Diavik Waste Rock Project: Objectives, Construction, Current Conclusions and Implications

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ABSTRACT
The Diavik Waste Rock Project was initiated in 2004 to study the physicochemical processes occurring at various scales in waste rock that can produce acid mine drainage (AMD). Companies and governments typically rely on laboratory humidity cell experiments to predict AMD potential from waste rock piles. However, these small-scale experiments cannot capture heterogeneities within the waste rock piles that influence the processes that cause AMD. The Diavik Waste Rock Project is a complementary laboratory and field research program to characterize physicochemical processes occurring in waste rock and compare effluent from a few kilograms of waste rock in laboratory experiments, 6 tonnes in 2 m scale experiments, 100,000 tonnes in each 15 m high experimental test pile, and >100 million tonnes in the operational waste rock pile. Characterizing the thermal and gas transport regimes, permafrost formation, and effluent chemistry and loadings will help refine the closure plan for the Diavik waste dumps to reduce the risk of discharging effluent that cannot be assimilated by the surrounding environment. Determining the scale-up effects from laboratory column experiments through operational dumps will help mining companies better predict the AMD-generating potential of full-scale waste rock piles.

Key Words: waste rock, acid mine drainage, research, closure planning

INTRODUCTION
Physicochemical processes that occur in waste rock piles that impact effluent water and produce acid mine drainage (AMD) include oxygen and thermal transport, geochemical reactions, and water flow. Mining companies and governments typically rely on laboratory humidity cell experiments to predict the generation of AMD from waste rock piles. However, these small-scale experiments cannot adequately capture heterogeneities within the waste rock piles that can influence AMD generation.

The Diavik Waste Rock Project is a multi-disciplinary, university-industry collaborative research project to investigate processes that affect AMD in low sulfur waste rock at various scales. The project consists of laboratory humidity cell experiments, 2 m scale field experiments, 15 m high, 100,000 tonne experimental waste rock piles ("test piles"), and instruments installed in boreholes in the >100 million tonne operational waste rock dump.

A series of papers have been submitted to this issue that describe the project: laboratory studies (Stanton *et al*. submitted); test pile hydrology (Fretz et al., submitted), gas transport (Amos et al., submitted), microbiology (Bailey et al., submitted a), and effluent geochemistry (Bailey et al., submitted b) from the test piles; and the mineralogy of cuttings (Hannam et al., submitted) and thermal modelling (Pham et al, submitted), from boreholes installed in the operational waste dump. This paper provides information on project objectives, test pile construction, and current conclusions and applications of the research to the Diavik diamond mine and the broader mining community.

Site description

Diavik Diamond Mine (Diavik) is an operating open pit and underground diamond mine in the Northwest Territories, Canada (Figure 1). The mine site is in the zone of continuous permafrost in the treeless "barren lands" of the Canadian Arctic. Winter persists from September through May with a mean annual air temperature (1998-2007) of -8.5 ºC. Maximum mean temperatures occur in July (18ºC) and minimum mean temperatures occur in January/February (-31ºC; Environment Canada 2011). A thin 1.5 to 5 m thawed layer develops in the ground surface in warm months. The area receives little precipitation, with an annual average (1999-2006) of 280 mm, 60% of which occurs as snow (Environment Canada 2011).

Figure 1: Location of Diavik Diamond Mine (Smith et al., 2011)

Diavik started production in 2003 and approximately 6 million carats of gem-quality diamonds are produced annually. The diamondiferous kimberlite ore bodies that are being mined are located underwater in the oligotrophic lake Lac de Gras. Two water-retaining dikes have been constructed into the lake to permit open pit mining of the three ore bodies, referred to as A154N, A154S and A418. All mine infrastructure, including waste rock and tailings storage facilities, is located on a 20 km^2 island within Lac de Gras (Figure 2).

Figure 2: Diavik Diamond Mine Site Map (2010) with Test Piles research area area encircled and locations of the drill holes in the operational waste dump (white dots)

Waste rock management

The country rock surrounding the ore bodies consists of Archean granite and pegmatite granite that is massive and moderately to coarsely crystalline. The granite contains metasedimentary biotite schist xenoliths and the region is cut by a series of Proterozoic diabase dikes. The granite and pegmatite granite contain only trace sulfides and are considered non-acid generating (NAG) with very low potential to leach metals during weathering. The diabase dikes contain trace sulfides but because of its very low abundance, the diabase is considered geochemically insignificant. The biotite schist contains locally disseminated pyrrhotite ($Fe_{1-x}S$) and other minor sulfides and is considered potentially acid generating (PAG). All rock types contain little carbonate minerals and the silicate mineral assemblage provides little neutralization potential.

Diavik segregates waste rock based on sulfur content rather than lithology because of the irregularity and range of sizes of the biotite schist xenoliths. The waste rock is segregated into Type I (<0.04 wt. %S), Type II (0.04-0.08 wt. %S), and Type III (> 0.08 wt.%S). Type I waste rock is comprised of granite, Type II waste rock is comprised of granite with some amount of biotite schist and Type III waste rock is comprised of granite with a greater amount of biotite schist. Type I waste rock is considered NAG, Type II waste rock is of uncertain acid generating potential and Type III waste rock is considered PAG due to the biotite schist (pyrrhotite) content. To date, waste segregation has been conservative which has resulted in sulfur concentrations for Type III waste rock lower than the operational target of 0.08 wt. %S.

Type I waste rock is used for construction materials on site with minor volumes stockpiled. Excess Type I, the little Type II waste rock produced (<5% per year) and the Type III waste rock are stockpiled in designated areas of the permanent waste rock dump. At the end of mine life the waste rock dump will be about 70 m high, cover up to 3.5 km^2 and will contain 120 Mt of waste rock. Up to 75% of the waste rock in the dump could be Type III.

PROJECT OBJECTIVES

The Diavik Waste Rock Project was initiated in 2004 and has objectives that are of interest to both academic researchers and industry. The research program was designed to answer discipline-specific questions, as well as questions that require input from multiple disciplines. Specific objectives of the ongoing research can be summarized by the following series of questions:

1. What mechanisms control the flow of water through an unsaturated, coarse grained waste rock pile where interior temperatures fall below the freezing point of water for a number of months each year? How much water can percolate downward within the active zone that forms each summer? How will flow mechanisms be modified should a permanent frozen core develop?
2. To what extent does the thermal state within the test piles control the observed variation in the rates of oxidation of sulfide minerals and the dissolution rates of carbonate and aluminosilicate minerals? What are the impacts of these processes on the drainage water quality?
3. What laboratory procedures and interpretation approaches are required to develop refined long-term estimates of the magnitude and timing of solute loads derived from waste rock piles?
4. In waste rock piles where interior temperatures fall below the freezing point of water, what role do microorganisms play in the biogeochemical evolution of water chemistry?
5. Can existing numerical models of flow and reactive transport in unsaturated porous media be modified to simulate the hydrologic and geochemical behaviour observed in the test piles under Arctic conditions?
6. How effective are a thermal blanket (Type I waste rock) and a lower permeability layer (a till layer beneath the thermal cover) in modifying hydrologic, thermal, and geochemical conditions inside a waste rock pile?
7. To what degree could inter-annual and decadal climate variations in northern Canada modify the hydrologic and geochemical behaviour of mine waste stockpiles, with consequent impacts on environmental loadings? How robust are current design concepts?
8. What strategies are needed to understand and describe the coupling of thermal and advective gas transport processes that are observed in the test piles?

DESIGN AND CONSTRUCTION SUMMARY

Laboratory experiments

The laboratory scale experiments consist of standardized static and kinetic testing of Type I, Type II and Type III Diavik waste rock. Static testing and waste rock characterization included paste pH, total sulfur, sulfate-sulfur, sulfide-sulfur, neutralization potential (NP), total carbon, net acid generation, whole-rock analysis, particle size distribution, mean surface area, and acid base accounting (ABA).

Kinetic testing consists of 36 humidity cells each containing about 1 kg of waste rock. Half of the cells are being tested at room temperature (22ºC) and the other half at 4ºC. At each temperature, tests include six cells of each Type I, Type II and Type III waste rock. Kinetic testing was initiated in 2005 and leachate continues to be analysed for pH, Eh, electrical conductivity (EC), alkalinity, anions, cations and nutrients.

Two cells at each temperature were inoculated with a bacterial consortium including *Acidithiobacillus ferrooxidans.* Bacterial population types were determined and enumerations of acidophilic iron oxidizing bacteria, acidophilic sulfur oxidizing bacteria and neutrophilic iron oxidizing bacteria were conducted using the most probable number technique.

Experimental waste rock piles

The test pile dimensions were based on results from preliminary thermal modelling that included gas and water transport, kinetically controlled sulfide oxidation, heat transfer, and ice formation (Blowes *et al.* 2006). Based on modelling results, the test pile dimensions were set to be 15 m high with four instrumentation planes at the angle of repose spaced 5 m apart to capture any potential $O_{2(g)}$ gradients and seasonal fluctuations in the temperature regime. The crest width was set to be 20 m wide to accommodate 240 t haul trucks.

Three test piles were constructed: a Type I run-of-mine test pile (Type I test pile), a Type III run-of-mine test pile (Type III test pile) and a Type III run-of-mine test pile that was re-sloped and covered with 1.5 m of till and 3 m of Type I run-of-mine waste rock (Covered test pile). The Covered test pile design was based on an approved closure concept for the Type III areas of the operational waste rock dump. The Type I and Type III test piles are approximately 15 m high with bases of 50 m × 60 m and the Covered test pile is approximately 15 m high with a base of 80 m × 120 m.

The foundations of each test pile consisted of run-of-mine waste rock overlain with sand-sized material to act as bedding for a high-density polyethylene (HDPE) geomembrane liner. The HDPE liner was installed to capture all water that infiltrates the test piles, and perforated drain lines were installed to collect and direct the water to design discharge points (Figure 3a). The liner bedding was graded to ensure the liner collected all infiltrating water and directed the water to the drain line and discharge points. The drain lines discharge to instrumentation trailers for geochemical and flow measurements. Within the instrumentation trailers, outflow from each drain line is directed to a series of flow-through cells including a geochemical sampling cell, a cell for continuous measurement of pH, a cell for continuous measurement of electrical conductivity (EC) and a tipping bucket for flow measurements (Figure 3b).

Crushed Type I waste rock was placed over the liner for protection during construction. Three clusters of basal collection lysimeters (BCL) were installed on this crush layer to permit the calculation and comparison of the flux-averaged solute loads and spatial variability in flow as part of the scale-up examination. Each BCL cluster consisted of two 4 m × 4 m boxes and two 2 m × 2 m boxes (each about 1 m high; Figure 3c). The BCLs were filled with run-of-mine waste rock for compositional and textural consistency with the bulk test pile (i.e., Type I waste rock for the Type I test pile and Type III waste rock for the Type III and Covered test piles). One of the BCL clusters was positioned beneath a batter and two clusters were positioned beneath the crest of each test pile. Each BCL box drains through a dedicated, heat traced drain line to an instrumentation trailer for the same geochemical and flow measurements as the basal drain. Run-of-mine rock was placed around the BCL clusters on the base of the pile for further protection during pile construction.

(a)

(b)

(c)

(d)

Figure 3: Key construction phases of the test piles: (a) impermeable liner with basal drain line directing flow to the bottom right corner; (b) flow-through cells and tipping buckets for sampling and measurements of basal drain and basal collection lysimeter effluent; (c) basal collection lysimeter clusters and drain lines; (d) instrumented tip face of one test pile (white protective PVC conduit visible). All figures from Smith *et al*. (2011).

The test piles were constructed by end-dumping and push-dumping methods with 100 t and 240 t haul trucks and a 70 t crawler dozer, the same methods and equipment used to construct the operational waste dump. Run-of-mine rock was dumped to the limits of each design instrumentation face. Samples for particle size distribution and sulfur content were collected from almost every load of waste rock delivered during construction of the test piles, as well as from each instrumentation face. At each angle-of-repose (37º) instrumentation face, a series of instruments was installed (Figure 3d). Instruments included:

- Gas sampling lines (typically ¼-inch low density polyethylene tubing) for measurement of internal test pile $O_{2(g)}$ and $CO_{2(g)}$ compositions;
- Thermistor strings for measuring the thermal evolution within the test piles;
- Access ports for thermal conductivity measurements (2-inch or 3-inch PVC pipe) using a linear heat source probe;
- Air permeability probes (perforated plastic balls and attached tubing for differential pressure measurements) to calculate internal pile permeability to air;
- Access ports for *in situ* microbiology microcosms (2-inch PVC well casing and screen intervals with nylon screen bags containing approximately 10 g of crushed pyrite) for characterization of microbiological populations and succession;
- Custom-made time-domain reflectometer (TDR) probes (after Nichol *et al*. 2002, 2003) for point measurements of volumetric water content; and
- Soil water suction samplers (SWSS) for discrete pore water samples.

The SWSS and TDR probes were aligned above the BCL to permit scale-up analysis of geochemistry and flow from point measurements to the 2 × 2 m scale, 4 m × 4 m scale and the 50 × 60 m scale (80 × 120 m for the Covered test pile) of the basal drain.

All instrument leads were installed within flexible PVC conduit for protection during construction. Excavators covered the instrument lines with 0.5 m of run-of-mine rock for protection before dumping resumed. The instrument leads were protected and buried below the crest to allow construction to proceed. When test pile construction was complete, the instrument leads were excavated and extended. Tensiometers were installed post-construction in the Type III and Covered test piles.

The Covered test pile outer batters were re-sloped to 18º and a 1.5 m thick till layer and a 3 m thick Type I waste rock cover were placed on the Type III core. Instruments were also installed within the till layer and

Type I cover. Additional instruments, including thermistors, SWSS, tensiometers and ECH_2O probes (Decagon brand; for moisture content measurement), were installed in drill holes in the Covered test pile in 2011.

In addition to the three large test piles, a series of three active zone lysimeters (AZLs) were constructed to monitor the flow and geochemistry of the active zone. Two tanks were filled with and surrounded by Type I waste rock (Type I AZL), two tanks were filled with and surrounded by Type III waste rock (Type III AZLs) and two tanks were filled with and surrounded by Type III waste rock that was capped with 1.5 m of till and 3 m of Type I run-of-mine (Covered AZLs), as per the Covered test pile configuration. The tanks are approximately 2 m in diameter and 2 m high with the tops of the tanks at the same elevation as the top of the test piles. The Type I and Type III AZL drain to an instrumentation trailer with discharge directed to a series of flow-through cells and a tipping bucket, as described for the basal drain and BCLs. The Covered AZLs were fitted with stand-pipe piezometers but to date the Covered AZLs have not produced any water.

Smith *et al*. (2009 and 2011) provide a comprehensive discussion of the test piles design and construction.

Instruments in the operational waste rock pile (full-scale)

Instruments have been installed in two horizontal lines at the base of a 40 m lift and within five vertical drill holes in the operational waste dump for measurements at an operational scale ("full-scale"). The horizontal instrument lines consist of gas sampling lines, air permeability probes, SWSS and thermistors.

Three boreholes, ranging from 32 m to 40 m depth, are clustered in one area of the dump. The fourth drill hole is located in a Type II area near the northern batter of the operational dump and is 40 m deep (Figure 2). The final drill hole is 80 m deep and is located in a Type III area of the waste dump over the low point of the original topography (i.e. the thickest part of the operational waste dump). These drill holes are instrumented with gas sampling lines, thermal conductivity and microbiology access ports, SWSS, thermistors, permeability probes, and ECH_2O probes. At depths greater than 12 m, the SWSS are dual-chamber SWSS (either PVC Soil Moisture brand or stainless steel Soil Measurement brand), appropriate for sample recovery at greater depths. The boreholes are backfilled with Type I crushed rock. During installation of the drill holes, cuttings were collected and are being analysed for mineralogy, and carbon and sulfur content.

CURRENT RESEARCH CONCLUSIONS

Data collection started in May 2007 and field data collection is on-going. Preliminary interpretations of the available data include:

- The Type I and Type III test piles are permeable to air (average permeability of 1.7×10^{-9} m^2) with wind induced gas transport enhancing oxygen transport (Amos *et al*. 2009). Oxygen concentrations remain near atmospheric levels and oxygen supply does not limit sulfide mineral oxidation;
- Type I test pile sulfur concentrations are low (0.035 wt.%S) and sulfide oxidation is balanced by acid neutralization (seepage remains circum-neutral);
- Type III test pile sulfur concentrations are low (0.058 wt.%S) but at levels where sulfide oxidation rates exceed acid neutralization rates. Type III test pile effluent pH fluctuates seasonally with near-neutral pH in the spring/early summer, dropping to pH ~4 towards the end of the summer;
- The uncovered test piles continue to freeze and thaw annually. A cooling trend from 2007 to 2009 was not continued in 2010;
- The till layer on the Covered test pile acts as a thermal blanket;
- Preliminary thermal conductive modelling for a warming climate (scenario similar to the A1B scenario of the International Panel on Climate Change) suggests that, within 100 years, an active

zone of 7 m will develop in an uncovered operational dump (at a location far from the batter) and an active zone of 3.9 m will develop in an operational dump with a 1.5 m till cover and a 3 m run-of-mine rock cover;

- Preliminary hydrology studies indicate infiltration and preferential flow is limited to high intensity rainfall events and flow to the test pile basal drains is dominated by batter flow;
- The Type I test pile has not attained hydrologic equilibrium;
- Acidophilic sulfur oxidizing bacteria were present in 2006, decreased in 2007 and 2008, and rebounded in 2009 in the Type III test pile;
- Neutrophilic sulfur oxidizing bacteria (*T. thiparus* and related species) were detected in effluent, and dominated the microbial populations in the Type I and Type III test pile effluent;
- Preliminary scale-up calculations from humidity cells to AZL-scale suggest scaling based on the surface area of exposed sulfur provides a better estimate of geochemical loadings than calculations based on mass of rock, surface area of rock, or mass of sulfur;
- The reactive transport code MIN3P (Mayer *et al.*,2002*)* used to simulate the geochemical evolution of the laboratory humidity cells may be an appropriate tool for simulating the geochemical evolution of the Diavik waste rock at larger scales; and
- Mineralogical analyses of drill cuttings of biotite schist (contained in Type III waste rock) identified marcasite (FeS_2) alteration rims on pyrrhotite grains, indicating sulfide mineral oxidation in waste rock stored subaerially at Diavik.

APPLICATION OF RESEARCH RESULTS TO DIAVIK AND THE MINING COMMUNITY

Construction of the test piles was completed in 2006 (for the Type I and Type III test piles) and 2007 (for the Covered test pile) and boreholes were installed in the operational dump in 2010 and 2011. Due to the low precipitation at Diavik, the test piles are only now beginning to achieve hydrologic equilibrium and produce results that can be interpreted with broader application. It will be several years before trends in data from the full-scale (operational waste dump) instruments will be identified.

Despite the long-term commitment required to obtain applicable data, the Diavik Waste Rock Project (laboratory, AZLs, test piles, and operational waste rock pile) will provide Diavik with reliable data that can be applied to closure planning for the operational waste rock dump. The data will provide Diavik with an opportunity to refine the closure concepts for the waste dump to reduce the risk of discharging effluent that cannot be assimilated by the surrounding environment.

Other mines in northern Canada and the Arctic in general will be able to use the results from the test piles and full-scale pile to better understand the environmental risk of low-sulfide waste rock stockpiles in areas of continuous permafrost. In particular, an appreciation of the rate and extent of permafrost formation and the effect of permafrost on stockpile hydrology, sulfide oxidation rates and drainage chemistry in cold climates, and effects of climate warming on stockpile permafrost stability will allow for more rigorous closure planning.

Understanding the scale-up effects by comparing data from the laboratory humidity cells (1 kg of waste rock) through 2 m scale AZL experiments (6 t of waste rock), 15 m scale test piles (100,000 t of waste rock) and the operational waste rock dump (>100 Mt of waste rock) will benefit mines world-wide in the pre-construction phase as well as those in operation. Notably, the benefits could include a more accurate prediction of long-term environmental geochemistry of waste rock based on small-scale, affordable, standardized laboratory experiments.

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