluction sheet: A broad deposit of non-sorted, water-saturated, locally derived materials that is moving or has moved down slope.

Solifluction terrace: A low step, or bench, with a straight or lobate front, the latter reflecting local differences in the rate of *solifluction* movement.

Sorted circle: A sorted circle is a *patterned ground* form that is equi-dimensional in several directions, with a dominantly circular outline, and a sorted appearance commonly due to a border of stones surrounding a central area of finer material.

Sorted net: A sorted net is a type of *patterned ground* with cells that are equi-dimensional in several directions, neither dominantly circular nor polygonal, with a sorted appearance commonly due to borders of stones surrounding central areas of finer material.

Sorted polygon: A sorted polygon is a *patterned ground* form that is equi-dimensional in several directions, with a dominantly polygonal outline, and a sorted appearance commonly due to a border of stones surrounding a central area of finer material.

Sorted step: A sorted step is a *patterned ground* feature with a step-like form and a down slope border of stones embanking an area of relatively fine-grained bare ground upslope.

Sorted stripe: Sorted stripes form *patterned ground* with a striped and sorted appearance, due to parallel strips of stones and intervening strips of finer material, oriented down the steepest available slope.

Specific heat capacity: The amount of heat required to raise the temperature of a unit mass of a substance by one degree.

Sporadic discontinuous permafrost: 1. (North-American usage) Permafrost underlying 10 to 35 percent of the exposed land surface. 2. (Russian usage) Permafrost underlying 5 to 30 percent of the exposed land surface.

Static cryosol: A mineral soil showing little or no evidence of *cryoturbation*, with permafrost within 1 m below the surface.

Stone-banked (solifluction) lobe: A *solifluction lobe* with a stony front.

Stone-bankeded (solifluction) terrace: A *solifluction terrace* with a stony front.

Stone garland: A stone garland is the down slope border of stones along a *sorted step*, embanking an area of relatively fine-grained bare ground upslope.

Stony earth circle: A type of non-sorted circle developed in gravelly materials.

String fen: A *peatland* with roughly parallel narrow ridges of *peat* dominated by fenland vegetation interspersed with slight depressions, many of which contain shallow pools.

Subglacial permafrost: Permafrost beneath a glacier.

Subglacial talik: A layer or body of *unfrozen ground* beneath a glacier in an area with permafrost.

Sublimation ice: Ice formed by reverse sublimation of water vapour onto cold surfaces.

Subpermafrost water: Water occurring in the *noncryotic ground* below the permafrost.

Subsea permafrost: Permafrost occurring beneath the sea bottom.

Subsea talik: A layer or body of *unfrozen ground* beneath the sea bottom, and forming part of the *subsea permafrost*.

Supercooling: Cooling of a liquid to a temperature below its *freezing point*, without causing solidification.

Suprapermafrost water: Water occurring in *unfrozen ground* above perennially *frozen.*

Surface freezing index: The cumulative number of *degree-days* below 0°C for the surface temperature (of the ground, pavement, etc.) during a given time period.

Surface thawing index: The cumulative number of *degree-days* above 0°C for the surface temperature (of the ground, pavement, etc.) during a given period.

Suscitic cryogenic fabric: A distinct soil micro-morphology, resulting from the effects of freezing and thawing processes, in which coarser soil particles have vertical or near vertical orientation.

Syngenetic ice: *Ground ice* developed during the formation of *syngenetic permafrost*.

Syngenetic ice wedge: An *ice wedge* developed during the formation of *syngenetic permafrost.*

Syngenetic permafrost: Permafrost that formed through a rise of the *permafrost table* during the deposition of additional sediment or other earth material on the ground surface.

Talik: A layer or body of *unfrozen ground* occurring in a permafrost area due to a local anomaly in thermal, hydrological, hydro-geological, or hydro-chemical conditions.

Temperature profile: The graphic or analytical expression of the variation in ground temperature with depth.

Thaw basin: A depression of the *permafrost table* created by naturally induced thawing.

Thaw bulb: A zone of *thawed ground* below or surrounding a man-made structure placed on or in permafrost and maintained at temperatures above 0°C.

Thaw consolidation: Time-dependent compression resulting from thawing of *frozen ground* and subsequent draining of excess water.

Thaw consolidation ratio: A dimensionless ratio describing the relationship between the rate of thaw and the rate of consolidation of a thawing soil, which is considered to be a measure of the relative rates of generation and expulsion of excess water during thaw.

Thaw penetration: The downward movement of the *thawing front* during thawing of *frozen ground*.

Thaw-sensitive permafrost: Perennially *frozen ground* which, upon thawing, will experience significant *thaw settlement* and suffer loss of strength to a value significantly lower than that for similar material in an unfrozen condition.

Thaw settlement: Compression of the ground due to *thaw*.

Thaw sink: A closed *thaw basin* with subterranean drainage.

Thaw slumping: A slope failure mechanism characterized by the melting of *ground ice*, and downslope sliding and flowing of the resulting debris.

Thaw-stable permafrost: Perennially *frozen ground* which, upon thawing, will not experience either significant *thaw settlement* or loss of strength.

Thaw strain: The amount that *frozen ground* compresses upon thawing.

Thaw unconformity: A boundary sometimes identified in perennially *frozen ground*, representing the base of a *relict active layer*, as well as the corresponding earlier *permafrost table*.

Thaw weakening: The reduction in shear strength due to the decrease in effective stresses resulting from the generation and slow dissipation of excess pore pressures when frozen soils containing ice are thawing.

Thawed ground: Previously *frozen ground* in which all ice has melted.

Thawing (of frozen ground): Melting of the ice in *frozen ground*, usually as a result of a rise in temperature.

Thawing front: The advancing boundary between *thawed ground* and *frozen.*

Thawing index: The cumulative number of *degree-days* above 0°C for a given time period.

Thermal conductivity: The quantity of heat that will flow through a unit area of a substance in unit time under a unit temperature gradient.

Thermal-contraction crack: A tensile fracture resulting from thermal stresses in *frozen ground*.

Thermal-contraction-crack ice: Ice formed in *thermal contraction cracks* in the ground.

Thermal diffusivity: The ratio of the *thermal conductivity* to the *volumetric heat capacity*.

Thermal erosion: The erosion of *ice-bearing permafrost* by the combined thermal and mechanical action of moving water.

Thermal expansion (or contraction) coefficient: The volume change per unit volume of a substance due to a one degree change in its temperature.

Thermal pile: A foundation pile on which natural convection or forced circulation cooling systems or devices have been installed to remove heat from the round.

Thermal properties of frozen ground: The properties of the ground governing the flow of heat through it, and its freezing and thawing conditions.

Thermal regime of the ground: A general term encompassing the temperature distribution and heat flows in the ground and their time-dependence.

Thermal talik: A layer or body of *unfrozen ground* (in a permafrost area) in which the temperature is above 0°C due to the local *thermal regime of the ground*.

Thermo-erosional cirque: The usually steep, horseshoe-shaped headwall of a *retrogressive thaw slump*.

Thermo-erosional niche: A recess at the base of a river bank or coastal bluff, produced by *thermal erosion* of ice-bonded *permafrost.*

Thermokarst: The process by which characteristic landforms result from the thawing of *ice-rich permafrost* or the melting of *massive ice*.

Thermokarst lake: A lake occupying a closed depression formed by settlement of the ground following thawing of *ice-rich permafrost* or the melting of *massive ice.*

Thermokarst mound: A hummock remaining after melting of the *ice wedges* surrounding an *ice wedge polygon.*

Thermokarst terrain: The often irregular topography resulting from the melting of excess *ground ice* and subsequent *thaw settlement.*

Thermosyphon: A passive heat transfer device installed to remove heat from the ground.

Thufur: Perennial hummocks formed in either the *active layer* in permafrost areas, or in the *seasonally frozen ground* in non-permafrost areas, during freezing of the ground.

Total annual freezing index: The cumulative number of *degree-days*, calculated by adding all the negative mean daily air temperatures (°C) for a specific station during a calendar year.

Total annual thawing index: The cumulative number of *degree-days*, calculated by adding all the positive mean daily air temperatures (°C) for a specific station during a calendar year.

Total water content (of frozen ground): The total amount of water (unfrozen water plus ice) contained in soil or rock.

Transient talik: A layer or body of *unfrozen ground* (in a permafrost area) that is gradually being eliminated by freezing.

Tundra: Treeless terrain, with a continuous cover of vegetation, found at both high latitudes and high altitudes.

Turbic cryosol: A mineral soil showing marked evidence of *cryoturbation*, as indicated by broken horizons and displaced material.

Turf-banked (solifluction) lobe: A *solifluction lobe* with its front covered by a vegetation mat.

Turf-banked (solifluction) terrace: A *solifluction terrace* with its front covered by a vegetation mat.

Turf hummock: A hummock consisting of vegetation and organic matter with or without a core of mineral soil or stones.

Two-layer permafrost: Ground in which two layers of permafrost are separated by a layer of *unfrozen ground*.

Two-phase thermosyphon: A passive heat transfer device, filled with a temperature-dependent liquid/vapour combination, installed to remove heat from the ground.

Unfrozen ground: Soil or rock that does not contain any ice.

Unfrozen water content: The amount of unfrozen (liquid) water contained in frozen soil or rock upward freezing: The advance of a *freezing front* upwards from the *permafrost table* during annual freezing of the *active layer*.

Vein ice: A comprehensive term for ice of any origin occupying cracks in permafrost.

Volumetric heat capacity: The amount of heat required to raise the temperature of a unit volume of a substance by one degree.

Volumetric latent heat of fusion: The amount of heat required to melt all the ice (or freeze all the *pore water*) in a unit volume of soil or rock.

Volumetric (total) water content: The ratio of the volume of the water and ice in a sample to the volume of the whole sample, expressed as a fraction (or, less commonly, as a percentage).

Waterbody encircling a palsa: A water-filled depression surrounding a *palsa*.

Wedge ice: Ice occurring in an *ice wedge.*

Well-bonded permafrost: *Ice-bearing permafrost* in which all the soil particles are held together by ice.

Young's modulus: The ratio of increase in stress acting on a test specimen, to the resulting increase in strain, under constant transverse stress.

Zero curtain: The persistence of a nearly constant temperature, very close to the *freezing point*, during annual freezing (and occasionally during thawing) of the *active layer.*

Zone of gas-hydrate stability: That portion of the subsurface where the conditions of temperature and pressure are suitable for the formation and preservation of *gas hydrates*.