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Mine Waste Management in Wet, Mountainous Terrain: Some British Columbia Perspectives

Part I – Setting, Past, and Present

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Abstract

The province of British Columbia has long been one of the world's major mining jurisdictions. Historically, mining played a major role in the development and economy of the province, and this continues to be the case today. Many of B.C.'s mines are operating in mountainous, wet terrain that poses a formidable challenge to management of tailings, waste rock, and discharge effluent. British Columbians take immense pride in the beauty and splendour of their province, which they consider the "*Best Place on Earth*", and the protection and preservation of this heritage is the pre-eminent requirement to be factored into mine waste management solutions. Those solutions have changed significantly over the course of four decades, and have reflected advances in the state of practice, technology, and societal and regulatory expectations and processes. The mining industry has met these challenges, and continues to do so as ever more difficult terrain and ambitious projects are contemplated.

A Long and Storied Mining Heritage

The history of mining in B.C. long pre-dates the arrival of the first European settlers. Mining activity in the Province began with the First Nations peoples in the north, who gathered and traded obsidian (volcanic glass) from the area of Mt. Edziza as far back as 9-10 thousand years ago (Fladmark, 1984). Members of the Tahltan First Nation were also perhaps the first to exploit B.C.'s mineral wealth for trade and export, there being evidence of quarried Mt. Edziza obsidian, used for arrowheads and tools, at prehistoric sites in Alaska, Yukon, the Northwest Territories, Alberta, and throughout British Columbia. While the Tahltan undoubtedly faced a number of challenges in obtaining the obsidian, management of mine waste was not among them. Times have changed.

Mining in B.C. entered a new chapter with the arrival of settlers from Europe in the 19th century. B.C. became one of the world's significant mining regions since the mid-1800s and remains to this day an important producer, exporting substantial amounts of copper, gold, silver, lead, zinc, molybdenum, coal and industrial minerals every year. The Hudson's Bay Company first started mining coal on Vancouver Island in the 1840's. The discovery of gold along the Fraser River in the 1850's sparked the Cariboo gold rush, which facilitated the settlement of many parts of that region. Indeed, the search for, development, and export of B.C.'s vast mineral resources collectively have constituted a key driver of the province's growth and development, a process that continues today with mine exploration and development in B.C.'s northwest, which has in turn led to a go decision for the Northwest Transmission Line, a $404-million, 344-kilometre transmission line project key to unlocking the immense mineral wealth in that part of the province, a projected scheduled for completion in 2013.

By the early 1960's, technology had advanced so as to make feasible large scale open-pit production. Many significant open pit copper mines opened in B.C. around that time, including the enormous Highland Valley Copper operation, today the largest copper mine in Canada and one of the largest copper mining and concentrating operations in the world. Other open pit mines are currently being operated, constructed, or contemplated, in considerably more mountainous terrain and wet climates than a number of the province's earlier open pit operations.

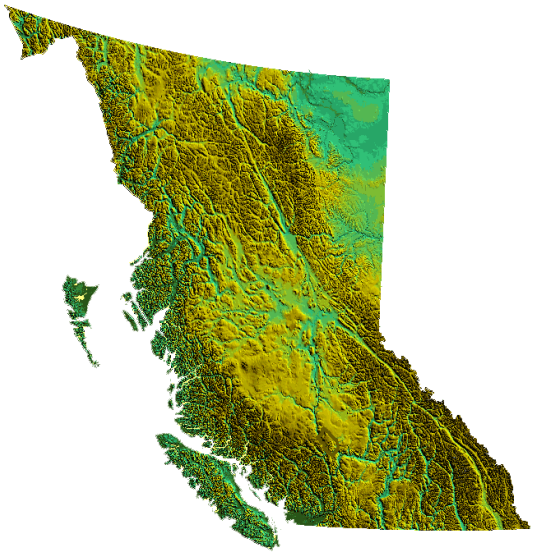
As of 2010, according to the B.C. Ministry of Energy and Mines (MEM) per Grieve et al. (2011), mining projects in various phases from advanced exploration and studies through operating mines were as listed in Table 1.

Table 1: Status of Mining Projects in B.C. (2010)

Mineral Resource Type	Operating Facilities	Selected Major Exploration Projects	Proposed Mines
Metal	9	114	13
Coal	10	5	7
Industrial Minerals	36	4	3

The Best Place on Earth

The Province of British Columbia encompasses much of the Canadian Cordillera, the westernmost of Canada's main physiographic and geological regions. In geologic lingo, the Canadian Cordillera comprises the deformed western margin of the North American craton, and a series of accreted terranes added to North America over geologic time, subsequently deformed and displaced northward along major faults (Claque, 1989). In layman's terms, the Cordillera is a series of mountain ranges, up to 900 km wide, bounded by the Coast Mountain Range to the west, and the Rocky Mountains to the east, with diverse geology, terrain, climate, and vegetation. Vertical relief in mountainous areas ranges between about 1,000 m and 3,000 m. Climate is controlled mainly by the proximity to the Pacific Ocean, and the mountain belts paralleling the coastline, and varies from a temperate, wet coastal climate to a drier, colder continental climate to the east. Atmospheric circulation is predominantly eastward, with moist air masses and cyclonic storm systems generated over the Pacific that move inland. Mean annual precipitation ranges from up to 4 m per year along the coastline, to less than 400 mm in the interior plateau region of central B.C. Precipitation is orographically-enhanced, so precipitation increases markedly with elevation, particularly near the coast, and micro-climates are commonplace. Snow depths in the western portion of the Cordillera can reach several meters.



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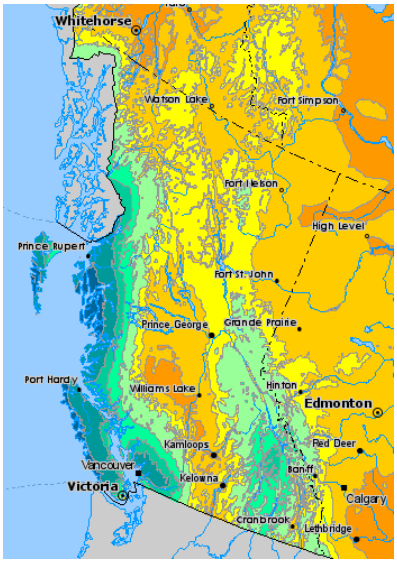


Source: http://atlas.nrcan.gc.ca/site/english/maps/environment/climate/precipitation/

Figure 1: Relief and precipitation maps of B.C.

British Columbia is endowed with unsurpassed wilderness scenery and plentiful natural resources, including its immense mineral wealth. The mountainous landscapes of B.C. are vast, varied and spectacular, and British Columbians take immense pride in the beauty of their province, as does the writer, gazing out an airplane window over the majestic Coast Mountain range, resplendent with its rugged, imposing and barren glacially-sculpted peaks, expansive ice fields and stunning glaciers plodding their way inexorably into the verdant green valleys below. British Columbians embrace an individual and collective sense of responsibility to maintain and nurture this heritage, and amongst no individual or group is this sense of heritage and stewardship more culturally-ingrained than amongst the First Nations peoples who have plied these picturesque but harsh lands and water ways for thousands of years. Several years ago, in one of those all too rare moments of lucidity in B.C. politics, the provincial government adopted for the province the slogan "*The Best Place on Earth*", a statement with which British Columbians can declare near unanimous agreement.

For the writer, looking up from the laptop computer for a brief respite in the writing of this paper, and gazing again out the airplane window at the majestic peaks and glaciers of Mt. Waddington, nowhere in the province is this slogan more demonstrably incontestable than in the mountains. However, from the perspective of mine development and operation and, in particular, secure storage of mine waste that achieves all environmental protection expectations, one also realizes that, from a mine waste management perspective, B.C. can make a strong claim to be "*The Most Challenging Place on Earth*". These challenges arise not merely from the rugged terrain far below, but also from the societal and regulatory demands that mine waste management be executed fully in keeping with the aforementioned sense of pride, heritage and stewardship. But before evaluating how these challenges are being addressed now, it is edifying to contemplate how they were tackled in the past.

Evolving Practices and Expectations – That Was Then….

As with other mining jurisdictions around the world, for early mine activities in B.C., mine waste management comprised dumping of tailings and waste rock wherever convenient. As noted by Davies et al. (2000), legal precedents gradually brought an end to uninhibited disposal of tailings in most of

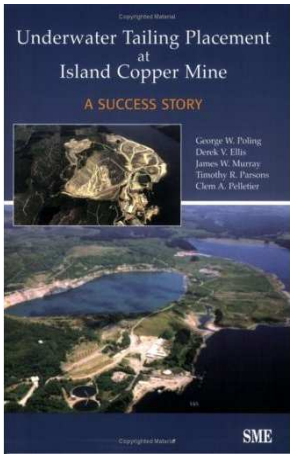
the western world, with a complete cessation of such practices occurring by about 1930. In B.C. as in other developed nation jurisdictions, by the 1950's many fundamental dam engineering principles were understood and had started to be applied to tailings dams. Sound civil engineering designs were applied to tailings dams on an industry wide basis for the first time beginning in the 1960's, and tailings dam design has since evolved into a formal specialist engineering discipline. In a seminal paper, Klohn (1972) charted this progression in terms of the design and regulation of tailings impoundments in British Columbia.

Similarly to the development of improved engineering and operation of tailings impoundments, waste rock dumps in B.C. are now investigated, designed, operated and monitored with safety, stability, and eventual reclamation foremost in mind (e.g. Eaton, 2000, Hawley, 2000).

A more recent but no less significant advance in mine waste management has been the consideration of metal leaching and acid rock drainage issues beginning at the very outset of projects. Such considerations are now fully integrated with mine waste management designs, operations, and closure.

A significant contribution to this progression of formal engineering of mine waste facilities, and the integration of geochemical and other environmental protection aspects, has derived from B.C. experience as documented by the likes of Klohn (1972), Kolhman and Plewes (2011), Leonoff (1994), and Price and Errington (1998).

As mine waste management engineering standards and practices have evolved over the years, so too have the societal and regulatory expectations and requirements to which those standards and practices must conform. It provides useful perspective for any discussion of mine waste management in B.C. today to review that progression, as mine waste solutions considered acceptable mere decades ago seem almost unimaginable today. For example, the Island Copper Mine, located near Port Hardy at the northern tip of Vancouver Island, was in 1971 granted a permit to discharge 40,000 tpd of potentially acid generating (PAG) tailings into Rupert Inlet, a deep fjord near the minesite. By the time the mine closed in 1995, 400 Mtonnes of tailings had been so discharged, and 800 Mtonnes of waste rock produced, most of which similarly was placed within Rupert Inlet. The Dept. of Fisheries and Oceans (DFO), judged on-land disposal of the potentially acid generating tailings to pose a greater risk to the marine environment, including the nearby Marble River, the main spawning river for Chinook salmon in the area, than submarine tailings disposal.



Source:http://archives.library.uvic.ca/featured_collections/esa/fonds_island_copper_mines/default.html

Figure 2: Island Copper Mine, near Port Hardy, northern Vancouver Island

While there was considerably greater mixing, upwelling, and dispersion of the tailings than had been anticipated, with suspended tailings observed some 35 km from the discharge point (although < 1% of the tailings escaped from the predicted deposition area), Waldichuck and Buchanan (1980) concluded:

- *Tailings are being distributed over a much wider area, including intertidal and shallow subtidal areas. This was not anticipated when the disposal system was planned.*
- *The tailings appear to be relatively non-toxic, judging by the colonization of the intertidal tailings deposits by marine plants and animals.*
- *Metals are not being bio-accumulated in appreciable amounts by organisms anywhere in Rupert Inlet or Quatsino Sound.*
- *The present evidence on ecological impact does not warrant changing the tailings disposal system to an alternative system such as land disposal.*

Poling et al. (2002) document the Island Copper submarine tailings disposal experience, and monitored effects, to five years after closure. Overall, the Island Copper Mine experience indicated the most significant impact was direct smothering of benthic marine life unable to move out of the way of the tailings. However, this impact was transient and was mitigated by the rapid re-colonization by bottom-dwelling creatures, and marine life had extensively re-colonized the tailings-covered bottom within a one to two year period after tailings deposition had ceased.

Another case study worthy of note is that of the Granisle open pit copper mine, located on Sterrett Island within Babine Lake, a lake of major fisheries and recreational significance, and the longest natural lake in B.C. The mine operated from 1966 through 1982. Tailings were discharged into Granisle's Pond No. 2 tailings impoundment from 1970 through 1982. With insufficient area on Sterrett Island for a tailings impoundment, three rockfill causeways were dumped within Babine Lake to connect, and enclose an area between, Sterrett Island and nearby McDonald Island. For one of the dams, rockfill was dumped into lake water up to 25 m in depth, onto lakebottom sediments that included up to 4.5 m of very soft, highly plastic post-glacial lacustrine clays, which were largely displaced such that the dam was founded primarily on dense glacial till (Klohn, 1981). The rockfill causeways were blanketed with spigotted tailings, and tailings disposal initiated within the enclosed areas, and the dams and the tailings deposit progressively raised to between 40 m and 60 m above the level of Babine Lake. With no cores within the dams, there were periodic plumes of fine tailings noted beyond the causeways until wide tailings beaches had become established, under-drainage measures constructed, and seepage gradients thus reduced.

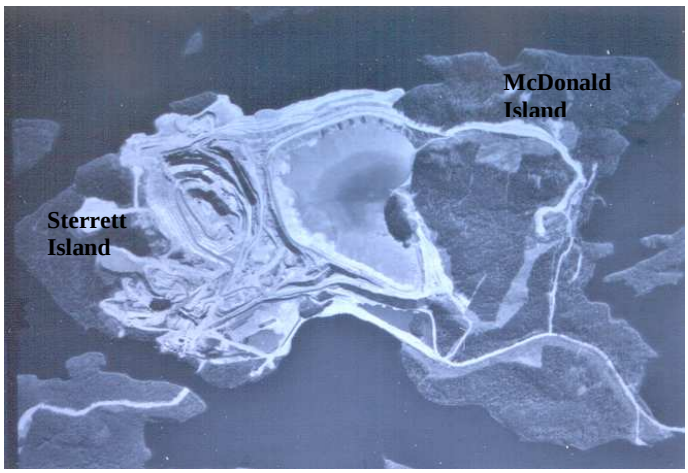


Figure 3: Granisle Mine tailings impoundment: Babine Lake, central B.C.

Chalmers et al. (2008) recount the history of tailings management at the Myra Falls lead-zinc mine on Vancouver Island. Ore production is primarily from underground, although a small open pit was developed. Waste rock and tailings produced from this operation are acid generating. Mining and processing operations commenced in 1966, and through 2008 had produced about 23 million tonnes of tailings. The mine is located within Strathcona Provincial Park on central Vancouver Island, the oldest of B.C.'s provincial parks. The site is constrained by steep mountains, with Myra Creek running right through the site. From 1966 through 1984, about 5.5 million tonnes of high sulphide tailings were discharged sub-aqueously into nearby Buttle Lake, 23 km long and about 1.5 km wide, which drains into Campbell River.

These examples illustrate that, for a brief period from the mid 1960's to the early 1970's, when mine developments were faced with a choice of developing on-land impoundments for tailings storage, in some cases requiring flooding of potentially acid-generating tailings, or making use of nearby water bodies for sub-aqueous disposal without the need for containment structures, the risk management and decision-making paradigms of the day periodically yielded a preference, and thus permit, for the latter over the former.

…And This is Now

Times have changed, and the evolution of tailings management at the Myra Falls mine exemplifies this well. In 1985, in response to public trepidation over tailings discharge into Buttle Lake, and in particular a significant monitored increase in dissolved zinc levels at the upper end of the lake at the outlet of Myra Creek, the mine commenced tailings storage into an on-land facility (van Dyk, 1987), some significant aspects of which are as follows:

- Containment was provided by an upstream-constructed dam of spigotted, sulphide-bearing tailings, with an under-drainage system to intercept seepage and direct it to sumps for pumping to the water treatment facility, with a positive gradient from the creek to the drains to prevent seepage from reaching Myra Creek.
- At closure, the tailings impoundment is to be capped with a dry cover, with non-contact water runoff shed towards Myra Creek, and seepage collected by the under-drainage system and pumped for water treatment over the long term.
- A diversion channel was required immediately upgradient of the tailings impoundment, to divert flows from very steep creeks vulnerable to debris torrent activity.
- The dam is situated in an area of high seismic hazard (in 1946 a magnitude 7 earthquake occurred with its epicentre 27 km from the mine), and an area with average annual precipitation of about 2.6 m.


Figure 4: Aerial views of Myra Falls minesite and upper end of Buttle Lake

The tailings impoundment significantly enlarged the site extent for which water collection and treatment was required. Some years into the dam's construction, to upgrade the seismic resistance of the tailings impoundment, the following were undertaken:

- Construction of a perimeter toe buttress, comprised in part of potentially acid-generating waste rock. The foundation soils underlying portions of this buttress required densification via dynamic compaction (Plewes et al, 2010).
- Upgrading of the toe under-drainage system for seepage collection and pump-back.
- Repositioning of Myra Creek itself, and armouring of the lower slopes of the toe buttress to prevent erosive failure due to high storm flows in Myra Creek.

Tailings management at Myra Falls thus transitioned from sub-aqueous storage in a passive system (Buttle Lake) to a complex, operationally-intensive, active system, with non-flooded impoundment of acid-generating tailings, and significantly expansion of the site footprint for which water collection and treatment will be required throughout closure. Remarkably, the scientific argument for ending tailings discharge into Buttle Lake appears, at least in retrospect, to have been dubious. Monitored zinc levels at the upper end of Buttle Lake did indeed increase from 1969 through 1979, but that period coincided with the most rapid rate of production of waste rock at the mine site, and in 1983 a surface and groundwater interception system was constructed to address that issue, as a result of which monitored zinc levels at the outlet of Myra Creek into Buttle Lake were already diminishing prior to the termination of subaqueous lake discharge in 1984.

A 1995 MEND report (Rescan, 1995) on the tailings in Buttle Lake concluded "*active oxidation of particulate sulphides and concomitant release of metals in the aerobic zone is strongly inhibited; very little, if any, surface oxidation can be accommodated by the existing data*". MEND (1989) observed that the tailings within the south basin of Buttle Lake were being covered by natural sediments, effluxes of metals from the sediments were very low, and stated "*it is reasonable to conclude that the submerged tailings are having no impact on Buttle Lake water quality at the present time. As burial by natural sediments continues, this conclusion will be reinforced*". Pederson (2002), following a detailed study of Buttle Lake, concluded "*the disposal under water of freshly-milled tailings highly enriched in metal sulphides prevents acid generation and consequent metal release*". Pederson et al. (1999) noted "*the quantum of metal possibly being released to the deep waters in the lake from the submerged deposits appears to be so small as to be not measureable*".

Nonetheless, public speculation and angst had myopically focussed on the sub-aqueous tailings discharge as the source for the monitored water quality effects, to say nothing of the emotive aspects of

tailings being discharged into a picturesque and tranquil lake within a provincial park, and the permitting agencies bowed to public perception.

Two recent regulatory rejections of proposed open pit mines in B.C., and the EIA terms of reference for another, serve to reinforce how societal and regulatory expectations in terms of mine waste management have transformed in the last few decades. The rejections of the Kemess North Project in 2007 and the Prosperity Project in 2011 both stemmed from the proposed use of lakes for mine waste storage.

The Kemess North Project represented a proposed new open pit development that would take advantage of the infrastructure developed for the Kemess South Mine, which was mined out in early 2011. The project would have extended the Kemess Mine life by at least 11 years, with production increased from 55,000 tpd to 120,000 tpd. Over 700 million tonnes of potentially acid generating waste rock and tailings were to be placed within Duncan Lake, the capacity of which would be expanded via perimeter dams up to 90 m in height. The project was scrutinized and, after a protracted process, rebuffed by a joint provincial-federal environmental review panel, which concluded "*the economic and social benefits provided by the Project, on balance, are outweighed by the risks of significant adverse environmental, social and cultural effects, some of which may not emerge until many years after mining operations cease*" (Joint Review Panel, 2007).

Tellingly, the panel agreed with the proponent that the waste rock and tailings management plan proposed for the project "*is the only waste disposal alternative which is environmentally effective, and technically and economically feasible*". The panel indicated it "*generally supports the proposed water quality mitigation and contingency measures (including the Proponent's commitments). The Panel believes that, if the Project proceeds, these measures would be effective in ensuring that all applicable receiving water quality standards, guidelines and objectives can be met at all stages, providing that the ongoing site management regime remains effective throughout the post-closure period. If that proviso were satisfied, the Panel believes that the Project would not have a significant adverse effect on downstream water quality in the Project area*". In short, irrespective of a solid scientific case, conceded to be such by the panel, the project was rejected, undoubtedly to some degree out of the panel's recognition of the "*need to consider Aboriginal traditional use, social and cultural/heritage values, including the spiritual values that Aboriginal groups attribute to an intact Duncan (Amazay) Lake*". There resistance on the part of local First Nations peoples to the use of Duncan Lake as a mine waste impoundment was sustained and vociferous.

Under a provincial review process, the B.C. government approved the proposed Prosperity Project in January 2011, on the basis that environmental effects would be outweighed by jobs, spinoff benefits and millions of dollars in tax revenue for regional and provincial governments. For this project, the perhaps unfortunately-named Fish Lake was proposed as the tailings storage facility. However, in July 2010, a federal government review panel, the terms of reference of which by design excluded consideration of economic benefits, concluded that the proposed mine would have significant adverse environmental effects on such aspects as fish and fish habitat and potential or established Aboriginal rights or title (Canadian Environmental Assessment Agency, 2010). The project proponent has subsequently submitted a revised project description that includes a tailings impoundment that preserves Fish Lake, for additional capital cost of $300 million as reported[1] by the proponent, in hopes that this reconfiguration will address federal concerns and win project approval.

[1] See http://www.tasekomines.com/tko/Prosperity.asp.

The Kitsault molybdenum mine is located about 140 km north of Prince Rupert, BC, and south of the head of Alice Arm, an inlet of the Pacific Ocean, and was in production between 1968 to 1972, and 1981 to 1982. For this latter phase of the operation, the tailings were discharged into Alice Arm, at a depth of 50 m below mean sea level (AMEC, 2010). In 1977, federal legislation had prohibited discharge of tailings to submarine receiving environments, and a specific legislated exemption was made for the Kitsault Mine, the Alice Arm Tailings Deposit Regulations, which were later formally repealed. Avanti Kitsault Mine Ltd. now proposes to construct and operate an open pit mine on the site with at a production rate of between 40,000 to 50,000 tpd. Resumption of submarine tailings disposal into Alice Arm was not amongst the alternatives considered.

Clearly then, regulatory and societal expectation is towards storage of tailings and waste rock in terrestrial facilities, irrespective of whether or not there is, nearby, a natural body of water that would provide a secure repository for tailings and/or waste rock, and also irrespective of compelling scientific evidence and economic arguments in favour of such repositories. There have been some exceptions in recent years, such as at the now-closed Eskay Creek gold mine, where Albino Lake was used for submergence of potentially acid generating waste rock, and Tom MacKay Lake was permitted in 2000 for sub-aqueous tailings disposal. Crucially, neither was a fish-bearing lake.

Difficult though it can be for the mining industry and its consultants to rationalize, ultimately even the most compelling scientific and economic case can merely serve to inform, rather than dictate to, processes of public decision-making. Emotive issues and spiritual considerations, however intangible and irrelevant to objective scientific discourse and economic analysis, are nonetheless very real to the public and an important and often decisive factor in decision-making. Such intangibles are particularly significant as they pertain to the environment in B.C.

A somewhat related challenge is that government regulatory and review processes, despite the best of intentions and sincere and determined recent attempts at stream-lining and harmonization, remain somewhat byzantine and arduous in nature. Project proponents are often left attempting to put the ball between continually shifting goalposts, and perhaps reticent to propose mine waste management schemes that make scientific sense, instead defaulting to whatever scheme is most likely to elicit a permit with the least amount of commotion. This is a pernicious trend, for it leads to a situation where sound science, which should be enlightening debate and public deliberations and decision-making, can in the interest of expediency be jettisoned at the very outset in order to chart and pursue the path of least resistance in navigation of the permitting minefield and expediting the arrival at the promised land of a permit in the shortest time possible. Sound science can thus be sacrificed at the altar of permitting expediency. This occurs irrespective of whether or not that path of least resistance coincides with a comprehensive evaluation of all potential alternatives and a path, however laborious, from which the best possible and most informed decision can emerge.

So the paradigm in which the mining industry today operates dictates that, instead of natural basins as repositories for waste rock and, in particular, tailings, the industry must engineer, construct, monitor and maintain large embankment dams and impoundments, many of which must be maintained in a flooded condition in perpetuity. Stewardship of such facilities from design to closure, and beyond, constitutes no mean feat in a province where in many places water bodies are ubiquitous, rainfall and snowfall are substantial, and terrain readily amenable to the development of impoundments required to remain stable in perpetuity can be hard to come by. To fully comprehend the scope of these challenges, and the most effective means with which to tackle them, it is necessary to contemplate the manner in which the B.C. landscape was sculpted, a mere moment ago on the geologic timescale.

Legacies of the Wisconsian Glaciation

Glaciers are believed to have first formed in the Canadian Cordillera about 9 mya (Denton and Armstrong, 1969). The cooling that led to the penultimate glaciation, the Wisconsian, began about 29 kya (Fulton et al., 2004). At the nadir of the Wisconsian glaciation, all of B.C. save for a few high peaks was covered by the Cordilleran ice sheet. Deglaciation began about 14.5 kya, and by 10 kya, ice cover in the province was roughly equivalent to that of today. Glaciers in B.C. have since waxed and waned many times during the Holocene. Menounos et al. (2009), in a study of glaciers in the Canadian Cordillera, noted that glaciers in this region "*reached their maximum Holocene positions during the early 18th or mid-19th century*", and "*were still close to their maximum positions in the early 1900s*", further noting that "*glaciers advanced during the Little Ice Age in response to cold conditions that coincided with times of sunspot minima*".

Alpine glaciers gradually widened and deepened valleys, and tended to produce U-shaped valleys in contrast to valleys formed entirely via stream erosion that tend to be more V-shaped. These U-shaped valleys are typically infilled with a complex sequence of glacial drift and post-glacial sediments. Adjoining valleys where tributary glaciers once merged with larger glaciers in deeper valleys formed hanging valleys, and many tailings impoundments and waste rock facilities have been constructed in such valleys, one example being the Highland Valley Copper tailings impoundment (Scott et al., 1988, Singh et al., 2008). While such valleys can present convenient geometry for construction of a mine waste impoundment, from a tailings dam designer's perspective, the Wisconsian bequeathed a decidedly mixed legacy.

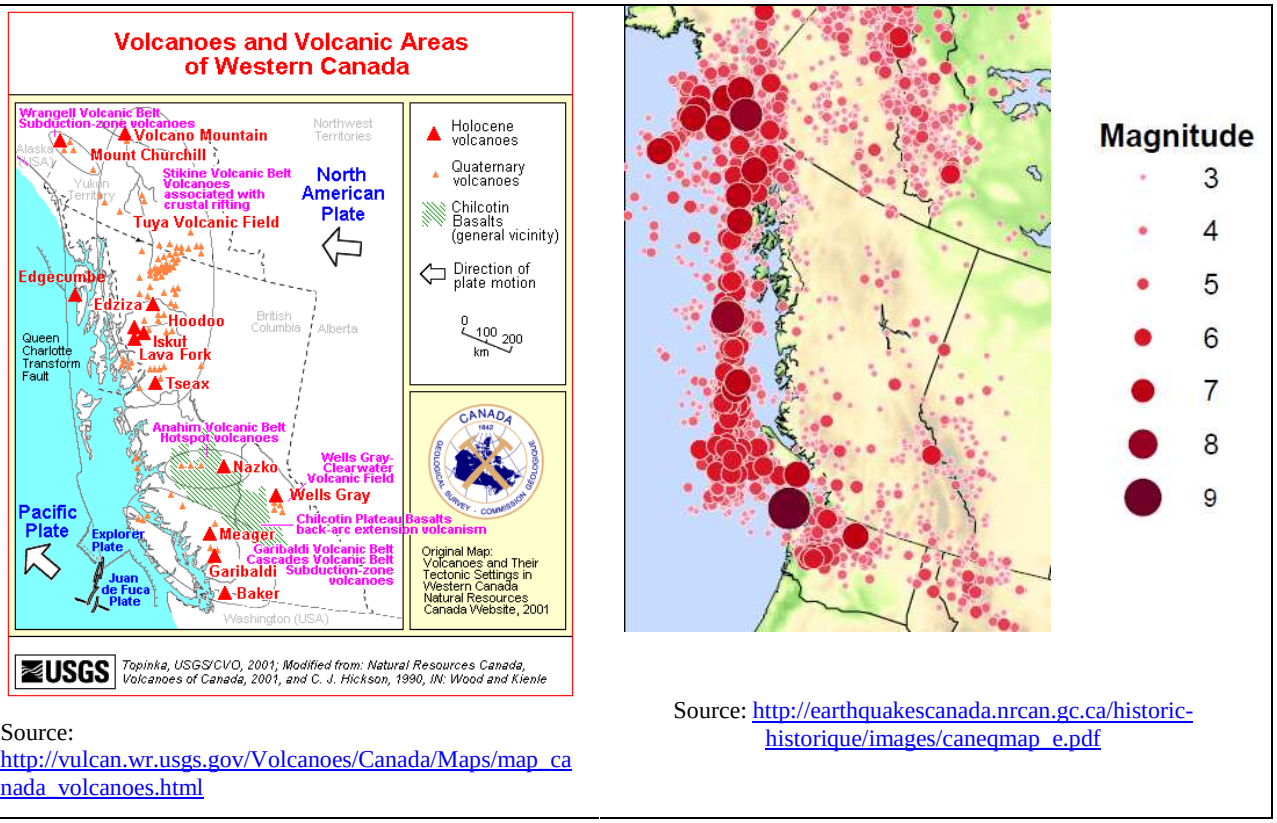
The Good – Glacial Tills for Construction

One of the legacies of the Wisconsian glaciation are the extensive deposits of glacial till and glaciofluvial sediments that are so widely used in the construction of tailings dams and waste rock dump covers. Glacial till is the most extensive of all surficial materials within the Cordillera, and comprises a broadly graded mixture from clay through cobble sizes, deposited in sub-glacial and supra-glacial settings. The well-graded nature and clay/silt content of many tills throughout the province make for a fill material that, when well compacted, is of very low hydraulic conductivity, hence its common use as the seepage barrier element in many earthfill and earthfill-rockfill tailings dams throughout the province. Lodgement (basal) till, deposited below and over-ridden by glaciers, is very dense, and where largely continuous and with significant clay and silt content, forms an effective seepage barrier (i.e. a natural liner) within tailings impoundments. In general, there is a direct relationship between local bedrock type and till composition and texture, with tills derived from volcanic rocks, carbonates, mudstone, shale, or slate typically having a clay and silt rich matrix, and thus more effective as core, liner, and cover material. Tills derived from such rock types as granite, sandstone, and metamorphic rocks typically have a matrix dominated by sand sizes.

The Bad - Geo-Hazards Abound

Gazing again out the airplane window to the splendour below, like any Geotechnical Engineer, the writer in a sense experiences double vision, simultaneously savouring terrain of indescribable beauty while soberly pondering terrain rife with geo-hazards, another legacy of the Wisconsian. Over the course of a two hour flight from Vancouver in the south to Terrace along the north coast, and then on a helicopter excursion to a remote advanced exploration project, one sees abundant instances of rockfalls, rock avalanches, large landslides involving hundreds of meters of mountain slopes, slope failures at lower elevations in glacial sediments (likely of glaciolacustrine depositional origin), evidence of failed

landslide dams, snow avalanches, debris avalanches and debris flows and fans, stream avulsions, rapid river down-cutting, large flood events, and so forth.



Source: http://vulcan.wr.usgs.gov/Volcanoes/Canada/Maps/map_canada_volcanoes.html

Source: http://earthquakescanada.nrcan.gc.ca/historic-historique/images/caneqmap_e.pdf

Figure 5: Volcanic and seismic hazards in B.C.

One also sees rivers and streams choked with sediment and glacial flour, with total suspended solids (TSS) levels orders of magnitude higher than what would be dictated by Canada's Metal Mining Effluent Regulations (MMER) for effluent released from mining operations. The evidence of glacial retreat since the Little Ice Age, which in western North America ended in the mid- to late-19th century (Luckman, 2000), is everywhere to see, starkly defined by Little Ice Age trim lines and sharply crested moraine ridges. While uncovering and making accessible additional mineral wealth, glacial retreat itself generates geomorphic hazards (Moore et al., 2009, Holm et al., 2003) such as debris flows, rockfalls, jökulhlaups (sudden releases of ice-dammed glacial lakes), sackung (slope sagging) above glacially-undercut slopes, periodic large landslides from over-steepened valley walls, outburst floods from moraine-dammed lakes, and debris flows from moraine deposits. The terrain is as difficult to manage as it is scenic to view.

To add to this, there are larger scale geohazards to content with, the underlying mechanisms of which are rooted deep within the earth's interior, and are largely responsible for the B.C.'s spectacular scenery. Being located along the Pacific "*Rim of Fire*", the coastal mountain ranges of B.C. are susceptible to significant seismic hazard, although the seismic hazard diminishes significantly further inland. Moreover, there are a number of volcanic belts within the province, the largest and most recently active of which is the Stikine Volcanic Belt in the northwest, the most active volcanic region in Canada, containing more than 100 volcanoes, three of which erupted in the last few hundred years.

And the Ugly – Glaciolacustrine Sediments

Notwithstanding all of the above, from a geotechnical perspective, perhaps the most unfortunate and ubiquitous legacy of the Wisconsian is the prevalence of glaciolacustrine sediments, widespread throughout many areas of the province, including valleys in mountainous areas. Glaciolacustrine deposits are typically well-stratified (varved), having been deposited in ice-damned lakes during glacial retreat. Such deposits can be of very low shear strength, and can occur at considerable depth within complex glacial drift sequences. Particularly troublesome are glaciolacustrine sediments that exist below lodgement (basal) tills, for these sediments, despite being heavily-overconsolidated and "hard", are often pre-sheared by glacial drag to very low, residual shear strength. Such deposits are responsible for many landslides within the province, and create much heartburn for geotechnical engineers responsible for tailings dam and waste rock dump design and stability. That the presence of such soils within the limits of a tailings impoundment serves to greatly limit seepage offers but limited solace.

Figure 6: Slide in pre-sheared glaciolacustrine deposit (left) and slickensided surface (right)

The Kemess Mine tailings dam (Martin et al., 2002, Lysay et al., 2007) is largely founded on a pre-sheared glaciolacustrine unit, which has necessitated a very gentle (6.5H:1V overall) downstream slope, numerous geotechnical investigation campaigns, complex two- and three-dimensional stability analyses, stress-deformation analyses, extensive instrumentation with inclinometers and piezometers, shear key excavations, and much attention on the part of the writer and the review board for the project. As a result of this experience, and the pervasiveness of such deposits throughout B.C., it is the writer's view that not only should any site investigation, be it for a tailings dam or a waste rock dump, specifically focus on the potential presence of any such material, such investigations should, where the glacial history of the site may have favoured a glacial lake depositional environment, seek to conclusively demonstrate its absence. Further, it is critical to evaluate the glaciolacustrine facies (depositional environment, structure, gradation, etc.), as not all soils classified as glaciolacustrine in origin are necessarily or equally geotechnically problematic.

B.C.'s Golden Triangle

One area presenting all of the aforementioned geo-hazards coincides with what may soon become B.C.'s next booming mining region: the area known as the Golden Triangle, in the northwest of the province. According to the B.C. Geological Survey Minfile database, there are 935 documented mineral occurrences indentified in the Golden Triangle, of which 67 are currently in the resource category. The area encompasses about 10,000 km^2, bounded by Telegraph Creek in the North, the Stewart area in the south, and the Coast Mountain range on the west, extending east for about 75 km. Pat Daly staked in 1916 what would eventually become the Premier Mine, one of the richest gold mines in the world, located 22 km north of Stewart. In 1948, Tom McQuillan and Einar Kvale

discovered and staked the copper mineralization that eventually became the Granduc mine, which required a 21-km access tunnel, and access roads constructed over glaciers. With an average snowfall of about 20 m per year, the challenges at Granduc were daunting to say the least, and in 1965 a massive snow avalanche claimed the lives of 26 miners there.

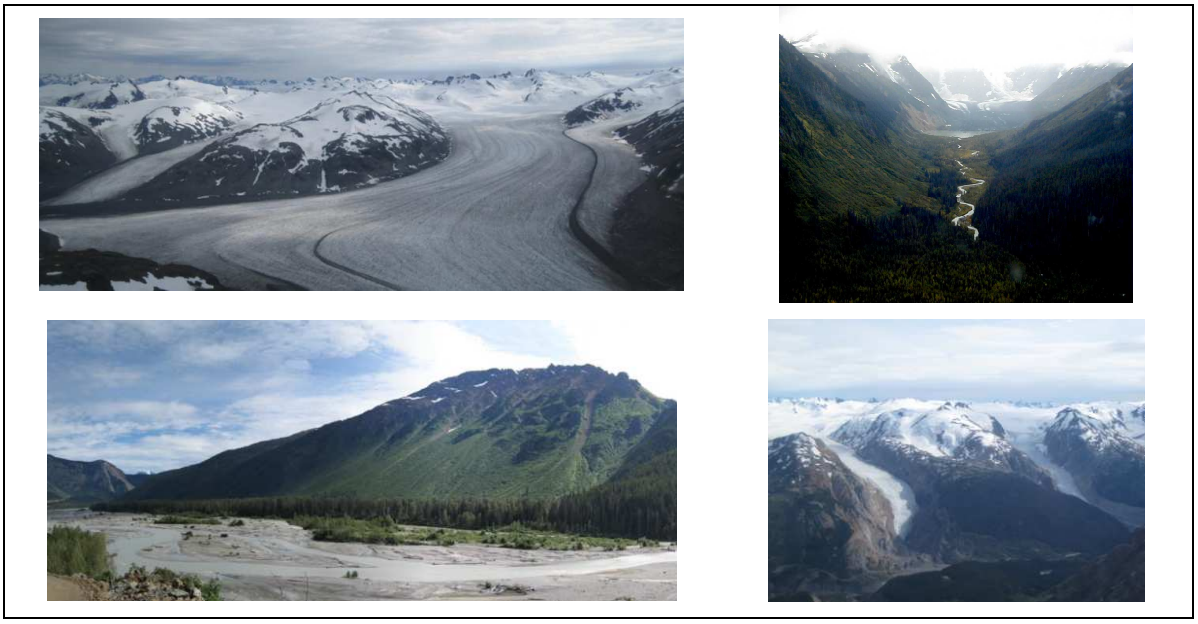


Figure 7: Typical terrain in the Golden Triangle area of northwestern B.C.

The early mining forays into the Golden Triangle were relatively low throughput, high grade, underground mines, a more modern version being the recently closed Eskay Creek gold mine. As summarized in Table 2, which is but a sample of the current projects in the Golden Triangle, world-scale, open pit mines are now being contemplated in the region. Given the scope of these projects, the quantity and nature of the mine wastes that will be generated, the climatic conditions, and the terrain typical of the region, examples of which are shown in Figure 7, it is clear that intriguing times lie ahead for the mining industry in B.C., replete with challenges for mine waste management, perhaps the most daunting of which relates to water management aspects.

Table 2: Representative Projects in the Golden Triangle Region

Property	Ore	Mill Throughput Rate (tpd)	Stated Reserve and Projected Mine Life	Potentially Acid Generating Tailings and/or Waste Rock?	Project Status
Red Chris [1]	Cu, Au	30,000	300 Mtonnes, 28 years	Yes	EA certificate in hand, permitting in progress
Galore Creek [2]	Cu, Au, Ag	95,000	528 Mtonnes, 18 years	Yes	Pre-feasibility study completed
Kitsault [3]	Mo	40,000	215 Mtonnes, 15 years	Yes	EA in progress
KSM [4]	Au, Cu, Ag, Mo	120,000	2,141 Mtonnes, 52 years	Yes	Pre- feasibility study completed
Schaft Creek [5]	Cu, Mo, Au	120,000	1,000 Mtonnes, 23 years	Yes	Feasibility study in progress, due late 2011

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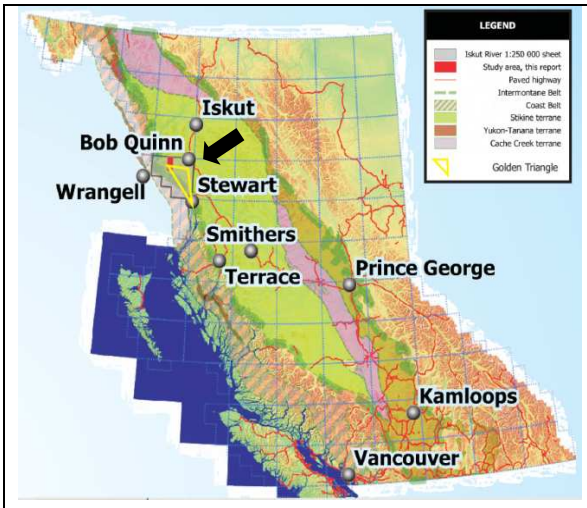
2. http://www.novagold.com/section.asp?pageid=18745
3. http://a100.gov.bc.ca/appsdata/epic/documents/p356/1277424455380_ac29d4b70b89f20b0f633e6fc5a22d5c888db2363cd4169ca5392bc6e5b5b2da.pdf
4. http://www.seabridgegold.net/readmore.php?newsid=322
5. http://www.copperfoxmetals.com/s/NewsReleases.asp?ReportID=466137&_Type=&_Title=Measured-and-Indicated-Resource-Estimate-Exceeds-1-Billion-Tonnes-at-Schaft



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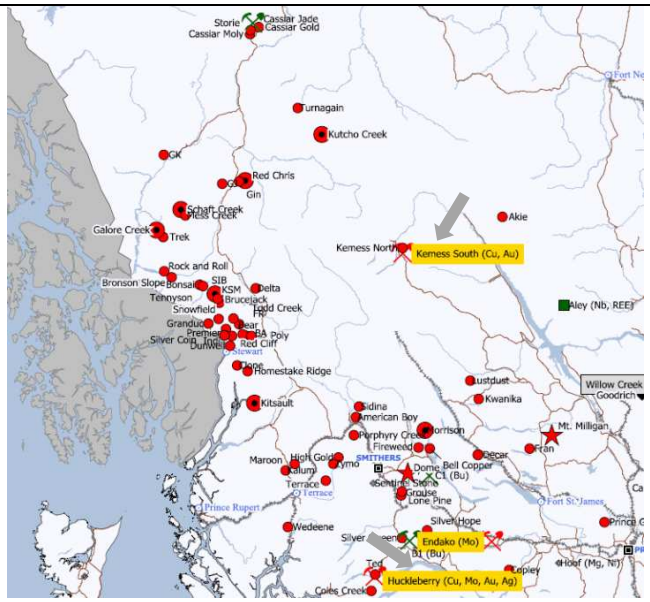


http://www.em.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/OpenFiles/2011/Documents/OF2011-1/OF2011-1_11x17.pdf

Figure 8: The Golden Triangle, mines and advanced exploration projects in B.C.'s northwest

Water Management

B.C. is home to Canada's tenth largest waterway, the Fraser River, as well as several hundred other rivers, creeks, streams, ponds and lakes that offer fish, clean, fresh water, recreation, and other benefits British Columbians enjoy. The Fraser River and other major B.C. rivers provide the spawning and rearing habit for the five species of wild salmon that are such an indelible part of the province's heritage. B.C. is rich in water resources and diverse eco-systems supported by those resources, and British Columbians are rightly adamant that this resource be responsibly stewarded and preserved. Given the mountainous terrain and very wet climate in B.C.'s coastal mountains, mining operations there have no shortage of water to manage, and a formidable and at times daunting task in handling it.

Effluent discharges from metal mines throughout Canada are subject to the Metal Mining Effluent Regulations (MMER) promulgated by the Federal government in 2002 under the Fisheries Act. The MMER stipulates discharge limits for arsenic, copper, cyanide, lead, nickel, zinc, total suspended solids (TSS) and radium 226, and require effluent to be non-acutely lethal to rainbow trout. There are also provincial water quality guidelines to be achieved for many other parameters, as set out by B.C.'s Ministry of Environment. The Canadian Council of Ministers of the Environment (CCME) which plays a role in reviewing and recommending water quality standards. There is no shortage of water quality regulations to which mines must adhere, and detection limit creep does not serve to simplify matters.

Huckleberry Mine – From Closed Circuit to Surplus Discharge

Obviously, the most effective means of compliance with effluent discharge regulations is to not have to discharge any effluent to begin with. Johnson and Letient (2001) described the water balance for the Huckleberry Mine, an 18,500 tpd open pit copper mine located in the transitional zone between the Coast Mountains to the west and the interior Nechako Plateau to the east. The site experiences on average nearly 1100 mm of precipitation annually. For the initial years of the operation, despite the wet climate, the tailings management facility was operated as a closed system (i.e. zero discharge). This was due in part to the relatively confined area of the initial tailings impoundment, and to the water consumption in the voids within PAG waste rock that was co-disposed with the tailings, as well as tailings voids, until the tailings facility was expanded to include the mined-out and backfilled Main Zone Pit. At that point in time, as had always been projected, the water balance for the enlarged, unified tailings impoundment area changed from essentially in balance to net annual surplus, and from that time forward (late 2004), the options were to either accommodate an increasing water surplus, and thus accelerate dams construction, or, subject to water quality requirements being achieved, discharge surplus water. Huckleberry commenced discharge of surplus water in July 2006, upon completion of a permitting process that required extensive studies in support of a permit amendment from the B.C. Ministry of Environment. Love et al. (2006) provide an overview of the process involved with regards to baseline studies, predictive modelling and risk assessment, mitigation strategies, and site-specific environmental effects monitoring plans. Besides these studies, there are also public consultations where it is not uncommon to encounter substantial opposition to mine effluent discharge. Given the efforts, regulatory processes, and timelines involved, operations in B.C. that anticipate a water balance change during the operational life that necessitates a change from a closed-circuit to surplus discharge, and thus a permit amendment, are well-advised to commence the process far in advance of the anticipated required date of discharge.

From a water management perspective, Huckleberry benefits from a tight site configuration wherein the contributing catchment is not excessively large relative to the area of the tailings impoundment. Many of B.C.'s mines, however, do not enjoy this advantage.

Kemess Mine – Closed Circuit and Accumulated Water Surplus

The Kemess open pit gold and copper mine, operated by Northgate Minerals Corporation, is located in the Omineca range of north-central British Columbia, 430 km northwest of Prince George. The mine began operation in May of 1998, and mill operations ceased in early 2011. The Kemess area has a typical interior continental climate, with temperature extreme between -50ºC and 30º. Mean annual precipitation is about 850 mm, most of which occurs as snowfall.

Figure 9: Huckleberry mine site: 1993 and 2007

The Kemess tailings dam was constructed across a valley with a catchment of about 21.4 km^2. A diversion system was constructed to divert about 10.1 km^2 of that area. The diversion system, described by Bent et al. (2001), and as shown schematically in Figure 10, comprises two earth fill diversion dams, a run-of-the-river intake, two buried diversion conduits and a buried water release conduit that discharges into South Kemess creek beyond the downstream toe of the tailings dam. Water impounded behind the South Diversion Dam is released gradually over the low flow winter months to maintain fisheries habitat in South Kemess Creek. Owing to topography and pipeline grade constraints, the release conduit (reinforced concrete encased steel pipeline) from the South Diversion Dam reservoir passes below the core of the dam. Needless to say, the detail of the conduit through the dam core received extensive design and construction attention, and the conduit will be filled upon decommissioning. As is evident from Figure 10, the very steep terrain within the impoundment area, with numerous avalanche chutes and active talus slopes, precluded the use of diversion channels, to divert catchments downstream of the two intakes and the run-of-river East Diversion intake.

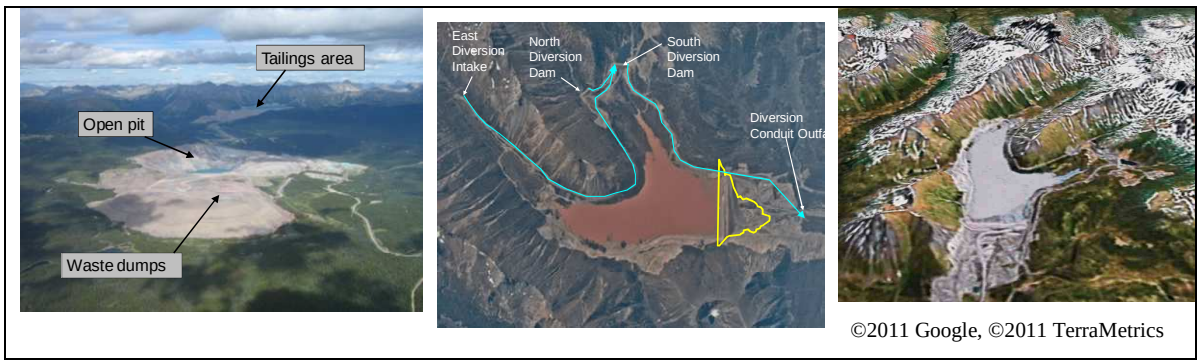


Figure 10: Kemess Mine tailings facility: setting and diversion system

As a result of the wet climate and the constraints imposed on runoff diversions, the Kemess tailings facility operated under a net annual water balance surplus. Despite this, the facility was operated as a closed circuit. As a consequence, the volume of water in the pond increased at a rate averaging about 1.2 million m^3 per year. Given the large size of the impoundment, however, this surplus could be accommodated by only a slight increase in the annual required dam crest elevations. By the end of tailings discharge into the facility, the water pond volume was about 20 million m^3, far in excess of that actually required to maintain a viable reclaim water pond. Further, the net annual water balance surplus made it difficult to maintain above-water tailings beaches in front of the clay till core dam, and it was only once cycloned sand production began in 2002 that sub-aerial beaches could be developed and consistently maintained between the water pond and the till core.

Kemess faced another water management challenge in terms of drainage from its ex-pit waste rock dumps. As noted by McConnachie et al. (2009) elevated levels of selenium appeared unexpectedly in seepage from one of the NPAG waste rock dumps, which flowed into fish-bearing waters. Selenium was first identified as a potential concern in 2000, two years into the mine's operation, on the basis of kinetic test work undertaken for the various waste rock types (Stogran et al., 2004). Since 2004, when selenium was noted as an element of concern at Kemess by the B.C. Ministry of Environment, Kemess has undertaken extensive investigations, studies, and remedial measures to address the issue. Affected water was intercepted and pumped into the mill process water system. On the basis of the extensive studies taken, including effects of selenium on local fish populations, Kemess has proposed to the Ministry of Environment that a site-specific limit for selenium be established. A till cover is being constructed over the leach cap waste dump that has been identified as the source.

Kemess has successfully grappled with its water management challenges, for both anticipated issues (tailings facility water balance surplus) and unanticipated issues (selenium leaching from the waste rock dump). The terrain and climate at other sites will present greater water management challenges still, most particularly in the Golden Triangle region.

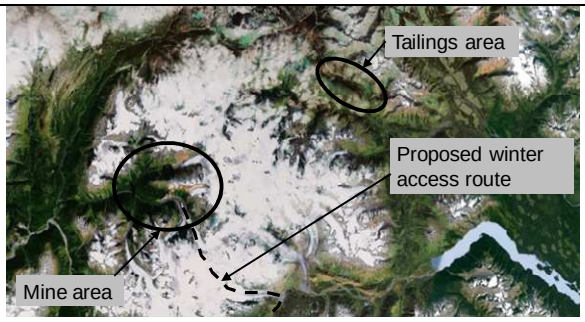
Surplus Water Discharge from the Start – KSM Project

The proposed KSM project (see Table 2) is located about 65 km northwest of the port of Stewart. As outlined in the pre-feasibility study for this project (Wardrop, 2011), given the rugged terrain and prevalence of ice fields and glaciers, the mine area is to be connected to the process plant, and the main site access road, via a 23 km tunnel. A second, parallel 23 km tunnel is to accommodate slurried ore pipelines, a water pipeline, and electrical powerlines. A winter access road is proposed, about 29 km of which would cross over several glaciers to provide temporary access during construction of the project.

Total annual precipitation in the project area is high, ranging between 1.4 m to 2.4 m, orographically-controlled. The water balance for the tailings facility (retained by dams with an ultimate height of up to 240 m) is projected to be in surplus at an average rate of 0.23 m^3/sec, resulting in an average total projected annual surplus of about 7.3 million m^3, despite a perimeter diversion system, which is to include a tunnel. As stated in the pre-feasibility study, "*management of surplus water may use a combination of storage, discharge during freshet, or treatment and discharge*".

In the mine area, to reduce the catchment contributing runoff to the area of the waste rock dumps, two diversion tunnels (each with twinned tunnels, for a total of four tunnels, totalling 21.8 km in length) are planned for diversion of glacial melt water and non-contact valley runoff. Contact water in the mine area is to be stored behind a 156-m high earthfill and rockfill embankment dam. Mine contact water stored in the pond is to be treated with a high density sludge lime water treatment plant, with the plant discharging year-round at a rate of between 1.3 m^3/s to 2.2 m^3/s (41 to 69 million m^3 annually). Flows in the diversion tunnels will generate power, as will flows in the water pipeline from the tailings facility to the water treatment plant in the mine area. As the waste rock is largely PAG and will not be flooded at closure, permanent site access will be maintained, via the access tunnel, and the water treatment plant will remain in operation to treat ARD runoff indefinitely.

Mine area



Regional setting

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Figure 11: KSM Project area

B.C.'s mining industry has a proud history of facing daunting hurdles and overcoming them. The water management challenges in the Golden Triangle region, against which those faced by Kemess and Huckleberry pale to seeming insignificance by comparison, pose another such hurdle that the mining industry in B.C. is now confronting with its characteristic "can do" pioneering resolve.

Caught Between a Fish and a High Place

One water management challenge common to all mines in B.C. indeed all mines in Canada, is the Fisheries Act, enacted by the Federal Government in 1868. Section 35 of the Fisheries Act stipulates that deposition of tailings and waste rock in natural water bodies is not permitted if it results in the harmful alteration, disruption or destruction of fish habitat unless authorized by the Minister. MMER forms an addendum to the Fisheries Act, and defines a "*tailings impoundment area*" as: "*a) a water or place set out in Schedule 2; or b) a disposal area that is confined by anthropogenic or natural structures or by both, but does not include a disposal area that is, or is part of, a natural water body that is frequented by fish*". This is not to say that any "*water body that is frequented by fish*" is automatically off limits as a mine waste repository, but an Order in Council is required in order to designate any such water body as a tailings impoundment, and thus achieve an exemption, in the form of a listing in Schedule 2 of the MMER.

Achieving an exemption from the Fisheries Act in the form of a Schedule 2 listing is a long and arduous add-on to permitting challenges and timelines that are already byzantine and tortuous in nature. That said, no process can ever be ideal, and given the importance that Canadians in general and British Columbians in particular ascribe to the nation's water resources and the fisheries they support, it is surely only fitting that such proposals be very thoroughly scrutinized and critiqued, given broad public support for the objectives enshrined within the Fisheries Act, as a means of environmental protection and preserving B.C.'s splendour for future generations. The Mining Association of Canada (MAC, 2008 and 2011) has repeatedly gone on record to state "*Canadians should be assured that the use of this option is not approached lightly or without serious consideration of its environmental and social implications and examination of all possible alternatives*".

However, as observed by MAC (2011), frequently "*a mine is located in an area that has lots of water, so avoiding a natural water body is difficult*", which decidedly understates the situation in the mountainous, wet terrain encompassing so much of B.C. Water displays unswerving proclivity to occupy low areas that characteristically represent the most physically and geochemically stable repository sites for mine waste, and in particular tailings. So where Coleridge's beleaguered ancient mariner lamented "*water, water everywhere, nor even a drop to drink*", those responsible for mine waste solutions in B.C. could well paraphrase "*water, water everywhere, nor any home for mine waste*", at least not one commensurate with well-established laws of physics. Increasingly, in seeking stable, long term solutions for mine waste storage, the mining industry in B.C. can literally find itself caught between a fish and a high place.

It is imperative to recognize that permitting and construction timelines are critical to mining companies, which are highly incentivized to bring new projects on-line as quickly as possible. Permitting processes, constraints, costs, and timelines thus drive many project decisions, most particularly mine waste management solutions. This reality, and the societal expectations as reflected and applied via the Fisheries Act, together with the ubiquitous law of unintended consequences, has in the writer's experience led to the following situations, amongst others:

- Mining companies unprepared to even consider certain sites, well-suited to secure long term storage of mine waste, as part of an alternatives evaluation. Potentially viable and secure sites are thus discarded at the very outset of the evaluative process, for fear of complicating the permitting process and of offending emotional sensibilities of the stakeholders in that process.
- Tailings impoundment configurations, and dam alignments, are determined as much by the Fisheries Act as they are by considerations of of geotechnics, hydrogeology, spillways, and long term stability and security.
- Design and construction of critical dam safety features, such as closure spillways, are dictated to a significant extent by fisheries issues.

In short, the path of least permitting resistance can be incongruent with the most appropriate mine waste storage solution for the long term. However discordant such situations as these may be to a geotechnical engineer and tailings dam designer who holds paramount long term stability and safety of mine waste impoundment structures, implementation of the principles of sustainability inevitably involves tradeoffs that must reflect the paradigms and public expectations of the day. That is entirely proper. It is disconcerting however that many of these tradeoffs are neither recognized in terms of their existence, nor appreciated in terms of their ramifications. No doubt it will be our descendants, living with the legacy of these decisions, who will with the clarity and benefit of hindsight better comprehend them. Nonetheless, it is surely obligatory for us in the here and now to examine and

evaluate all mine waste management alternatives, including those that may raise hackles on the part of some, and to do so openly, honestly, and objectively, however impolitic it may be to do so.

Conclusion

The mining industry in B.C. operates in a setting perhaps as unmatched in its mine waste challenges as it is in its splendour and beauty. Contending with rugged terrain, a wet climate, a plethora of geo-hazards, ever more stringent water quality standards, an increasingly risk-averse public, arduous and protracted permitting processes, and requirements to avoid natural water bodies to the greatest extent possible as enshrined within the Fisheries Act, the mining industry in B.C. certainly has its work cut out for it. Nonetheless, British Columbians have high expectations of the industry in this regard, as indeed the industry does of itself. Mine waste management solutions have evolved rapidly over the last few decades in response to these expectations and improved industry standards worldwide, and B.C. mining operations and expertise have made, and continue to make, a significant contribution to that effort. Much has changed over the course of a few decades. Irrespective of those changes and improvements, mine wastes, and how we design, manage and close them today, are creating a legacy for future generations. The creation of this legacy, how we manage it, and how it may come to be judged by future generations in this province that truly is the "*Best Place on Earth*", are examined in a companion paper (Martin, 2011b).

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