Case Studies Of Adaptation To Climate Change In The Yukon Mining Sector:

From Planning And Operation To Remediation And Restoration

Northern Climate ExChange
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1.0 Introduction

For the mining industry in the Yukon, dealing with a rugged landscape and climate extremes has always been a costly part of "doing business". Historically the industry adapted to known climate extremes, through engineering response, by adjusting operations in concert with the annual seasonal cycle, and through development of flexible but robust transport systems. It was generally, and not unreasonably, assumed that prevailing climate conditions were an immutable fact of life, and the climate future would be very much like the past. The symptoms of a changing climate in the Yukon however, have recently been manifest in increased precipitation, permafrost degradation, increased incidence of extreme events, and shifting seasons. Consequent events such as flooding and soil liquefaction have the potential to add to the costs of mining by disrupting mine operations and transportation. Historically the dominant vulnerability of the Yukon mining industry has been dependence on mineral prices and the health of the industry fluctuates with global mineral prices (a fact underlined when, in the course of this project, mineral prices eased, employment in the industry declined, and one of the three operating hard-rock mines closed temporarily). Changing climatic conditions could increase operating costs and could potentially exacerbate vulnerabilities associated with exposure to global market conditions.

This research examines climate change vulnerability and adaptation in three stages in the life of a mine, (i) inception and planning, (ii) operating, and (iii) post-closure (or remediation and restoration) through case studies located in the Yukon Territory, Canada. The report aims to provide insights on ways to enhance the competitiveness and adaptive capacity of the mining sector in a changing climate.

2.0 Background

In the Yukon Territory the average annual temperature has risen approximately 3°C over the past fifty years, and climate change scenarios suggest that warming will continue and in some instances accelerate in the future (Scenarios Network for Alaska Planning, 2011). There are already indications that shoulder-seasons are shifting with fall freeze-up occurring later and spring thaw earlier, permafrost degradation, changes in precipitation, and an increase in the frequency and intensity of extreme weather events. Of particular importance to the mining industry are implications for transportation networks, infrastructure, hydrology and operations (e.g. the length of the operating season).

Climate change effects on mining

Mines in the Yukon lie in the discontinuous permafrost zone. In many areas the permafrost is relatively warm and has the potential to degrade as annual temperatures increase, leading to soil liquefaction, slope and retaining wall failure, and subsequent operating and transport disruptions (Pearce et al. 2011). It is anticipated that increased glacial melt, spring run-off as snow-pack melts earlier, and variability in precipitation will change hydrological regimes (Environment Yukon, 2013). Changes in hydrogeology are a concern for the mining industry, for which managing on-site water is a central fact of operations. The annual cycle of mining activity may change as shoulder season characteristics change but these changes would not all necessarily be negative. The cold Yukon climate and permafrost conditions present major engineering challenges for the mining industry, difficult transportation conditions, restricted access seasons, and high freight and labour costs. A warming climate may create new opportunities for the industry as seasonal mining operations (for example placer mining in the Klondike), would be enhanced by a longer operating season and by permafrost degradation.

Changing climate has the potential to stress regional infrastructure that serves the mining industry. Mines in the Yukon depend on an extensive highway and power generation network. The former may be degraded because of permafrost melt exacerbated by the volume of traffic, and washouts and slope failure. Future expansion of the mining industry would place greater pressure on the existing hydro-grid, but capacity to increase power production may be compromised by seasonal changes in river flow (Government of Yukon 2013)

Past adaptation to climate and weather extremes

From the Klondike gold rush at the end of the nineteenth century, to the present, the mining industry has grappled with and adapted to climate extremes. In the Klondike, demands for water for placer mining combined with a paucity of supply in summer resulted in water diversions to carry water from a neighboring watershed and technology was applied to melt permafrost and release gold bearing gravels. The mining industry throughout the Yukon responded to climate extremes that made operations difficult or restricted transportation through cold climate engineering and seasonal adjustment of operations. Adapting to climate and weather was simply part of the cost of doing business. Climate extremes were expected and broadly predictable, and it was not an unreasonable expectation that the future would be very much like the past. However, there is now increasing scientific and experiential evidence that the climate of the Yukon is changing and past experiences with extreme conditions may not be indicative of the capacity to adapt in the future; what has been termed the 'death of stationarity' in the general literature (Milly et al 2008).

Public concern and environmental quality

The evolving physical reality of climate change in the Yukon has been paralleled with public concern about environmental quality, and the emergence of more stringent regulatory regimes. From a broad environmental perspective concern about climate change and mining centers on potential impacts on landscapes and consequent implications for flora, fauna and human populations. Northern mines generally sit in areas that have a propensity to be highly sensitive to disturbance, or to impacts associated with the degradation of detritus from mining operations. Especially pertinent in the Yukon is that these landscapes often constitute First Nation Traditional Territories, sustaining fish and wildlife that provide cultural and nutritional sustenance for local populations.

Governance and regulations

Historically mine regulation in the Yukon was fairly lenient with mines having to conform to basic land-use regulations regarding operation and remediation. The former were regulated through the Yukon Quartz and Placer Mining acts, and through the Yukon Water Board, which was primarily concerned with ensuring adequate water supply for the industry, and maintaining stream quality. Over the past twenty years more stringent regulation of the industry has emerged reflected in the provisions of the Yukon land Claim Agreement, the introduction of Yukon Land-Use Planning Act, and importantly the Yukon Environmental and Social-Economic Assessment Board (YESAB). YESAB has been operating for approximately fifteen years, and its central mandate is to protect the environmental and social integrity of the Yukon, while fostering responsible development in the territory that reflects the values of Yukoners and respects the contributions of First Nations. Hypothetically, at least, YESAB is well positioned to ensure that emerging mines include potential future climate change events in project design. The Water Board is also responding to the challenges presented by shifts in the hydrological regime and is undertaking a review to identify possible changes in regulatory requirements.

Water is used in the extraction and milling of potash, with the magnitude of water use varying significantly by mine type. Conventional mines, where ore is physically extracted by machinery operating deep underground and transported to the surface, is less water-intensive than solution mining, where ore is extracted by injecting heated brine into potash deposits, allowing potash to dissolve into the brine, and then pumping the potash-rich brine back to the surface. Following extraction, water is used similarly in both types of mines in different aspects of milling, such as flotation, drying and sizing, and also during tailings disposal, as tailings-saturated brine is injected deep underground.

The reliance on water makes the industry sensitive to water availability, although no major stresses due to water shortage were reported during this research. Notably, operations are sensitive to excess moisture and flooding. Recent excess moisture events in Saskatchewan have been problematic for the potash industry, since they result in increased volumes of brine for disposal, increased operating costs, and higher potential for flooding from offsite surface water. In addition, due to the nature and location of their facilities and equipment the industry is sensitive to extreme weather events and extreme temperatures. This research examines these and other climate sensitivities and their related adaptation actions in six mine case studies (four producing and two not producing) in the Qu'Appelle River Watershed. The names of specific mines and mining companies are kept confidential, unless the companies have given consent for the disclosure of these names.

Yukon landscape

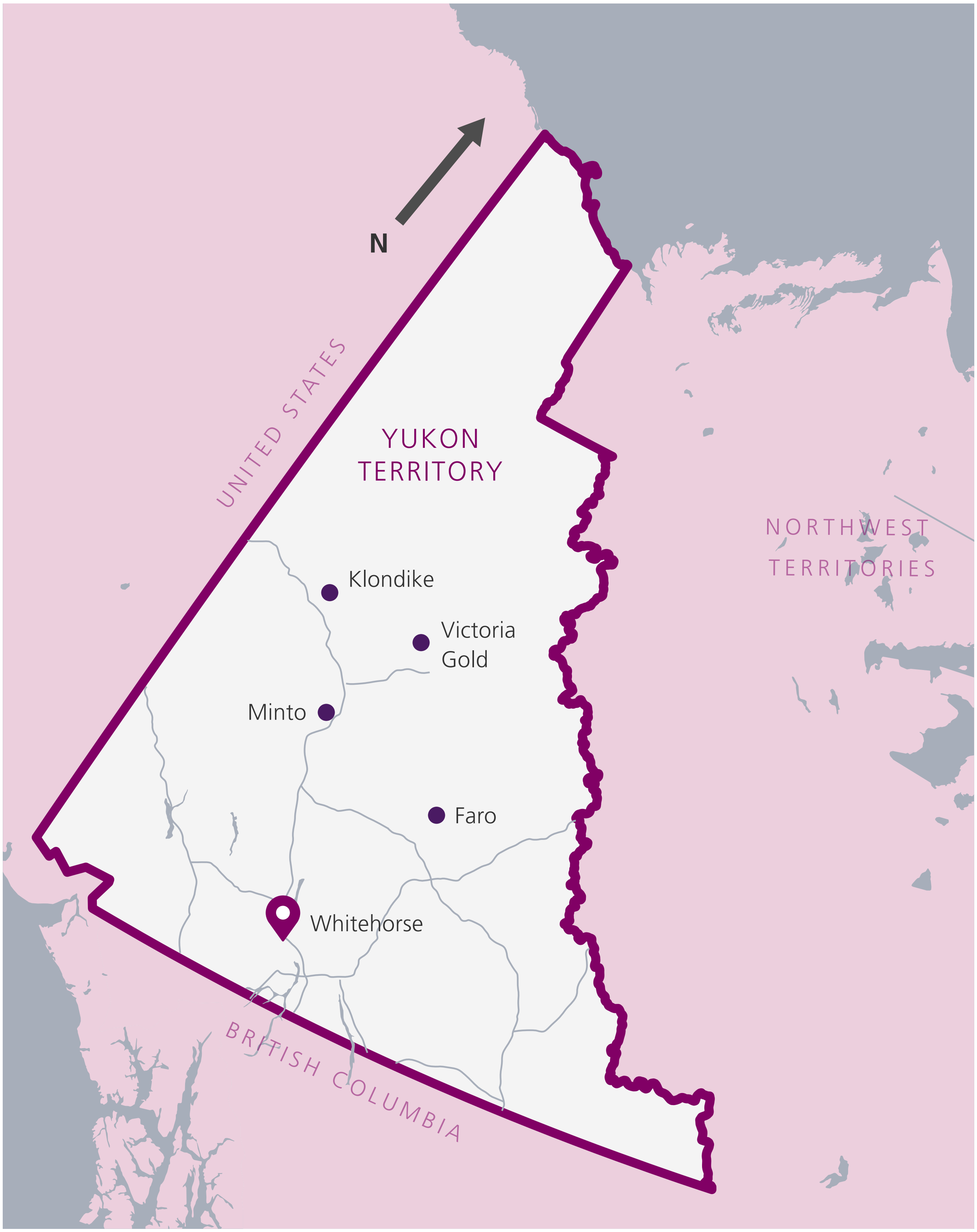
3.0 Approach

This research draws on key informant interviews with mine professionals and document analysis to identify how climate change adaptation can enhance the competitiveness of the Yukon mining sector. Key informants were selected based on their practical and applied knowledge, and expertise in the Yukon mining industry. These individuals included operational or environmental personnel employed by mining companies (n=4), representatives of mining organizations (n=3), and knowledgeable individuals in Territorial ministries responsible for some aspect of mining operations, regulations and/or remediation (n=4). A semi-structured interview guide was employed, and questions were open-ended to allow respondents to describe their experiences and actions from their perspectives and in terms relevant to their expertise. The interview guide was organized around the themes of vulnerability (exposure-sensitivity and adaptive capacity) and adaptation to climate change. Interview data was complimented with an analysis of secondary sources of information including, peer-reviewed literature and government and industry reports.

There are three stages in the life of a mine, inception and planning, operating, and post-closure (or remediation and restoration). Planning ideally anticipates the environmental stresses a mine may experience, and informs mine design; operation involves working on a day by day basis and addressing climate induced issues as they arise; and remediation planning should ensure that in the long run that the interaction between climate and mine detritus doesn't have a deleterious impact on the physical environment. While this report has documented events that are probably symptomatic of a changing climate in the Yukon, much of the experience is recent, occurring over the past decade, and no mine has experienced such events through its life cycle. Consequently, this research examines climate change vulnerability and adaptation in three stages in the life of a mine, (i) inception and planning, (ii) operating, and (iii) post-closure (or remediation and restoration). Victoria Gold is a new venture currently in the planning and construction phase, introduced into an environment where the possibility of climate change is recognized. Capstone Resources Minto Mine was designed almost twenty years ago, before the mining industry acknowledged that climate change was an issue, and subsequently has had to respond to a number of climate-induced challenges. Faro (and other mines) exemplify the challenges of remediating relict mine sites in the context of a changing climate.

Capstone Resources Minto Mine in the central Yukon. Photo Credit: Capstone Mining Corp.

Map of case study locations, Yukon Territory



4.0 Case Studies

In the Yukon Territory the average annual temperature has risen approximately 3°C over the past fifty years, and climate change scenarios suggest that warming will continue and in some instances accelerate in the future (Scenarios Network for Alaska Planning, 2011). There are already indications that shoulder-seasons are shifting with fall freeze-up occurring later and spring thaw earlier, permafrost degradation, changes in precipitation, and an increase in the frequency and intensity of extreme weather events. Of particular importance to the mining industry are implications for transportation networks, infrastructure, hydrology and operations (e.g. the length of the operating season).

4.1 Incipient Mines

There are currently two mines in the development stage that have the opportunity to incorporate expectations about future climate trends into design. The proposed Casino Project copper\gold project in the in the western central Yukon is in the planning stage, and if the project comes to fruition will the Territory's largest mine. Victoria Golds' property has moved from the design to the construction stage, and exemplifies some of the issues faced by mines that may be operating in the context of a changing climate.

Victoria Gold's Eagle Gold Project

Victoria Gold's "Eagle Gold Project" is currently under construction and first production is targeted for 2016. The mine is located in the Mayo Mining District of Central Yukon Territory, a region characterized by rugged mountainous terrain and harsh winters that has been intermittently mined for more than a century. The mine-site lies at 640 4' N latitude and 1350 50' W some 85 kilometers from Mayo, the district's service center, to which it is connected by a combination of mining road and territorial highway. It is estimated that there are 95 million tonnes of ore on the site, potentially yielding 2.3 million ounces of gold, and that the mine will have a lifespan of approximately nine years. Ore will be extracted in an open pit operation and hauled to the on-site processing plant where it will be crushed and subsequently heat-leeched and gold stripped from the resultant solution. Waste rock from the operation will be stored in two facilities, one north and one south of the open pit operation. Victoria Gold will be the first mine in the Yukon planned to anticipate events associated with a changing climate through its entire life cycle.

Historic Perspective

Historically the major challenge facing mining in the Mayo region has been winter climate events, with extreme cold and snow and ice conditions and considerable seasonal variations in the hydrological regime affecting both mine-site conditions and transport. Winter temperatures average some -20 C and the area is underlain by discontinuous permafrost. Elevation, aspect, and seasonal weather extremes give rise to significant variations in local conditions. Local hydrology varies markedly through the year. Spring brings snowmelt, freshets[1] , and consequent high water, while summer may be characterized by near drought conditions and low stream-flow. Adapting to such extreme conditions has always been a fact of life for mining in this part of the Yukon, and historic adaptations included engineering to ensure mine and infrastructure were robust to withstand extreme winter and post-winter events, and to manage hydrological fluctuations. Operations were tailored to "the rhythm of the land", with mines closed in winter and materials stock-piled in anticipation of transport disruptions or equipment failures. Mine planning was based on expectations of an extreme but more or less predictable annual climatic cycle and the notion that the future would be very much like the past.

Contemporary Conditions

Winter climate conditions that historically impacted mining in the Mayo region remain the dominant hazard for contemporary operations. Snow accumulation and extreme cold adversely affect both equipment and transportation, and traditional responses in addressing these hazards come into play including infrastructure design and stockpiling of resources. There is evidence that annual mean temperatures are increasing, and the Scenarios Network for Alaska and Arctic Planning (SNAP) has documented consistent increases in both temperature and precipitation in the Mayo Region over the past thirty years), and freeze-thaw characteristics are changing, with earlier ice break up and increased water flow swelling regional creeks and rivers and increased flooding. Discontinuous permafrost is present throughout the region, and because there is a long history of mining in the area it is known from both experience and science that permafrost underlying Victoria Gold's mine-site is quite warm, and probably warmer than in the past, potentially giving rise to liquefaction risk.

While there is some evidence that climate in the region is changing there is considerable uncertainty about future conditions and trends because of the paucity of good quality standardized long-term data. Meteorological stations in this part of the Yukon are relatively few, widely distributed, lie in a variety of topographical contexts, and have varied recording histories. Victoria Gold is keenly aware of these data deficiencies, and consequently accessed climate model data and forecasting to assist in site planning. Climate modeling reduces uncertainty to some extent, but local topographic conditions and the paucity of long term local base-line data place limitations on the reliability of climate projections. Adaptation to this uncertainty takes two dominant forms. Intensive mine-site monitoring to detail permafrost and hydrological conditions, and site planning and engineering to create plant and infrastructure robust enough to accommodate anticipated extreme events.

1 Freshet: a flood resulting from heavy rain or a spring thaw.

Climate-Related Events and Responses

1) Permafrost on site - Permafrost in the vicinity of the mine-site is discontinuous, but is very warm (0-1C range) and indications are that it is warmer than in the past. Detailed monitoring and modification of site design to ensure stability of infrastructure and mine components.

2) Variable temperatures associated with site topography - Site layout reflects microclimate variations and siting of spoil heap to take advantage of temperature differentiation.

3) Extreme cold and snow accumulation - Building design (e.g. roof pitches) so that snow loading is not a problem. The spoil heap will be operative only two hundred and fifty days of the year because of snow accumulation.

4) Hydrology and flooding - Freshets have always been problematic in this region, but over the last few years the incidence of floods has been increasing, and there is expectation that this trend will continue as winter thaw characteristics change. In recognition that the spring drainage regime may be changing site engineering is designed to accommodate 100-500 year events. Older culverts bridges and access roads from previous operations in the area are being replaced or upgraded. Essentially the precautionary principle is being applied, with over-engineering and building for high capacity events reflecting both the sense that the landscape is changing and compensating for the paucity of reliable climate data.

Victoria Gold's Eagle Gold Project in the Mayo district in the northeast Yukon. Photo Credit: Victoria Gold Corp

Table 1. Victoria Gold Summary of Climate Related Events and Responses

CLIMATE RELATED EVENTS	IMPACTS	ADAPTIVE STRATEGIES
Permafrost degradation	Liquefaction resulting in potential sinking of equipment and foundations Affects operations and the location of mine infrastructure	Relocation of some infrastructure to minimize exposure to climate risks. Monitoring of surface and sub-surface conditions throughout site. Have to over-design to reflect potential changing conditions and relative paucity of long-term trend data.
Increased run-off and periodic creek flooding at break-up Increased freshets and summer precipitation	River crossings vulnerable, which affects transportation to\from mine-site Accelerated drainage on mine-site	Upgrade old culverts in region to accommodate increased spring flows. Construct\Upgrade bridges. On-site engineering to 100-500 year events. Mine-site water management to keep mine-site drainage separate from regional drainage system
Temperature variability on site	Affects site design and location of spoil-heap	Use of local geography to utilize different thermal regimes in siting spoil and waste heaps respectively
Shorter winter season	Loss of ice roads	Not currently an issue, but consideration given to possibility of air transport as a contingency
Long term events pursuant to mine closure	Weathering of site affects quality of landscape and down-stream environments.	Filing of remediation plan including climate projections; remediation plan posted at inception; climate modeling to identify probable conditions in post-closure environment

Victoria Gold is essentially responding to the region's known hazards, and to uncertainties about future climate trends. While there are indications that the local climate is changing, absence of good quality long-term climate data, and problems inherent in downscaling climate models in complex terrain make prognosis about future trends somewhat tenuous. While it may be accepted that local conditions are changing, for mine-planners and project managers gauging the appropriate response is difficult, especially when mines have a relatively short operating life. Answering the question " how much change to plan for through the operating life of the mine?" is fraught with difficulty and the answer has to be translated into hard business decisions, such as how much to invest in engineering responses to events that have not yet been experienced. In a broader temporal context because Victoria Gold is a new mine, it has full life-cycle-planning that incorporates expectations about climate change. The company pro-actively incorporated future climate considerations into operational design, and filed a remediation plan including climate modeling to identify probable conditions in post-closure environment.

Victoria Gold's endeavors to reduce uncertainty are reflected in planning for the Casino mine, which included an assessment of future climate trends (next 40 years) (completed by Knight Piesold Consulting). The assessment examined past climate trends in the Yukon and utilized downscaled models to assess whether historical data can represent conditions that may prevail through the life of the mine. The report's substantive conclusion was that there is considerable uncertainty about predictions of climate trends in the Yukon and that "potential changes be considered in climatic and hydrologic assessments, where appropriate".

4.2 Operating Mines

While mines in the development stage have the opprtunity to incorprate the possible impacts of a changing climate into design, existing mines that pre-date current concerns about climate change may have to address stresses or events that were not anticipated when they were planned. Placer mining in the Kondike has been long extablished and has adapted to a range of climate extremes, while Capstone Resources' mine at Minto in the central Yukon was developed some twenty years ago and over recent years has grappled with events that are probably symptomatic of a changing climate.

Klondike

Placer mining in the tributary creeks of the lower Klondike River started with the Gold Rush of 1898. Today the region's gold mining industry consists of a number of relatively small operations, and the level of activity varies in concert with the global price of gold (Pearce et al., 2009). Historically snow, ice, and extreme winter cold meant that extraction was largely confined to some six months of the year. Gold bearing gravels were largely often found in frozen muck and permafost, and permafrost thawing using a range of technologies and the use of hydriology for sluicing were important components of the production process. In the years following the Gold Rush demand for water for processing gold-bearing gravels was such that the lower Klondike system had to be augmented by water diverted from a nieghboring watershed.

Contemporary Conditions

Current climate trends appear to have a neutral to beneficial affect on mining in the Klondike. There is some anecdotal evidence that the region's permafrost may be becoming degraded and that spring hydrological patterns are changing. Recent modelling conducted by the Pacific Climate Consortium indicates a warming trend, greater variability in the weather and more extreme events (Hennessy et al, 2009). However base data are so limited, the terrain so complex and the meteorlogical record so sparse it is difficult to make confident predictions. Over the past few years there have been fluctuations in the onset of spring and fall, with the latter tending to occur later, providing a longer operating season. Warmer summers are perceived to be beneficial for the industry. Permafrost in the Klondike is relatively warm (-0.5 to 1.0c) and thaws relatively quickly when over-burden is stripped away to access gold bearing gravel, and increased summer temperatures would augment this process.

While a number of potential climate stresses have been identified in the Klondike region, including changing hydrology (Hennessy et al 2011), there is little evidence of consideration of future trends by the industry or proactive adaptation planning. This might be a reflection of the structure of the Klondike mining industry. It consists of a number of independent small scale (compared with hard-rock mining) companies split between locally based operations which have a long history in the Klondike, and to who mining might be characterised as both a culture and an economic mainstay, and companies from outside the Yukon. Numerous small scale operators and seasonality of operations would perhaps suggest that the Klondike mining industry is flexible and well positioned to respond to extreme events by varying the level of activity. However, conversations with the Placer Miners Association suggested that the the possibility of this occcurring might be overstated because many operations are capitalised through loans, and cash flow has to be maintained to meet financial obligations even as mineral prices fall.

The Klondike River has a rich history of mining starting with the Gold Rush of 1898. Photo credit: Gord McKenna

Capstone Resources Minto Mine

While the Victoria Gold property is being developed in an era when climate change is increasingly anticipated and accomodated in mine design, Capstone Resources Minto mine was planned in the early 1990's when a changing climate was not a major consideration. Minto is the largest operating mine in the Yukon, and in 2013 will be the only one operating on a year round basis. Planned in the 1990's and opened in 2007, the mine is located in the dicontinuous permafrost zone 240 km north of Whitehorse close to the Yukon River in the Traditional Teritory of the Selkirk First Nation. Initially it was expected that the Minto venture would yield 371 million pounds of copper over an anticipated life-span of eight years. The mine has expanded several times since inception, and recent discoveries are expected to extend mine life beyond 2020. Capstone assures some degree of long term financial stability for its operation by marketing through five year advanced contracts. The primary market for the mine are in Asia, and access to tidewater is via mine road and subsequentlty the Klondike Highway south to Skagway Alaska. Production at the mine-site follows a process of crushing, grinding and flotation to produce copper concentrates with significant gold and silver contents. Water is central to this process and when the mine was designed in the 1990's a storage pond to manage the flow of water at the site was designed to assure water availability throughout the year given an expectation of occasional seasonal summer drought. Climate related problems including flooding and permafrost degradation have beset the mine ever since it opened, and the nature of these problems and the manner in which Capstone has responded illustrate both the way in which a changing climate is manifest and the challenges faced by a mine responding and adapting as problems arise. The Selkirk First Nation, located down-stream from the mine has a strong vested interest in the maintenance of the region's environmental integrity and is a major player in ensuring that negative externalities from the mine-site are minimised.

Capstone purchased the Minto Mine from Sherwood Resources in 2007, and has made a number of modifications to deal with unanticipated extreme precipitation events and permafrost degradation. Rainfall and run-off events in 2008 and 2009 forced the company to ask for amendments to its water licence to release untreated water into the Yukon River system. In 2008 heavy rains resulted in flooding and the mine's water treatment plant was overwhelmed resulting in the release of some 350,000 cubic meters of untreated water into the Yukon River, and the effluent content (.05 mg per litre) was higher than Yukon licence standard of .01 mg per litre. Ironically the water storage pond had been designed to assure water availability throughout the year, given an expectation of occasional seasonal summer drought. The 2008 rainfall also washed out a four kilometre section of the mine haul road to Minto Landing, linking into the Klondike Highway. In 2009 the problem of excess water on the mine-site, this time attributed to unusually heavy spring melt, was exacerbated because the wall of as storage pit was partially collapsing because of permafrost melt, and 750000 CM of water were discharged into the Yukon River system (Munson, 2009).

The original mine stored tailings as a wet slurry, conveyed in a stream to a holding pond, but engineering studies revealed that marginally increased run-off would lead to tailings deposition next to the dam, which would potentially compromise its integrity. The solution was to introduce dry-stack tailing storage. This mitigated the immediate problem, and in the long run is viewed as a more effectively serving mine-site remediation. However, it is now known that the dry-stack is shifting (Minto Mine, 2013), either because it is located on an ice-lens or because permafrost beneath the stack is melting.

Adaptation Responses

There is considerable evidence that the water management issue reflects failure to realistically consider climate trends during mine design, and following the floods of 2008\2009 Capstone's management acknowledged that climate projections when the mine was designed failed to accommodate the possibility of climate change (Yukon News, August 15, 2009). Hydrological tests basic to obtaining a water licence were conducted in the early 1990's and a licence issued in 1n 1996; the mine started operating in 2006. The licence anticipated that the mine's dam would fill in two years; it took only five months.

Initial response to water accumulation was a reflection of the fact it wasn't anticipated. Following the flood the company gave some consideration to allowing water to accumulate on the mine-site and processing and releasing it in timed stages. However it was recognised that this would have compounded the problem because winter snowfall and spring freshets would merely add to the water volume and consequently Minto made releases into the Yukon system in excess of levels specified in its water licence. Longer term responses included digging ditches to manage on site water, development a of a new water management plan based on more recent hydrological data, and in 2010, construction of a new water treatment plant designed to treat 4000 cubic meters of water a day.

Movement of the dry-stack is acknowledged to be a problem (Minto Explorations, 2013) Dry-stack storage was designed to solve one climate induced problem but resulted in another, and while this response could perhaps be viewed as maladaptive it's illustrative of the capacity of a changing climate to translate into multiple stressors and the difficulty of identifying appropriate responses. The initial response is to monitor the situation and build an abutment to try and stabilize the stack. In the longer term the company is working jointly with the Selkirk First Nation to develop a strategy for addressing the issue (Minto Explorations, 2013).

Capstone has modified operations or expanded a number of times since inception, and with each stage has been preceded by an environmental review and submission of a closure\remediation plan. The possibility of climate change plays an increasingly rigorous role in the planning and assessment process, and climate projections using down-scaled modelling produced by SNAP are incorporated into the design process for the latest phase of mine expansion (November 2013). In this stage operations are to be moved underground, which may benefit closure and remediation because detritus will remain underground and not exposed to weathering.

Table 2. Minto Summary of Climate Related Events and Responses

Climate Event	IMPACTS	ADAPTIVE STRATEGIES
Seasonal freeze-thaw of Yukon River	Interrupts transport of ore	Relocation of some infrastructure to minimize exposure to climate risks. Monitoring of surface and sub-surface conditions throughout site. Have to over-design to reflect potential changing conditions and relative paucity of long-term trend data.
Unanticipated summer precipitation	Excessive run-off overwhelms water treatment plant. Mining access road washed out Potential slurry pond dam compromised	Initially release excess water into Yukon river system beyond loading stipulated in water license Digging of on-site drainage ditches to manage water Re-visit climate projection data for mine New water treatment plant Heavy on-site equipment repairs road Move to dry-stack storage
Permafrost degradation	Holding pond wall melting Dry stack shifting	Drain pond Abutment built to stabilize stack Reviewing engineering solutions Future climate change projections used to identify possible future trends in permafrost degradation as basis for identifying possible responses.

Lessons Learned

There are relevant lessons for the mining industry from Minto's experiences. These include the company's clear acknowledgement of climate change as an issue, the re-visiting of climate projections as a basis for an engineering response to hydrological problems, investment in the range of responses to climate generated stresses over the past six years, the increasing partnership with the Selkirk First Nation in identifying and addressing potential environmental externalities affecting their Traditional Territory, and incorporation of long-term climate projections based on assumptions about warming in planning and remediation.

Minto's response to unanticipated climate related events can best be characterised as necessity driven adaptive management. While this reflects management versatility, the mine's economic viability and marketing of ores in five year advance contracts gave it the capacity to bear the costs of responding and adapting as problems arose. A more economically marginal venture would perhaps be incapable of the same responses.

4.3 Mine Remediation

Weathering, hydrology, and permafrost degradation, working independently, or more likely in concert, potentially affect the integrity of detritus from defunct mines. Essentially remediation includes re-vegetation of spoil heaps and ascertaining that mine-site hydrology is restored to its natural state and toxins are retained on site and neutralised. Because it is expected that shifts in the physical environment will extend well into the future a changing climate poses significant immediate and long-term challenges for mine closure and remediation planning.

Historically problems associated with closure in the Yukon were due to underfunding of remediation, mine abandonment and the incidence of "orphan" mines. However, over recent years there is accumulating evidence that a changing climate, manifest in permafrost degradation and changes in precipitation patterns, have negatively impacted abandoned mine-sites (David Suzuki Foundation, 2009). At the Clinton Creek asbestos mine, which ceased operations in 1987 some 10 million tonnes of tailings were left on site. Permafrost degradation, which was not anticipated in site remediation planning, resulted in erosion of tailings into local fish habitats. The problem was ameliorated to some extent through construction of gabion beds and the site requires sustained monitoring (UMA Consulting, 2004 & 2008). In Faro, increased summer precipitation and spring runoff led to increased run-off, creating problems for drainage management (Oke 2012).

These experiences, combined with experiences from elsewhere in the Yukon, including precipitation changes and suspected permafrost degradation at Minto and the post closure review of the Brewery Creek mine (EBA 2011) have served to inform decision makers. There is an evolving culture of incorporating climate change prognoses into mine-site remediation planning, with both the Yukon Environmental and Socio-economic Assessment Board (YESAB) and the Water Board addressing the issue by increasingly requiring climate change assessments in proposal submissions. However while it is recognised that the natural environment is shifting, dealing with the possible consequences of such shifts is problematic. For example, it is anticipated that clean up of the Faro mine-site could take well over a century, and the climate unknowns over that time period are considerable. Climate forecasting and assessment of terrain conditions have long been important components of mine-site remediation planning, but it is now recognised that a more dynamic approach is required. Instead of looking at recent past climate trends, modelling and projections are now employed incorporating climate change scenarios to anticipate future climate and weather trends post-closure. Building on this, ideally, are expectations about permafrost and groundwater behaviour. Long-term local level historical meteorological data are basic to both conventional climate projections and adjusting downscaled climate modeling; however, a scan of data for Yukon reveals that such data are inconsistent and spatially and temporally "spotty".

While formidable challenges are faced in remediating mines abandoned before climate change was recognised as an issue and consequently was not factored into long term planning, experience over the last several years has served to inform emerging approaches to remediation. For mines in development, such as

Victoria Gold expectations about climate change can be built into full life-cycle planning including closure. Remediation plans are posted when a mine is developed, and modified through its life as operations change or new information becomes available. Adaptive management is the only strategy open to currently operating mines (rather than pro-active full life-cycle planning), and climate change prognoses are incorporated into remediation planning, with Minto using SNAP projections to identify the probable nature of the post-closure environment and grappling with identifying appropriate remediation measures. Measures under consideration require good quality climate data. Evapotranspiration cover may be a relatively cost effective option for remediating waste and tailings. This involves leaving tailings in place and isolating them by covering with a layer of soil and clay and planting grasses and shrubs with extensive root systems to impede the downward percolation of water, which will be returned to the atmosphere through transpiration or evaporation. In a sub-Arctic environment this requires an accurate assessment of future evapotranspiration rates and rainfall. Another option for reclamation is a frozen base cover system, where tailings are underlain by an impermeable frozen base to prevent percolation of contaminants; this requires knowledge of the probable future behavior of permafrost to ascertain it remains frozen to prevent infiltration (Minto Explorations 2011).

Faro Mine

The derelict Faro mine, located some 200 km north east of Whitehorse, was one of the world's largest zinc mines. It operated from 1970 until 1997, and in 1998 its owner, Curragh Resources declared bankruptcy (Pearce et al. 2009). The Federal and Territorial Governments were obliged to assume responsibility for the mine, which can best be described as an environmental mess with a large quantity of waste, comprising crushed rock/ore, and tailings made up of lead, zinc, copper in various forms and other minerals such as metal sulphides which are potentially harmful to the environment. The mine's toxic waste pond contains some 55 million tonnes of acid generating waste and there are 70 million tonnes of tailings and 376 million tonnes of waste rock located at the site, with the potential to generate acid and release metals into the aquatic environment. Toxicity of the site may have been enhanced because of high grading of ores when the mine was operating. One of the major challenges at the site is to contain water contaminated with site detritus separate from the pristine local drainage system (notably Rose Creek). Ultimately, water on the site will have to be processed to remove toxins and metals before release into the broader environment.

Climate-Related Events and Responses

Clean up of detritus at Faro, a formidable task in a stable environment, is especially challenging because remediation will be taking place in the context of current and long term long climate change. Acknowledgement that climate change would be an issue affecting the site took some time. It was not clearly and overtly identified as an issue until 2007 when an independent peer assessment of remediation provided an overview of progress to date and the prognosis for the future. Reference to climate change appeared some 23 times in the summary document, and it was concluded that not enough attention had been played to the issue in the remediation process and more needed to be known about it. The long term and uncertain nature of climate change was acknowledged and the panel advocated adaptive management but provided little substantive detail on possible responses (Independent Peer Panel, 2007).

In the summer of 2008 the region experienced intense rainfall that caused erosion at the mine-site, in 2012 spring melt-water threatened to overwhelm the site (Oke 2012), and given the prognosis for increased precipitation and accelerated spring run-off in the central Yukon this problem could potentially worsen. Management of site hydrology and ensuring that mine-site water doesn't contaminate the larger context watershed is a major concern. Additionally, accelerated permafrost melt could increase slope instability and increase the potential for leeching. The bacteria that contribute to the production of Acid Rock Drainage (ARD) are active at the mine-site, and it is expected that metals released in ARD will continue to increase for hundreds of years. Site remediation will be a centuries long process, and while it is some sixteen years since the mine ceased operation there is, as yet, no detailed remediation plan in place. Site activity is best described as "care and maintenance", with the objective of neutralizing the site to ascertain that detritus and possible contamination are contained while a full remediation plan is being developed. Key components of this are a ground water interception system, monitoring to anticipate acidification by checking for sulphate levels in water, and managing the interaction between climate and the mine landscape so that site conditions don't deteriorate. In 1993 clean up costs were estimated to be $124m; a conservative current estimate of costs is now $700m.

Derelict Faro Mine closed in 1998 was once one of the world's largest zinc mines. Photo Credit : Yukon News

The broad components of the long term Faro closure and remediation plan involve stabilizing the site by upgrading dams containing tailings to ensure they can withstand natural events such as earthquakes and floods. All waste rock will be re-sloped to improve long-term stability and covered with soil, and a "state of the art" water treatment plant installed to clean water at the site (SRK Consulting, 2008). All these components require evaluation of future climate events or their impact, including precipitation and run-off forecasts and permafrost evaluation. Climate change projections play an important role in these evaluations.

Lessons Learned

Remediation at Faro would have been costly to Governments even if climate change were not a consideration because the financial provisions made by the mine's owners for post operation clean-up were grossly inadequate. Although the Faro mine was developed and abandoned before climate change emerged as a substantive issue, it demonstrates the capacity of unanticipated climate related events to exacerbate costs. Lessons that have been learned from the Faro experience are the necessity of rigorous "cradle to grave" mine planning that incorporates climate change considerations, and ensuring that companies realistically factor the costs of remediation into their operations.

5.0 Conclusions

It was clear through the course of this project that the dominant sensitivity of the Yukon mining industry is to global mineral prices, but as the Minto case example exemplified, climate change is an emerging issue with potential to impact capital and operating costs. While there is increasing awareness of the implications of a changing climate for the industry, identifying and developing appropriate responses is fraught with difficulties. Relatively little is known about the evolving climate, and generally adaptive management has emerged as the strategy for dealing with uncertainty. Emerging mines have the opportunity to incorporate climate change prognoses into full life cycle planning, but how much change they should anticipate is unclear. Existing mines have to address unanticipated climate related problems as they arise, and adjust closure and remediation plans as conditions change and more current information becomes available. Victoria Gold and Minto demonstrate positive responses to the prospect of a changing environment. In the case of Victoria Gold, climate modeling was employed to anticipate possible future conditions, and anticipation of a possible changing climate influenced mine-site design. Minto faced strong criticism for discharging untreated water into the Yukon system in its initial responses to unanticipated environmental stress (CBC News, July 7, 2009), but subsequently its response to multiple stressors has been robust. These stressors increased operating costs as the mine responded by making a number of expensive engineering modifications to address issues as they arose. Minto has perhaps been fortunate insomuch as its economic viability has enabled it to make investments in proactive initiatives that a more marginal operation faced with the same difficulties would probably be incapable of.

While attitudes towards climate change in the Yukon are evolving, this study identified a number of emerging positive initiatives enhancing ability to adapt to emerging climate conditions.

- Incorporation of climate modeling into mine planning processes.
- Evolution of an environmental assessment process that increasingly requires incorporation of climate change considerations into project design.
- Review of the behavior of closed mines to see what lessons can be learned for future mine planning and remediation.
- Recognition of the need for (and practice of) adaptive management.
- Introduction of full lifecycle planning that incorporates climate change considerations into mine life from inception to closure and remediation.
- Development of remediation plans that incorporate climate change projections and associated responses.
- Promotion of innovation and applied research and translation of research to the mining industry.
- Yukon mining industry has partnered with Yukon College to establish research chairs in mining, and two current projects are examining hydrology, and the application of biochar to mine-site remediation.

In all case examples, and in discussions with both the Yukon Chamber of Mines and YESAB, paucity and quality of data was identified as a major issue, not only for describing probable future climate trends, but also for translating trends into local impacts on permafrost, surface hydrology and ground-water. Modeling to identify future trends is difficult because historic climate data are inconsistent and spatially 'lumpy', and because complex local landscapes make downscaling of climate models difficult. Accurate assessment of permafrost and ground-water conditions are pertinent for all aspects of the Yukon mining industry and understanding climate trends are especially important for revising engineering standards. Applied research aimed at enhancing base-line data and translating what is known about emerging climate trends into probable physical impacts at the local level are practical actions that would reduce uncertainty and enhance the mining industry's ability to adapting to emerging challenges.

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