Characteristics of permafrost and ice-rich ground surrounding placer mining operations, Yukon Territory: guidelines for management practices

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1. INTRODUCTION

Permafrost is defined as ground that remains at or below $0^{o}C$ for at least two consecutive years. Its presence and thickness is dependent on a number of factors, namely: air temperature, snow cover, vegetation cover and the thermal properties of the ground. Overlying permafrost is the active layer - a thickness of ground which freezes in the winter and thaws in the summer. It plays a crucial role in the movement of water and is the thickness of ground which is able to support plant life. In Yukon placer mining areas, permafrost is of concern when it contains appreciable amounts of ice. Rock and coarse gravel may be frozen, however generally they do not contain much ice. Finer sediments, on the other hand, such as silt and sand contain much greater volumes of ice. Thawing of these frozen sediments is of concern since, once exposed, ice within them melts easily, and meltwater and sediment are easily transported to nearby streams.

2. REGIONAL CHARACTERISTICS OF PERMAFROST

Permafrost distribution is closely linked to climate and physiography. Areas with similar climate, physiography, and resulting flora and fauna are grouped into ecoregions belonging to broader ecozones. Throughout most of the northern Yukon ecozones, including the Taiga Plain and Taiga Cordillera permafrost is continuous. Further south, in the Boreal Cordillera, permafrost is discontinuous (Fig. 1). Within the Mackenzie Mountians, Ruby Ranges, Klondike Plateau and Northern Yukon Plateau, including the Mayo, Klondike, Indian River, Sixtymile, Fortymile, Clear Creek and Kluane placer mining areas, permafrost is extensive but discontinuous. In the Central Yukon Plateau, Southern Lakes and Pelly Mountains ecoregions, including the Lower Stewart, Dawson Range, Livingstone and Whitehorse South placer mining areas, permafrost is sporadic discontinuous, underlying perhaps only 25 % of the ground surface (Burn 2001).

Within the discontinuous permafrost zones in southern Yukon, permafrost in valley-bottoms may be less than 2 m thick, whereas permafrost in northern mining regions may be 40 to 60 m thick (e.g. EBA 1987; Burn 1991). Much of the permafrost in the unglaciated west-central portions of Yukon has been present since the late Pliocene/early Pleistocene, whereas permafrost in glaciolacustrine sediments of central and southern Yukon may only have developed since the last Late Wisconsinan glaciation (e.g. Froese and Hein 1996; Tarnocai 1990, Burn et al. 1986; Burn 1992). In unglaciated valley-bottoms of west-central Yukon thick sequences of organic, ice-rich, sediments known as muck overlie creek gravel. These colluvial sediments are silt and fine sand sized and have aggraded and preserved permafrost since the early Pleistocene (Hughes 1987; Fraser and

Burn 1997; Froese 1997; Kotler and Burn 2000). Older terrace sediments in this area, such as the White Channel Gravel, contain evidence of older permafrost, but no longer contain any ice. In glaciated portions of Yukon, till, glaciofluvial and glaciolacustrine sediments derived from as many as seven glaciations (Duk-Rodkin et al. 1995) are typically coarser, and do not contain the abundance of ice that Klondike, Sixtymile, Fortymile and Indian River mucks preserve. These are regional generalizations and many local variations in the distribution of sediment and permafrost exist. For example, sediments are ice-rich where groundwater is being injected through permafrost or where there are organic-rich sediments.

Permafrost temperatures at a depth where seasonal variations are attenuated are only slightly below 0^{o}C in most of Yukon (e.g. Burn 1992), making the ground more susceptible to thaw. Increases in air temperature or snowfall due to climate warming may cause permafrost to degrade naturally in areas where it is near 0^{o}C (Burn 1994). Other causes of ground temperature increase include fire and human disturbance. Upon thawing, ground settles, allowing water to pool forming thermokarst lakes. These lakes are actively forming in areas of central and southern Yukon (Burn and Friele 1989; Burn and Smith 1990).

3. LOCAL DISTRIBUTION OF PERMAFROST

There are four main variables which affect the local distribution of permafrost: elevation, aspect, the nature of the sediment, and the history of previous disturbance. Permafrost in the Mayo and Dawson areas is extensive and commonly occupies most hills and valleys. Its presence can often be diagnosed by the ubiquitous presence of *Picea mariana* (Black Spruce) and thick moss cover, including *Sphagnum* and *Polytrichum*.

Throughout the Yukon Plateau region, permafrost is more likely to be present in valley-bottoms. Low sun angle throughout the winter and persistent pooling of cold air combine to produce topographic enhancement. Winter temperatures in valley-bottoms may be as much as 9^{o}C below those of adjacent hilltops (e.g. Burn 1994). Furthermore, valleys receive less snowfall allowing for frost penetration earlier in the winter.

Permafrost, where discontinuous, is more likely to be absent from west and south-facing slopes which receive more solar heating than shaded north and east-facing slopes. Vegetation characteristics often reflect this distribution. Areas with *Betula, Salix and Pinus* commonly lack permafrost, whereas those dominated by *Picea* are underlain by permafrost.

Areas which have a long history of mining may not have predictable permafrost distribution as a result of previous disturbances. Indeed, since most of the permafrost in Yukon valley-bottoms is warm, disturbance by previous mining activity often obliterates it permanently. Such is the case along the major drainages of the Klondike area. Disturbance has the effect of removing excess ice, widening the valley-bottom, and likely allowing for more solar heating in winter. In such areas, it is unlikely that permafrost is re-established, although no studies have been done to confirm this.

4. ICE WITHIN PERMAFROST

Ice within sediments exists as buried ice, injection ice, pool ice, segregated ice, aggradational ice, ice wedge ice or pore ice. This ice may originate from the surface or from groundwater, but studies within the Klondike area indicate that most ice within sediments originates from surface rain or snow meltwater (Kotler and Burn 2000).

Buried ice

There is some evidence that large bodies of ice within the muck of the Klondike area may be transformed ice that originated as a buried snowbank (French and Pollard, 1986). This type of ice has sediment dispersed throughout it, but is difficult to identify.

Injection ice

This type of ice is formed when water is injected, usually upwards, into sediments from groundwater under pressure. It may freeze within sediments forming tabular ice bodies, upward-tapering dykes or pingos. The ground may be deformed as a result. In the Klondike, groundwater injection is suspected for the origin of several tabular and vertical ice bodies (e.g., Kotler and Burn, 2000). Hughes (1969) also identifies several hundred open-system pingos formed by groundwater injection within some valleys of the unglaciated Yukon Plateau.

Pool ice

Pool ice forms where water has frozen in a depression. In Yukon, this type of ice is most commonly found at the tops of ice wedges where they have eroded along their troughs. It does not constitute an appreciable amount of ice in valley-bottom sediments.

Segregated ice

Segregated ice forms when porewater freezes along subhorizontal layers. This forms lenses of ice which can be several centimetres to several metres thick, and tens of metres long (e.g., French and Harry 1990; Mackay 1971). Segregated ice, in the form of lenses, is most commonly found within fine-grained sediments. It gives the sediment a bedded appearance in section, and is cliff-forming. Ice lenses which form in fine grained sediments such as silts and clays can increase the apparent volume of sediment substantially, and is most commonly responsible for the process called frost heave.

Aggradational ice

The active layer above permafrost often contains more ice (segregated) than the underlying permafrost since it is usually saturated at the time when it starts to freeze in the fall. As sediments are deposited at the ground surface, segregated ice, which forms at the base of the active layer, may become part of the top of permafrost as thaw no longer reaches that depth. This ice-rich ground is found at the current top of permafrost, but may also occur deeper in sediments where there has been an active layer at some time in the past (e.g. Kotler and Burn 2000).

Ice wedges

Many areas that contain permafrost contain ice wedges. These polygonal forms are readily visible in areas where there is no tree cover, but may be less obvious in vegetated areas. Ice wedges are formed by repeated contraction and cracking of the ground, infilling by water, and subsequent freezing. They are almost always wedge-shaped when seen in section, but their dimensions can vary considerably. They can be from 1 m to 8 m high, and 10 cm to several metres wide. They are almost always found near the top of sediments and can account for a large volume of ice within them. Some of the largest ice wedges formed when climate was warmer and wetter near the end of the last glaciation. These are abundant in the unglaciated areas, however, their size and distribution varies greatly, and is largely influenced by their age and their geomorphic setting. (e.g. Kotler 1999).

5. FLUVIAL SYSTEMS IN PERMAFROST

The relation between fluvial systems and permafrost is varied, and dependent upon the size of the physical properties of the water body, and the distribution of permafrost around it.

Permafrost is only slightly permeable and, therefore, behaves as an aquiclude. Water therefore only flows under, within, or above it, in unfrozen zones. Streamflow and composition throughout the year can vary significantly dependent on the contribution from these various sources of intrapermafrost water. The contribution to baseflow in fluvial systems within northern Yukon is from groundwater, whereas less than 30 % derived from surface runoff (e.g. Clark et al. 2001). While the active layer is frozen in winter and spring, unfrozen subpermafrost water reaches the surface in the form of springs, forming thick icings in many of the creeks of central Yukon. As the active layer thaws, suprapermafrost water is able to contribute to streamflow. This water forms rills and channels on top of permafrost, and if sustained, erodes the underlying permafrost to form perennial channels. Many of the ephemeral and first order creeks of western Yukon, for example, flow on top of permafrost. Disruption of these types of suprapermafrost creeks by excavation leads to accelerated melting and downcutting of the stream channel (Fig. 2).

6. PERMAFROST DEGRADATION

Permafrost degradation results from any disturbance which causes ground temperature to rise above freezing. This disturbance can be natural due to changes in air temperature, snow cover, fire or river migration, for example, or due to human disturbance such as road construction, monitoring, excavation, stripping, creek diversion or building heating.

6.1 Types of degradation

Permafrost degradation can be subtle or spectacular. The types of degradation are governed chiefly by the amount of ice within the sediment, and the way in which it is being disturbed. The disturbance results in a number of distinct landforms.

Retrogressive thaw slumps

These disturbances occur commonly in ice-rich sediments with massive ice, such as the Klondike mucks, but occur occasionally in other ice-rich sediments. These features are bowl or horseshoe shaped and consist of a steep icy headwall (10^o to 80^o) and a mud slurry at the base (1^o to 10^o). There is often a transitional zone consisting of unsaturated blocks of sediment and vegetation pods which have fallen from the headwall.

The formation of these features is caused by the exposure of ice-rich sediments or massive ice. Commonly this involves removal of the insulating surface vegetation. In placer operations this is accomplished by cat stripping or ripping. Removal of surface vegetation also occurs naturally due to active-layer detachment, or by stream undercutting. Once exposed, ablation occurs naturally due to exposure to sunlight. Ablation is accelerated when high-pressure water is directed at the exposed surface (monitoring).

Once exposed, meltwater and saturated sediments slide or fall until progressive removal results in a vertical face. Mats of vegetation are often left overhanging the face, as they are resistant to erosion (Fig. 3). They contain less ice and are bound together by roots. These overhanging mats slow the melting of the underlying face by shading it, but eventually they fall, allowing rapid thawing to resume.

At the base of the headwall, the mud slurry moves downslope until it reaches a stream or lake. There, it is rapidly eroded. Since the slurry consists mostly of silt, it is easily carried in suspension by the stream or lake. Removal of the slurry material below facilitates further addition from the slump above.

In the transitional zone where drier blocks of sediments and vegetation have fallen, melting is slowed considerably as debris insulates frozen sediments below. These blocks of sediments and vegetation creep slowly to the base of the mudflow over time.

Upon initiation, thaw slumps develop rapidly and retreat at rates of up to 14 m per year (e.g. Burn and Friele, 1989). Erosion continues as long as there is exposed ice and downslope removal of material. Thaw slumps may occur only once in an area, and progress until they have removed all ice-rich sediment. They may also occur in pulses, where they stabilize by insulation and re-establishment of vegetation, but are subsequently reactivated by new disturbance. The stabilized areas of thaw slumps in placer areas of discontinuous permafrost usually do not re-establish permafrost, however many in continuous permafrost areas do. This type of cyclicity is common along the Beaufort Sea coast (e.g. Wolfe et al., 2000).

In mucks, ice-rich sediments containing large ice wedges and massive ice are usually located within 12-15 m of the ground surface. Natural or artificial thaw slumps having headwalls of this size are capable of releasing very large amounts of sediment into adjacent water bodies. The exact amount is dependent on the lateral extent of the disturbance, and the ice content of the sediments.

<u>Active layer detachments</u>

Active layer detachments are small failures (1 to 10 m wide) occurring at the contact between the permafrost and the active layer. Any disturbance which causes a deepening of the active layer will melt this ice-rich zone at the top of permafrost. This occurs naturally through air temperature increase, snow cover increase, or fire. This also occurs artificially by stripping, flooding, compacting of vegetation, or burning.

Once this ice is melted, sediments of the active layer and overlying vegetation slide rapidly downslope. These features are distinguished from thaw slumps, in that they do not have ice-rich headwalls, and that their flow track follows topography. Material accumulates in a compression zone, or toe, and may not reach a watercourse. The amount of sediment removed in these features is small, and therefore does not provide a significant source of sediment.

Although active layer detachments typically stabilize by drying and revegetation within two years, they are important initiators of retrogressive thaw slumps (e.g. Wolfe et al. 2000)

Block failures and debris flows

Block failures occur in ice-poor sediments. These sediments are usually gravels, sands and silts found in the glaciated Yukon and at some locations in the Klondike and Sixtymile areas. Since ice content is low, natural ablation or monitoring removes only pore ice. Block failures, therefore, are caused by slope undercutting or melting along vertical fractures in the sediment. These fractures may be several metres long. When ice in these fractures melts, large blocks of “dry” sediment detach and fall to the base of the face (Fig. 4). Block failures may also result from the eventual detachment of cohesive sediments. As a vertical exposure of “dry” sediment thaws inward, away from the face, a thickness of thawed sediment will stay in place due to the cohesiveness of the sediments. Eventually the weight of this sediment exceeds its strength and it detaches from the face. The erosion rates and amount of sediment released by block failures has not been quantified.

Debris flows are more common in coarser till and gravel sediments. Melting of pore ice within these ice-poor sediments decreases the cohesion or competency of the sediment. This results in downslope movement of the material by freefalling, cascading, or rolling to the base of the slope where it reaches the angle of repose. These types of flows are recognizable as gullies with fan shaped cones at the base.

Thermokarst lakes

Subsidence due to thawing of permafrost leads to the formation of depressions. These depressions collect water, eventually forming thermokarst lakes. These lakes are numerous throughout the Mayo mining area.

7. NATURAL STABILIZATION

The stabilization of disturbances in ice-rich ground is initiated when slump material loses excess water, and vegetation begins to take hold. The revegetation of a large retrogressive thaw slump along the Stewart River near Mayo is documented by Burn and Friele (1989) and Barleman et al. (2001). Casual observations of disturbances in the Klondike mucks indicate a similar vegetation succession.

Ice-rich sediments, such as some of the units within Klondike mucks, yield very little sediment when thawed (Fig. 5). The supersaturated slurry and vegetation pods which collect at the base of the headwall during natural melting or monitoring, flow slowly downhill. When melting slows, either by removal of all ice or insulation of remaining ice, the excess water eventually dries, leaving a layer of colluvial sediment (Fig. 6). The first colonizers of this dried silt surface are commonly unidentified species of brown to green moss. Within two years, *Funaria* and *Senecio congestus* (Mastodon flower) dominate the vegetation of the disturbed area. Isolated pods contain *Picea mariana, Salix* (Willow), *Sphagnum, Polytrichum* and various species of *Ericaceae*. Within 2 to 5 years a much more diverse vegetation cover develops with the appearance of *Equisetum arvense* (common Horsetail), *Epilobium angustifolium,* (Fireweed)*, E. palustre* and *Cinna latifolia* (wood reedgrass), among others, including *Polygonum alaskanum* (Knotweed). Within 5 to 9 years, the vegetation cover includes also *Hedysarum* (licorice-root), *Rubus* (raspberry), *Rosa acicularis* (Rose), *Ledum decumbens* (Labrador Tea), *Betula* (Birch) and *Salix*. The studies within the Mayo slump indicate the re-establishment of original forest floor blanket vegetation, such as *Vaccinium* and *Shepherdia Canadensis*, occurs within 20 to 25 years. In artificially disturbed areas, continued mining activity at any time during this succession may redisturb areas which may still contain ice, but natural channeling of the mud slurry may allow fringe areas to stabilize while the disturbance remains active (Fig 7).

Muck sediments may contain up to 95 % ice, and therefore thawing of sediments can leave the ground level significantly below the original ground surface. This causes widening of the valley and allows more sunlight to reach the valley bottom (Fig. 8). This, and warm ground temperatures probably inhibit the re-establishment of permafrost under these disturbed surfaces if it has been completely obliterated. However, no studies have been done to confirm this. If slump debris inslulates and preserves underlying ice, plant succession may progress until the sediments are disturbed again, initiating thaw below the revegetated surface (e.g. Fig. 6).

8. ARTIFICIAL DISTURBANCE OF PERMAFROST

8.1 Methods

Two activities related to placer mining are most effective in degrading permafrost: disturbance of insulative vegetation and monitoring.

Disturbing the insulative vegetative cover overlying permafrost is accelerated by compaction or stripping. The dominant insulative vegetation on the ground includes *Sphagnum, Polytrichum* and *Ericaceae.* Trees are dominantly *Picea mariana*. Since most permafrost within Yukon is thin and warm (e.g. Burn 1994), very little disturbance is required to raise ground temperatures above freezing, and initiate thawing. Vehicle, cat activity and stripping permanently damage the insulative vegetative cover. This leads to increased ground temperatures as more sunlight is able to reach the ground. Further, without tree cover, more snow is able to accumulate thus insulating and warming the ground. All these effects contribute to the thickening of the active layer, causing subsidence. The amount of subsidence is dependent on the ice content of the ground. Ice-rich ground, such as that found within the Klondike area, has on average up to 30 % excess ice within it, allowing for perhaps as much as 40 % decrease in thickness due to thawing excess ice and pore ice. Due to this melting and subsidence, disturbed areas become low spots, allowing water to pool and further degrade the underlying permafrost. On slopes, excess water caused by melting of the active layer may result in active layer detachment, or to the initiation of a retrogressive thaw slump. Ground less susceptible to disturbance and subsidence due to disruption of the insulating layer, is that which is coarser and lacks spruce and sphagnum cover.

Monitoring induces thermal-mechanical erosion of exposed permafrost. The method is more effective in ice-rich ground, where melting of excess ice and removal of thawed sediments from the base promotes accelerated slump failure. In addition to accelerated erosion and slumping, monitoring produces excess runoff, consisting of water and supersaturated sediment (Fig. 9). Excess runoff contributes to greater streamflow and may induce bank failure and slump erosion further downstream. The containment of runoff into well designed settling ponds is an effective means of reducing downstream flow and of containing sediment (Fig. 10).

8.2 Steam crossings and diversions

Most streams with flow great enough to require construction of bridges or reinforced crossings are free of permafrost and therefore should not present a risk of accelerated degradation. Disruption to smaller streams, flowing on top of permafrost due to diversion or movement of equipment can have a significant effect on patterns of erosion. These streams may be “perched” up to 18 m above creek gravel, and flow through extremely ice-rich sediments. Stream diversion, for example, will result in accelerated downcutting and widening of the original channel. This is followed by rapid gullying to the base of the ice-rich sediments, and subsequent widening by undercutting and thaw slumping. Stream diversion leading to undercutting of ice-rich ground will lead to slope failure and thaw slumping.

9. STREAM SEDIMENT INPUT

9.1 Ice Content

In unglaciated Yukon, valley-bottom mucks can generally be divided into four types: (1) saturated loess (fine sand and coarse silt); (2) loess and organic material with excess ice; (3) coarse organic material, and (4) sediments of low ice content. These four general types of sediments occur in sedimentary sequences distinguished by their colour, sediment type, ice type, and sediment-ice relations. Their physical properties differ in terms of their ice content and their susceptibility to thermal-mechanical erosion.

(1) Saturated loess

Stratigraphically, these sediments comprise the Reid-McConnell interglacial, and McConnell glacial units, or the Quartz Creek and Last Chance Creek Members of Kotler and Burn (2000). They are beige to olive-beige, and contain abundant grass and occasional mammal bones and tusks. They are removed easily through monitoring.

Preliminary investigations, although not statistically valid, indicate that the ice content within this type of sediment is approximately 65 % by volume. This type of sediment, when saturated, will consist of about 40 % porewater by volume. This indicates that this type of sediment may contain 25 % or more excess ice in the form of small ice lenses. When pore ice and excess ice are melted, 35 % of the volume is released as sediment. In other words, when 1 m^3 of this type of frozen sediment is thawed it will release 0.35 m^3 of dry sediment. This value may vary from 0.25 m^3 to 0.60 m^3, depending on whether or not the sediments contain excess ice. This value is difficult to estimate visually.

(2) loess and organic material

Collectively, sediments within this category comprise the post-McConnell colluvial deposits, or the Dago Hill Member of Kotler and Burn (2000). They are distinguished based on their prominent interbedding of silt and organic material, their darker brown colour, and their visibly high ice content. This ice is typically in the form of ice wedges and tabular ice lenses. These sediments range in thickness from 0 to 12 m.

Preliminary investigations indicate that bulk visible ice, such as ice wedges and ice lenses, occupies on average, 31 % of the volume of the sediments (Fig. 11). The other 69 % of the volume of the unit consists of sediment with a mean volumetric ice content of 70 +/- 15 %. Combined, this yields an average volumetric ice content of 79 % for sediments of this unit. In other words, 1 m^3 of this unit yields on average, 0.79 m^3 ice and 0.21 m^3 dry sediment (modified from Kotler, 1998).

(3) coarse organic material

Sediments of this type comprise Holocene post-glacial organic sequences consisting of branches, trees and roots. This material is found near the top of sediments when viewed in section, and can be 1 to 10 m thick. It is commonly thicker in the valley-bottoms of small creeks. The intertwined nature of the roots and branches makes it very resistant to erosion, even though ice content may be high. No volumetric estimations of ice content exist, but visible ice infilling voids and cavities, and ice formed within the organic material itself indicates that ice content may be high. Since most of this material is large, and the unit contains very little sediment, it is not a significant source of sediment in streams.

(4) sediments of low ice content

Casual observations indicate that sediments older than the Reid-McConnell glaciation do not contain appreciable amounts of ice, although evidence exists that they may have in the past. These sediments are bedded, beige to olive-brown, and contain isolated beds of organic material and tephra. They are extremely resistant to thermal-mechanical erosion, and are not easily removed, although they do contain permafrost. Ice content within these sediments may be between 30 %and 50 %, volumetrically. Generally, these older sediments are found south of Indian River along tributaries of the Yukon River.

9.2 Visual estimations of ice content

Kotler (1998) outlines a method for estimating the ice content of a muck exposure in the Klondike area, containing organic and ice-rich sediments of the Dago Hill Member. This method produces an estimate of the ice content of the sediments using visual examination of a cross-sectional exposure. In this method, the general stratigraphy of the exposure was noted, including the thickness, colour, the type of sediment, abundance of ice, and the type and abundance of organic material present in the unit. It was determined to be ice and organic rich sediment of the Dago Hill Member. The section was photographed and overlain with transparent grid paper. The number of squares occupied by visible ice was counted and related to the total number of squares covering the whole exposure. The percentage of the sectional area occupied by visible ice was determined. In this case, the ice was in the form of ice wedges. The ice wedges occupied 26 % of the *area* of the section. This value was corrected to 20 %, since ice wedges are rarely seen in cross section, and on average, occur at an angle of 40^{o} to the face (Mackay 1977).

An ice wedge making 40^{o} with the face, is 1.56 m long within a 1 m thick section (x = 1 m). If this section is of vertical thickness (depth) z, and lateral width y, then the *volume* of ice wedges (V_{iw}) within this 1 m thick section is:

$$[1] \qquad V_{iw} = 1.56\,(0.20zy) = 0.31zy$$

The sediments, occupying the other 69 % of the volume of the 1 m thick section, have an average volumetric ice content (I) of 70 %. The volume of ice within the rest of the 1 m thick section (V_{pi}), is therefore:

$$[2] \qquad V_{pi} = I[1(0.69zy)] = 0.70(0.69zy) = 0.48zy$$

The total volume of ice (V_t) within this 1 m thick section was determined to be:

$$[3] \qquad V_t = V_{iw} + V_{pi} = 0.79zy$$

In other words, 79 % of the volume of a 1 m thick section was occupied by ice. This value may vary considerably, since sediments of this unit had between 45 % and 95 % ice, and ice wedges occupied between 10 % and 35 % of the cross-sectional areas.

A volumetric estimation of the entire deposit can be made, if the extent of the ice-rich unit up the valley-side is known (x >1 m). The volume of sediment can be determined by integration, as z decreases up the valley side. The depth of the deposit up the valley-side, can be determined by drilling or by the use of ground penetrating radar (see preliminary investigations, Kotler 1998).

9.3 Sediment mobility

Most placer operations working in creeks with ice-rich overburden must use hydraulic monitoring to thaw and remove materials. Once thawed, it is impractical and even impossible to access the base of the resulting exposure due to the low strength of the supersaturated debris. As a result, most sediment removed from an exposure is flushed into settling ponds. Due to the fine nature (predominantly silt) of the sediment, most of it is carried in suspension and is extremely mobile. Operations which have constructed settling ponds may leave them when the current operation is complete. The pond will dry over time, leaving an extensive silt-dominated deposit. Diversion of a creek through this sediment may erode it and contribute significantly to stream sediment load. Care should be taken to isolate settling ponds so that they are not disturbed by future activity (Fig. 12).

Due to the long periods of time required for very fine silt and clay to settle out of suspension, low-volume settling ponds with high throughflow rates may not be effective at reducing stream sediment input. Therefore, settling ponds should be constructed so that they are high-volume, reinforced by coarser materials, and well away from the main stream.

10. SUGGESTED BEST MANAGEMENT PRACTICES

The following includes a list issues which should be addressed prior to, during, and following development of a placer mining operation. These are suggestions based on the information provided in this document, and should not be considered limiting. Some of these items are required under current operational guidelines.

10.1 Mining Plan

1. General stratigraphy of overburden sediments:

Observations of thickness, colour, abundance of ice, and organic content should be taken for each distinct unit of overburden, if exposed by previous operations.

2. Granular inventory of sediments overlying pay gravel:

If sediments are exposed by previous mining operations, each distinct unit should be bulk sampled for grain size analysis. The relative percentage of gravel (> 2mm), sand (0.063 – 2 mm), and silt (0.002 - 0.063 mm) within dry sediments should be determined.

3. Estimation of pore ice content:

A 5 cm diameter core, or bulk sample of approximate known volume should be taken of frozen sediment of each distinct unit. The sample should be allowed to thaw and dry completely to determine the volume of sediment released.

4. Estimation of bulk ice content:

A photograph of the sediment (if exposed) should be taken, and the *areal* estimation of bulk ice should be determined using the method outlined in 9.2.

5. Proposed routing of roads

The location of any proposed roads, cat trails or permanent structures should be indicated on a photograph. These roads should be located where they minimize damage and removal of surficial vegetation. Preferable locations include those underlain by coarser overburden, and those dominated by *Betula*.

6. Proximity of permafrost to existing watercourse

The location and depth of permafrost should be noted throughout the area proposed to be redisturbed. This can be accomplished by inserting a 2 m steel pole (1 cm diameter) into the ground from the top, and recording the depth at which ice is encountered. The location of any “perched” streams, flowing on top of permafrost should be noted on photographs or maps.

7. Description of existing vegetation

The mining plan should include a good photograph of representative vegetation in all areas which are to be disturbed.

8. Establishment of baseline

A baseline should be established perpendicular to the base of the creek, away from proposed activity. This can be in the form of flagging tape on trees. This facilitates future measurement of permafrost disturbance.

9. History of previous disturbance

A history of permafrost characteristics of the area, either through reports or personal communication should be summarized, in order to facilitate the estimation of the volume of ground ice (if any) remaining.

10.2 Mitigation Plan

1. Area stripped

The exact area of vegetation stripped each year should be recorded. It is suggested that this should not exceed 1000 m^2 per year, since the resulting permafrost degradation can lead to massive failure in sediments which are ice-rich.

2. Volume of water used per day

The length of time pumps of known capacity are used for monitoring should be carefully recorded. Extensive monitoring facilitates the transport of fine-grained sediment.

3. Headwall retreat

The distance of headwall retreat of slump failures should be measured once per week, using the baseline established in 10.1 (8).

4. Channeling of debris

Movement of slump debris, either natural, or facilitated by monitoring, should be channeled away from existing water courses and pre-existing, dried settling ponds. This may be accomplished by piling coarse organic material such as trees and branches which have fallen to the base, into levee structures. Coarser material such as sluice tailings can also be used for this purpose. Ultimately, this material must all be channeled into settling ponds.

5. Settling ponds

Settling ponds should be constructed of coarse material, and should be of sufficient volume (preferably longer rather than wide) to allow for sediment to settle out of suspension near the surface (several days). Preferably, several settling ponds are constructed in succession. Settling ponds should be constructed above the highest water level during spring flood.

6. Behavior of frozen sediments

The nature of failure of frozen sediments should be noted, i.e. do sediments slump and drip, fall as blocks or crumble.

10.3 Reclamation

1. Relocation of channel

If part of channel flow was diverted for monitoring, the original channel should be reconstructed, using coarse granular material, so that it is well away from any residual settling ponds and not subject to excessive erosion by spring meltwater.

2. Vegetation

Permafrost disturbances revegetate readily. However, as much of the original vegetation should be left in place as possible. A disturbed ice-rich area should NOT be covered with gravel, but rather left with its original material. No leveling is necessary.

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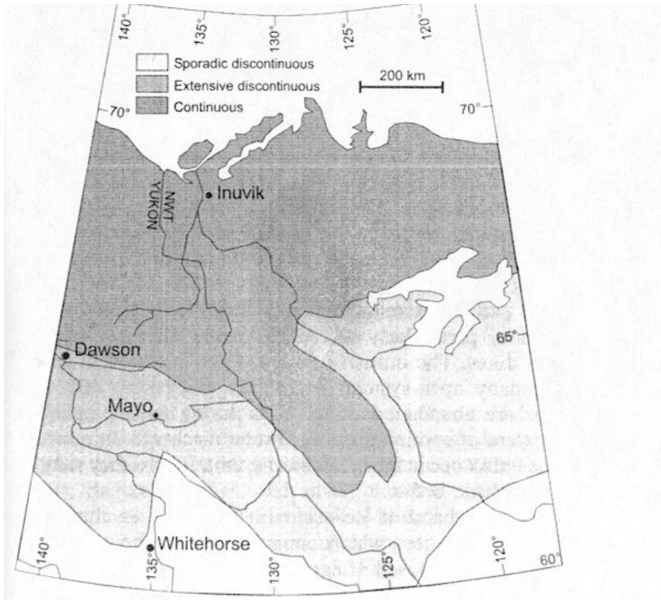

Figure 1: Permafrost distribution in Yukon Territory.

Figure 2: Monitoring along a small tributary of Hunker Creek. Water is being taken (note hose) from the creek, flowing on top of permafrost, 9 m above the new valley bottom.

Figure 3: Shading of ice-rich sediments by overhanging vegetation mat. This may slow melting considerably until the mat detaches and falls to the base of the headwall.

Figure 4: Thaw slumping and block failure in relatively ice-poor sediments, Quartz Creek. Thawing is occurring preferentially along ice wedges, while “drier” sediments fall as blocks to the base. Note establishment of moss on newly exposed surface (1 year), right.

Figure 5: Extremely ice-rich sediments (~95 % ice by volume), Hunker Creek. The headwall is approximately 10 m high. This unti would release very little sediment when thawed.

Figure 6: Thaw slump in previously disturbed and revegetated ice-rich sediments, Thistle Creek. The dry layer at the top represents old slump debris which had insulated the underlying ice, dried, and began to support vegetation now dominantly *Epilobium angustifolium*. Rnewed failure was initiated by monitoring.

Figure 7: Establishment of vegetation on slump debris, Thistle Creek. Here, it consists of remnant pods and abundant *Equisetum, Cinna Latifolia* and *Polygonum*. To the right of the photo, headwall retreat is continuing along an ice-rich section, three years after the initial mining disturbance. Note how debris is being channeled and appears as dried sediment at the front of the photo.

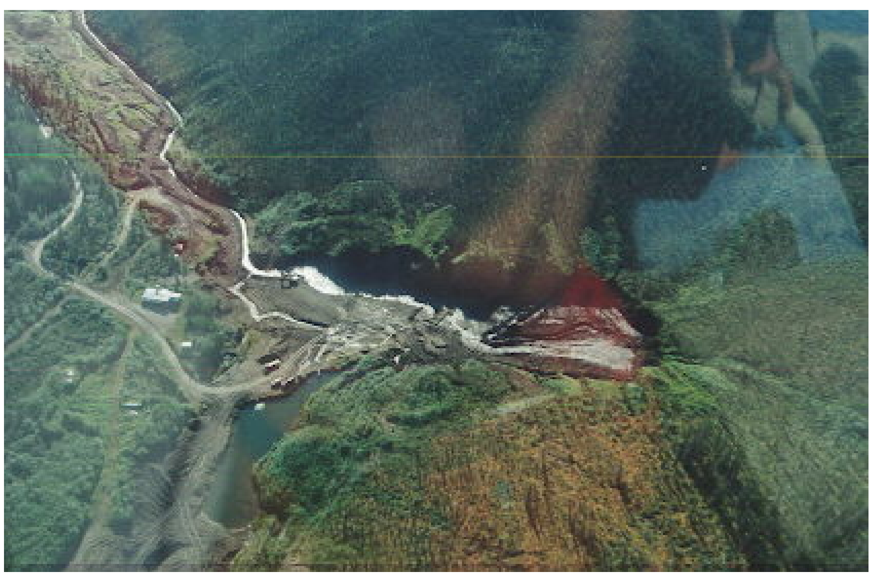

Figure 8: Active placer operation in ice-rich ground, Klondike area. Thawing of sediments lowers the ground surface significantly and widens the creek valley. Thawed sediments are being carried to the nearest stream without intermediate holding in a settling pond. Note the original ground surface with the creek at the left of the photo. Black spruce is present on the north-facing slope. Photo: W.P. Lebarge.

Figure 9: Monitoring of ice-rich ground, Klondike area. There is no containment method being used, allowing sediment and organic material to enter the creek directly.

Figure 10: View down Upper Bonanza Creek, showing a well-constructed, large volume settling pond. Sediment input is from the left, as indicated by the well-developed fan. Permafrost is present on the north-facing slope (left), and absent on the south-facing slope (right).

Figure 11: Ice-rich sediments, Last Chance Creek. These sediments are dominated by ice wedges in the upper half of the exposure, and segregated ice towards the bottom. Visually estimating the volume of ice wedges is essential in assessing the potential amount of sediment to be released upon thawing.

Figure 12: Erosion of thaw debris by stream, Hunker Creek. This dried debris was left by a previous mining operation. Spring thaw and renewed upstream mining is causing erosion of this sediment.