CONSTRUCTION OF TWO LARGE-SCALE WASTE ROCK PILES IN A CONTINUOUS PERMAFROST REGION[1]

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Abstract. The discovery of diamonds in Canada's North has led to renewed interest in the development of mining properties in the Arctic. At the Diavik Diamond Mine Inc. operation, open pit mining will lead to the construction of two 200 Mt permanent stockpiles of waste rock. A rigorous, quantitative framework for assessing the long-term environmental implications of storing waste rock in regions with continuous permafrost has yet to be developed. Our study involves the construction of two large-scale waste rock piles (15 m in height × 60 m × 50 m) to assess the evolution of the hydrology, geochemistry, temperature, and biogeochemistry of the waste rock piles over time. One test pile will contain rock with a sulfide content of < 0.04 wt% S and the other test pile contains rock with > 0.8 wt% S. Complementary studies involving conventional static and kinetic tests on small test samples have also been initiated. The results from this five-year study will assist mining companies and regulators in evaluating current waste rock pile designs. This paper describes the construction of test piles, preliminary modeling of heat transfer and oxygen transport within the piles, and additional testing planned to quantify the relationship between weathering rates in laboratory dissolution tests and those in waste rock piles in the field.

Additional Key Words: kinetic oxidation modeling, heat conduction, scale-up

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Introduction

The discovery of diamonds in Canada's North has led to renewed interest in the development of mining properties in the Arctic in the past decade. A rigorous, quantitative framework for assessing the long-term environmental implications of storing waste rock in regions with continuous permafrost has yet to be developed. At the Diavik Diamond Mine Inc., located 300 km northeast of Yellowknife, NT (Fig. 1), open pit mining will lead to the eventual development of two 200 Mt permanent stockpiles of waste rock to retain the excavated country rock that surrounds the diamond-bearing kimberlite pipes. The country rock consists of granite averaging <0.04 wt.% S (Type I rock) and biotite schist averaging >0.08 wt.% S (Type III rock). Both rock types contain low concentrations of carbonate minerals.

The conventional approach used to evaluate whether a particular waste rock is potentially acid generating is based on laboratory tests conducted on small volumes of rock. An assessment of the value of these small-scale tests is required if their results are to be applied to predict if and when low quality drainage may be released from field-scale stockpiles. Scaling issues are critical in the cost-effective and reliable prediction of acid mine drainage risks. Understanding the "scale-up" question is important to mining companies developing management plans for new and operating mine sites, and to the regulatory agencies that must evaluate these plans to confirm protection of the environment.

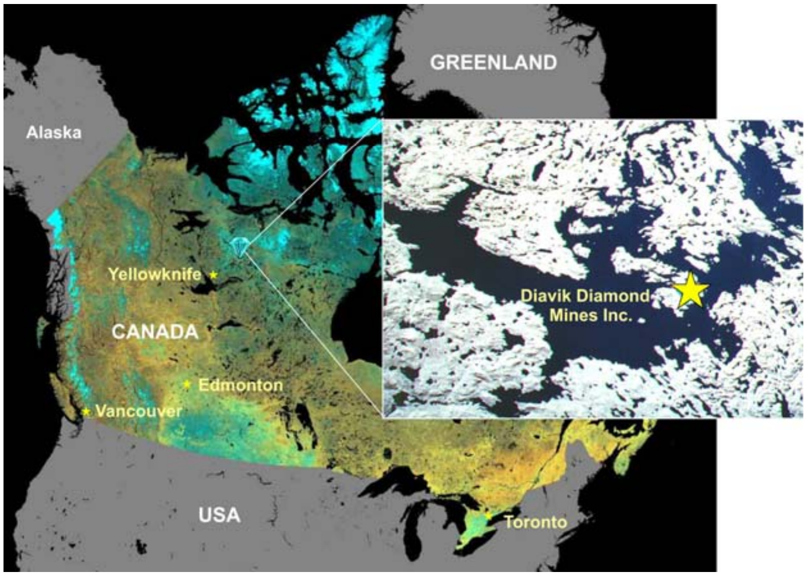

Figure 1. Location map for Diavik Diamond Mines Inc.

Objectives

The objectives of this study are to (1) describe the physical, geochemical, and microbiological processes affecting the weathering of waste rock in large stockpiles in cold climates, and (2) determine the relationship between laboratory dissolution test results and geochemical behavior of full-scale sulfide-bearing waste rock stockpiles. The objectives of the present paper are to describe the construction of test piles, preliminary modeling of heat transfer and O_2 transport within the piles, and additional testing planned to quantify the relationship between weathering rates in laboratory dissolution tests and those in waste rock piles in the field.

Methods

Experimental Approach

This study includes the construction of two large-scale waste rock piles (15 m in height × 60 m × 50 m) to assess the evolution of the hydrology, geochemistry, temperature, and biogeochemistry of the waste rock piles over time. One test pile will contain waste rock with a sulfide content of < 0.04 wt.% S (Type I rock) and the other test pile contains rock with > 0.08 wt.% S (Type III rock). Each test pile will be constructed on an impermeable liner to capture and measure all infiltrating water. During construction of the pile, a comprehensive instrumentation network will be installed within the interior of each test pile. Instrumentation includes thermistor strings, gas sampling ports, soil suction lysimeters, collection lysimeters, time domain reflectance probes, and access ports for thermo-conductivity measurements and microbiological sampling. The concept underlying the design of the test piles follows from earlier work at the Cluff Lake mine in northern Saskatchewan (Smith and Beckie, 2003; Nichol et al., 2005; Wagner et al., 2006).

Prior to initiating construction of the piles, thermal transport modeling was conducted to assess the rate of cooling that would occur after the piles were constructed. The thermal evolution of the test piles will reflect the interaction of the internal heat released by sulfide mineral oxidation and the cooling that will occur in this northern climatic regime. Input data for these simulations included sulfide-mineral oxidation rates, which were estimated from kinetic tests undertaken as part of the feasibility studies conducted prior to commissioning the mine.

Humidity cell tests (ASTM, 2000; Lapakko, 2003) are being performed on Type I and III rock samples to provide measurements of the rate of sulfide oxidation and the rate of release of dissolved metals. Humidity cells use run-of-mine rock sieved to a grain size of less than 1 cm, which is similar to the grain size used in the Diavik baseline environmental program. One sample of Type I (<0.04 wt.% S_T) and one sample of Type III (>0.08 wt.% S_T) rock are being tested. Each sample is being tested in duplicate at room temperature (20°C) and at a temperature representative of field conditions using cold rooms (4°C). Two additional samples, one Type I and one Type III, will be collected for similar testing. These samples will also be tested in duplicate at each temperature with bacterial inoculation.

In addition to the humidity cells, leaching column experiments will be conducted using columns 40 cm high and 10 cm in diameter. These columns will contain run-of-mine rock, sieved to < 1 cm diameter. The tests will be conducted at the mine site under ambient environmental conditions. Furthermore, similar field and laboratory testing will be conducted on Type II rock (0.04 wt.% S – 0.08 wt.% S) from the site. Because the design of field piles has not been completed, Type II rock will not be discussed in the present paper.

Analysis of Solids and Leachates

Samples of rock from the test piles were collected for humidity cell tests, leaching column experiments and mineralogical study at the start of the project, and will be collected during the construction of the test piles and during deconstruction after year five. These samples will be examined using X-ray diffraction (XRD), optical microscopy, secondary electron microscopy (SEM) coupled with energy dispersion analysis (EDXA), and surface analytical techniques including X-ray photoelectron spectroscopy (XPS). During construction of each pile, approximately 100 rock-samples (~7 kg each) will be collected on three to four tip faces (Fig. 2). These samples will be characterized for particle size distribution and surface area (Brunauer, 1938). After year five of the project, piles will be deconstructed and samples will be similarly collected and analyzed to assess the effects of weathering.

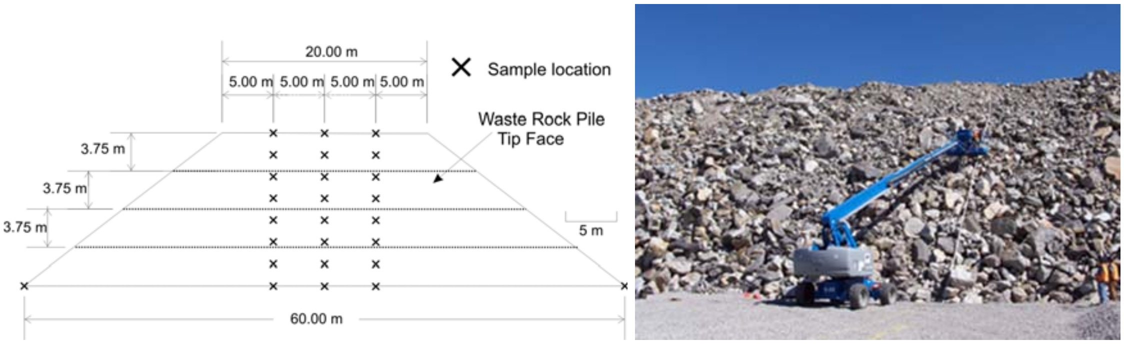

Figure 2. Diagram to the left is a cross-section of a waste rock pile showing waste rock sampling locations along the tip face. Three to four tip faces will be sampled for each pile. The photo to the right shows the sampling procedure on the tip face.

Each rock type collected for the test piles, humidity cell tests and leaching column experiments will be further characterized to determine its composition, and potential to generate acidic drainage, using a minimum of 10 samples for each rock type. These samples will be analyzed by acid base accounting (ABA) using the Sobek technique (Sobek *et al.*, 1978). Acid base accounting is used to provide a preliminary assessment of whether a rock type will generate acidic drainage when exposed to weathering under natural conditions. The static test analyses will include paste pH, slurry pH (surface rinse pH), total S, SO_4^{-2} S, sulfide S, neutralization potential (NP), total C (LECO induction furnace), total extractable carbonate from evolved CO_2 (Barker and Chatten, 1982), and Net Acid Generation (NAG) testing. Previous studies have indicated that finely crushed rock exhibits greater neutralization potential than coarse-grained samples of the same material (Jambor, 2003). Acid-base accounting tests, using the Sobek technique will be conducted on various grain sizes of materials to assess the relationship between particle size and ABA measurements for the Type I and III rock. In addition to static test analyses, the elemental composition of the rock will be determined by whole-rock analysis. At the end of the experiment, the weathered rock will be re-examined for physical, chemical, and mineralogical characteristics.

The oxidation of sulfide minerals in mine waste is catalyzed by chemolithotrophic bacteria of the *Thiobacillus* and *Acidithiobacillus* groups. Although *Acidithiobacillus ferrooxidans* is a mesophile (growth occurs from 10 to 35°C), some isolates have been shown to be capable of growth and Fe oxidation at temperatures as low as 2°C (Leduc et al., 1993). These bacteria may play an important role in the oxidation of sulfide minerals at the Diavik site. Observations made in waste rock piles at the nearby Ekati Diamond Mine indicate that temperatures within the pile decreased rapidly to less than 0°C, and that low temperatures prevail for most of the year. The viability and activity of sulfide-oxidizing bacteria under these extreme conditions are not well known. To assess the behavior of bacteria in the test piles, samples of the test pile materials were collected during construction, and will be collected during the monitoring phase and at the end of the experimental period. Three groups of Fe- and S-oxidizing bacteria were enumerated at two different temperatures, 20°C and 4°C. The three groups consist of acidophilic iron oxidizing bacteria (*Acidithiobacillus ferrooxidans*), acidophilic S oxidizing bacteria (*Acidithiobacillus thiooxidans*) and neutrophilic S oxidizing bacteria (*Thiobacillus thioparus*). The media compositions, incubation conditions, and enumeration procedure are described in detail in Blowes et al. (1995). The samples analyzed at 20°C and at 4°C were incubated for one month and four months, respectively, prior to enumeration. If either Fe- or S-oxidizing bacteria capable of growth at 4°C can be isolated, they will be further characterized by both biochemical and molecular techniques. Bacterial populations were also enumerated for the humidity cell tests and column leaching experiments following the same procedures as above and will be re-examined at the end of the study.

The leachate from the test piles, humidity cell tests and leaching column experiments will be analysed for pH, Eh, electrical conductivity, total dissolved solids, acidity/alkalinity, SO_4^{-2}, major ions, and trace metals.

Results and Discussion

Thermal Transport Modeling

To aid in the design of the instrumentation system within the test piles, and to gain initial insight to the thermal evolution of the test piles, preliminary modeling was conducted using a modified version of the two-dimensional finite difference model SULFIDOX (Brown et al., 2001; Linklater et al., 2005). This model incorporates gas and water transport; kinetically controlled sulfide oxidation (and associated heat generation); heat transfer and ice formation and melting. Simulations were based on Type III material, as it is associated with the greatest potential for heat release and acid generation. The geometry used in the modeling is shown in Fig. 3.

Modeling suggests that six months after summer-time construction, the near-surface temperature of the waste rock pile will decrease rapidly in response to the onset of winter, however, the temperature in deep regions will decrease slowly. Heat is lost mainly due to conduction through the base of the pile (Fig. 4). Note that latent heat associated with freeze/thaw result in local temperature changes in the profiles that are shown. Figure 5 shows the simulated distribution of O_2 in the waste rock pile one year after construction for two different sulfide oxidation rates. For higher oxidation rates (10^{-8} kg O_2 $m^{-3}s^{-1}$), internal regions of the heap are depleted in O_2 because the rates of O_2 consumption exceed rates of O_2 replenishment. If oxidation rates are $<10^{-9}$ kg (O_2) $m^{-3}s^{-1}$, oxygen will remain at near ambient levels throughout waste rock pile. The modeling suggested that it might take three or four years for permafrost to develop in the core of the pile at the higher oxidation rate. Subsequently, any water movement in the summer months may be restricted to the outer surfaces of the pile, with minimal chemical loadings released at the base of the test pile except along its outer edge. Depths of oxidation at this time will be confined to within about two meters of the outer surface of the heap. Data from the extensive set of thermistors and gas sampling ports will determine the accuracy of this model.

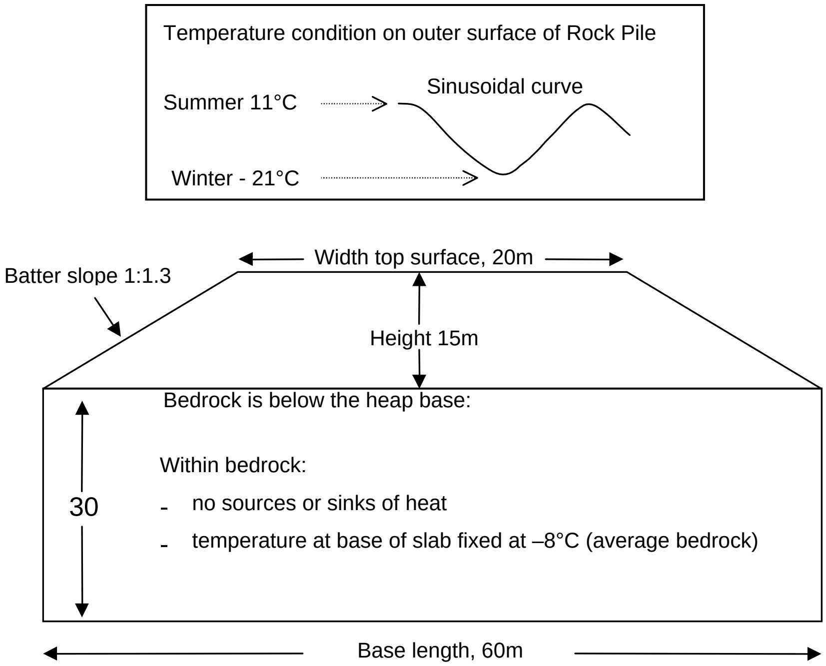

Figure 3. Schematic representation of the rock pile geometry used in the SULFIDOX model calculations.

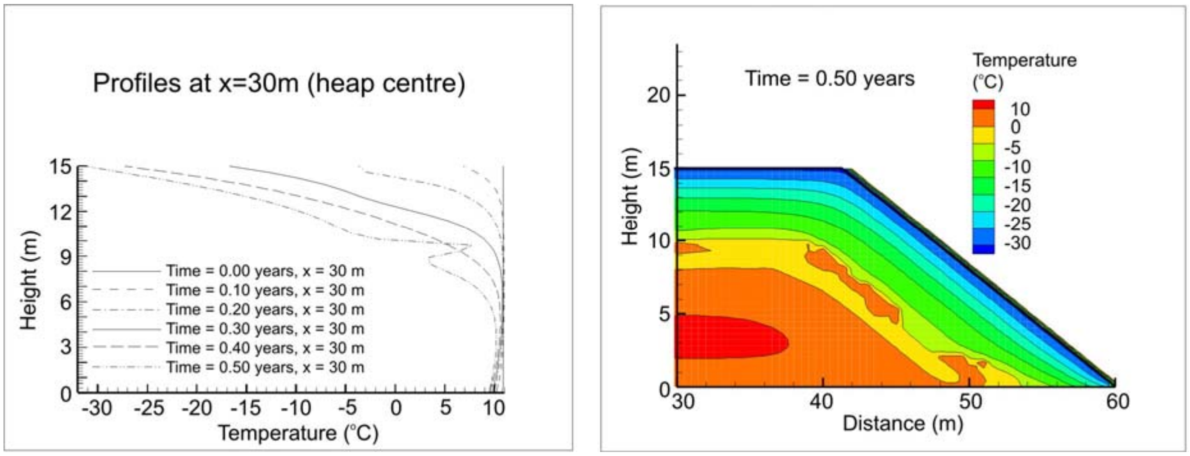

Figure 4. Simulated waste rock pile temperatures in the first six months, based on an oxidation rate of 10^{-9} kg (O_2) $m^{-3}s^{-1}$.

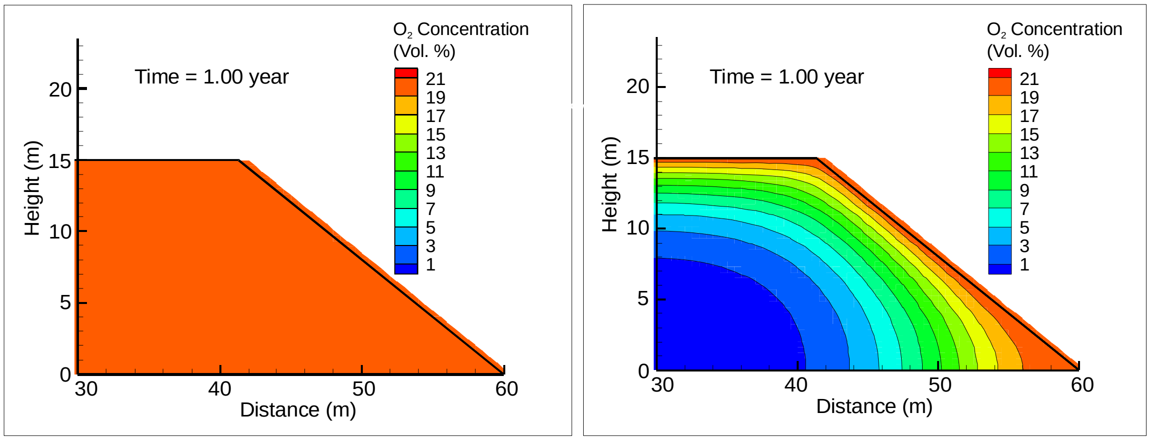

Figure 5. Simulated distribution of oxygen in the heap (1 year) for two different oxidation rates, 10^{-9} and 10^{-8} kg (O_2) $m^{-3}s^{-1}$, respectively.

Initial Construction of the Waste Rock Piles

Pad Construction. The construction of the foundations for the Type I and Type III rock piles was initiated in the spring of 2005. Dimensions for each pad were 50 m × 60 m, constructed from waste rock overlain by crushed kimberlite or esker sand for the Type I and Type III pads, respectively. Each pad was graded to a 2% slope for the collection of infiltrating meteoric water. To determine the temperature profile in the underlying bedrock, three boreholes were drilled vertically through each pad across the center to a depth of 10 m. Thermistor strings with sensors at 1 m intervals were installed into each borehole. In addition, thermistor strings were laid horizontally in trenches across the pad to record development of the active layer, in which freeze-thaw fluctuation occurs, along with the temperature variation beneath the pile during the changing seasons. A single 10 m borehole was drilled away from the test pads to record the background temperature of the bedrock. After the foundations of the test pads were graded to the design slope, an impermeable high density polyethylene (HDPE) liner was installed so that all water infiltrating to the base of the test pile would be captured, and isolated from the underlying esker sand or crushed kimberlite. For protection during pile construction, geotextile was placed over the HDPE liner followed by a 0.3 m layer of 2-inch minus crush composed of Type I rock (Fig. 6).

Basal Drainage System. Infiltrating water is collected from each test pad using 6-inch perforated PVC pipes that contains heat trace, which is regulated to between 2 °C and 5 °C to prevent the water from freezing. The Type I pad was constructed to allow water to collect diagonally along the center of the pad and discharge through the SW corner (Fig. 7). Water flow across the Type III pad is directed from the center of the pad to the perimeter, discharging through the NE and NW corners. Tipping bucket rain gauges will be used to maintain a continuous record of flow from the basal pad.

Figure 6. Photo to the left shows crushed rock being place over the impermeable liner of the Type I rock pad. Photo to the right shows the positions of the Type I pad (left) and Type III pad (right). The dimension of each pad is 50 m × 60 m. The L-shaped ramp adjacent to the test pads in the foreground will be used to tip rock onto the pads for construction of the waste rock piles. The arrow to the right of the photo is pointing North.

Figure 7. Photo to the left show the basal drainage ditch excavated diagonally across the center of the Type I pad exiting through the SW corner. Photo to the right shows the basal drainage ditches excavated around the perimeter of the Type III pad exiting though the NE and NW corners.

Cluster Lysimeter. Three clusters of different-sized basal lysimeters were placed at the base of the test pads to permit an examination of scale effects in flow variability and solute loadings. Each lysimeter cluster contains two 4 m × 4 m lysimeters and two 2 m × 2 m lysimeters (Fig. 8). The minimum height between the pad of the lysimeter and the top of the lysimeter wall is 0.8 m to prevent wicking effects. Each lysimeter is lined with an impermeable HDPE membrane that drains into a 1.5-inch PVC pipe housed in an insulated pipe. The bottom of each lysimeter pad and the 1.5-inch drainage pipe contains heat trace, which is regulated to between 2 °C and 5 °C to prevent ice buildup on the pad and blockage of the drainage pipes.

Figure 8. Photo to the left show three lysimeter clusters constructed over the Type III test pad. Loops of wire on the lysimeter pads are heat trace cable. The black 10-inch insulated pipe house the 1.5-inch drainage pipes exiting from each lysimeter. The photo to the right shows a completed cluster lysimeters with an impermeable HDPE liner.

Drainage pipes exiting each lysimeter are sloped across the rock pad through the SW corner of the Type I pad and the SE corner of the Type III pad and feed into a heated instrumentation shack located between the Type I and Type III pads (Fig. 9). The basal drain for the Type I pad also drains into the instrumentation shack. Inside the instrumentation shack, water discharging from the basal and cluster lysimeter drainage pipes flows into individual flow-through cells that continuously measure electrical conductivity. Water is then directed into tipping bucket rain gauges where discharge is continuously measured. Water from the tipping bucket rain gauges is then collected in individual sample containers for subsequent determination of the bulk geochemistry of the drainage from each lysimeter and basal drain. These samples will be analysed for pH, Eh, EC, TDS, acidity/alkalinity, sulfate, major ions, and trace metals.

Figure 9. Photo to the left shows cluster lysimeter drainage pipes directed into the instrumentation shack. The instrumentation shack is situated between the Type I and Type III rock pads. The photo to the right shows lysimeter drainage pipes entering the instrumentation shack.

Future Activities

Construction of the Type I and Type III rock piles will commence in the spring of 2006. During construction of the waste rock piles, material will be pushed or tipped outward from the top of the ramp (see Fig. 6, photo to the right) onto and across the Type I and Type III pads. Four tip faces will be instrumented with thermistors, soil suction lysimeters, gas sampling ports, TDR probes and access ports for thermo-conductivity profiling and microbiological sampling (Fig. 10 and Fig. 11). Preliminary work has pointed to the difficulty of placing instruments on a tip face because of the coarse nature of the waste rock at Diavik, and some mobilization of the rock forming the face during tipping. In addition to instrumentation on the tip faces, three continuously-draining collection lysimeters, each two meters in diameter, will be placed two meters below the top surface of each test pile, near the anticipated base of the active zone. We plan to deconstruct the Type III test pile in year four or five of this study, to permit internal sampling of waste rock and to observe the spatial characteristics of any ice formation that may develop within the pile.

Figure 10. Aerial view of waste rock pile showing locations of instrumentation along the tip faces (TDR = time domain reflectance probes and SWSS = soil water suction sampler).

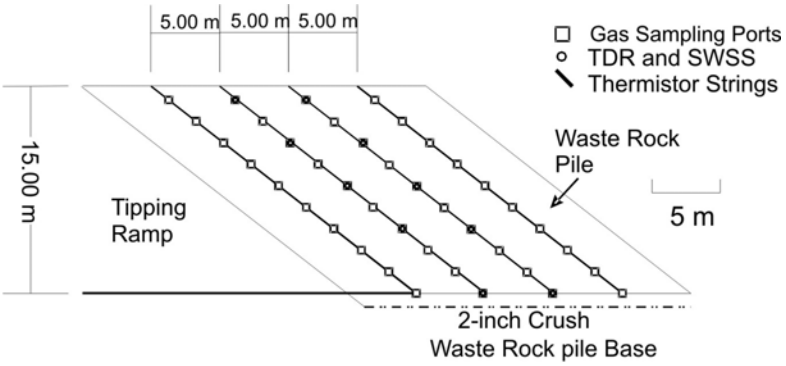

Figure 11. Cross-section of a waste rock pile showing the instrumentation along the tip faces (TDR = time domain reflectance probes and SWSS = soil water suction sampler).

Conclusion

The experiments described in this paper are designed to provide a rigorous examination of the hydrologic and thermal conditions inside the test piles and to document waste rock weathering observed in both laboratory and field settings. Samples will be subjected to detailed physical, chemical, mineralogical, and microbiological characterization before and after testing. Numerous field samples will be systematically collected for these analyses. During field tests, temperature, gas composition, and moisture conditions will be determined with a relatively high degree of spatial and temporal intensity. The reactions occurring will be reflected by (1) analysis of drainage collected at the base of the piles, and (2) analysis of weathered solids upon termination of the experiment. Thus, the reactants, reaction conditions, and reactions occurring in both the small-scale and field-scale tests will be described in detail. The test-pile instrumentation will also provide a detailed description of the spatial and temporal variation of hydrologic conditions within the piles, as well as insight on the distribution of drainage at the base.

The results from this study will quantify the release of acidity, metals, and other solutes from sulfide-bearing mine waste stockpiles in the Arctic environment. Our findings should promote more reliable evaluation of waste rock management systems. Scientific outputs from this project will include the development of a conceptual model of water flow in large, unsaturated piles; understanding the different physical mechanisms leading to cooling of large stockpiles in cold climates, including advective gas flow; a quantitative assessment of the value of small-scale measurements in providing information that can be used in predicting the physical and geochemical behaviour of full-scale sulfide-bearing stockpiles; and rigorous testing of the application of models of physico-chemical processes to full-scale systems by comparing the predictions with field data. The scale-up aspects of the program will contribute to the development of protocols based on a sound scientific understanding of scale relationships. Application of the conceptual models will allow more rigorous predictions of the behaviour of waste rock piles over time spans of many decades, which will be valuable in the assessment of the potential effects of climate change on system response.

Acknowledgements

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