Diavik Waste Rock Project

Northern Aspects and Scaling Predictions

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Site Location

[Map showing the location of Diavik Diamond Mine and Yellowknife in Canada]
Introduction – Site location
Diavik Waste Rock Project

Research Goals – Diavik Waste Rock Project

• Understand the geochemical, hydrological, and thermal conditions controlling the generation of acidic leachate from waste rock stockpiles in a permafrost environment.

• Determine the value of small-scale laboratory tests for predicting if and when low quality drainage may be released from a stockpile.
**Diavik Waste Rock Project**

**Introduction – Test piles background**

- Waste rock type/management

<table>
<thead>
<tr>
<th>Type</th>
<th>S Content (wt. %)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>&lt; 0.04</td>
<td>Predominantly granites</td>
</tr>
<tr>
<td></td>
<td>wt. % S</td>
<td></td>
</tr>
<tr>
<td>Type II</td>
<td>0.04 – 0.08</td>
<td>Predominantly granites with small amount of biotite schist</td>
</tr>
<tr>
<td></td>
<td>wt. % S</td>
<td></td>
</tr>
<tr>
<td>Type III</td>
<td>&gt;0.08</td>
<td>Predominantly granites with greater amount of biotite schist</td>
</tr>
<tr>
<td></td>
<td>wt. % S</td>
<td></td>
</tr>
</tbody>
</table>
Research Facilities

- Laboratory humidity cell experiments
  - 18 Cold room
  - 18 Room Temperature
- 2 m-scale active zone experiments
  - 2 Type I (low sulfide)
  - 2 Type III (higher sulfide)
- Test-scale waste rock piles
  - Type I (low sulfide)
  - Type III (higher sulfide)
  - Covered (Type III core with till and Type I cover)
- Instrumented full-scale waste rock dump
  - 4 x 40 m vertical drill holes
  - 1 x 80 m vertical drill hole
  - Horizontal instrument lines
Test Piles Research Area

Type I Test Pile
0.035 wt.% S

Type III Test Pile
0.053 wt.% S

Active Zone Lysimeters

Covered Test Pile
3 m Type I
1.5 m Till
13 m Type III
0.082 wt.% S
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- Permeability
- Hydrology
- Gas
- Thermal
- Data
- Pore water
- Microbiology
- Lysimeters
- Upper lysimeters
- Sampling station
- Effluent
Full-scale Instrumentation

- 3 drill holes
  - 32, 31 and 40 m deep
- 80 m drill hole
- 40 m drill hole
- Horizontal Installation
  - 120 m and 280 m

- Thermistors, Gas sampling lines, Thermal conductivity, Microbiology, SWSS, Permeability, $\text{ECH}_2\text{O}$ probes,
- Cuttings collected
  - Mineralogy, Sulfur and Carbon analysis
Journal Publications

- **Applied Geochemistry (2012)**

Conference Presentations and Proceedings

- **Tailing and Mine Waste (November 6-9, 2011, Vancouver)**
  - Pham et al., Diavik Waste Rock Project: Thermal transport in a covered waste rock test pile.
  - Smith et al., Diavik Waste Rock Project: Characterization of Particle Size, Sulfur Content and Acid Generating Potential.

- **2012 ICARD (May 20-26, 2012, Ottawa, ON, Canada.)**
  - Bailey et al., Diavik Waste Rock Project: Geochemistry of low sulfide content large-scale waste rock piles.
  - Bailey et al., Diavik Waste Rock Project: Microbiological succession in waste rock piles.
  - Pham et al., Diavik Waste Rock Project: Heat transport and the effects of climate change in a waste rock pile located in a continuous permafrost region of Northern Canada.
  - Smith et al., Diavik Waste Rock Project: Objectives, implications and current conclusions.
  - Stanton et al., Diavik Waste Rock Project: Laboratory studies.
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Research Highlights

Hydrology
TDR Locations – Type III Test Pile

- TDR sensors installed below crown of test pile
- Ambient air temperature restricts infiltration and water movement in the test pile.
- The portion of the test pile that contributes to outflow changes with the generation of the active-zone.
Wet-Up of Matrix Fraction (Type III Test Pile)

Green = 1m  Blue = 3m  Pink = 5m  Red = 9m

Wetting front reaches 3 m depth
Wetting front reaches at least 7 m depth, but not 9 m
Concurrent arrival of thaw front and wetting front at 9 m depth

Basal collection lysimeters at the base of the test pile recorded outflow starting in September of 2008.
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Annual Outflow Response (Type III Test Pile)

**Total Rainfall:**
- 2007: 92 mm (55% of Avg)
- 2008: 154 mm (92% of Avg)
- 2009: 74 mm (44% of Avg)
- 2010: 98 mm (58% of Avg)
- 2011: 146 mm (87% of Avg)

**Total Outflow:**
- 2007: 110 m³
- 2008: 150 m³
- 2009: 117 m³
- 2010: 213 m³
- 2011: 176 m³
Annual Outflow Response (Test Pile)

- Variations in the timing and magnitude of outflow over multiple years are a function of:
  - Timing of active-zone generation
  - Snow accumulation and melt
  - Timing and magnitude of rainfall events
  - Antecedent moisture contents and wetting front locations held in storage over the previous winter

- TDR, basal collection lysimeter, and basal drain response indicate that, in terms of outflow volumes, the test piles are batter dominated systems.
  - 100%, 84%, 94%, 97%, and 72% of total outflow in 2007, 2008, 2009, 2010, and 2011, respectively
Methods for estimating net infiltration

1. Water balance at the AZLs to back-out net infiltration

\[
\text{Net Infiltration} = \text{Rainfall} - \text{Evaporation} = \text{AZL Annual Outflow}
\]

2. FAO-Model to estimate evaporation

FAO Penman-Monteith formulation

\[
\text{ET}_0 = \text{reference evapotranspiration} = 0.408 \Delta (R_n - G) + \gamma (37/(T_{hr} + 273))u_2(e^o(T_{hr}) - e_a) \\
\Delta + \gamma (1 + 0.34u_2)
\]

Coefficient to determine actual evaporation

\[
E = K_e \text{ET}_0 K_f \\
E = \text{actual evaporation}
\]

\[
K_e = \text{soil evap. coefficient} \\
K_f = \text{frozen soil coefficient}
\]

Net infiltration = Rainfall – Actual Evaporation
## FAO-Model results

<table>
<thead>
<tr>
<th>Year</th>
<th>AZL with Min %NI</th>
<th>AZL with Max %NI</th>
<th>FAO Calculation</th>
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</thead>
<tbody>
<tr>
<td>2008</td>
<td>35%</td>
<td>54%</td>
<td>46%</td>
</tr>
<tr>
<td>2009</td>
<td>8%</td>
<td>15%</td>
<td>10%</td>
</tr>
<tr>
<td>2010</td>
<td>38%</td>
<td>43%</td>
<td>29%</td>
</tr>
<tr>
<td>Year</td>
<td>Test Pile</td>
<td>Rainfall (mm)</td>
<td>FAO % Net Infiltration</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>2007</td>
<td>Type I</td>
<td>92</td>
<td>31%</td>
</tr>
<tr>
<td>2007</td>
<td>Type III</td>
<td>153</td>
<td>48%</td>
</tr>
</tbody>
</table>
Research Highlights

Thermal Regime
Covered test pile: Cross section A-A and Profile

Thermistor location
Results: Active layer thickness

- The active layer stays within the 2 m thick Type I waste rock cover above the till.
- At the top of the till layer temperatures varied between 0 °C and -12.2 °C.
- At the base of the till temperatures varied between 0 °C and -8.2 °C.
- Underlying Type III waste rock remains colder than 0°C year round.
Results: Net radiation and heat fluxes

- **Net radiation**
  - Maximum value: 96.5 W m\(^{-2}\) in July
  - Minimum value: -69.7 W m\(^{-2}\) in mid Dec.
  - \(R_n (\text{W m}^{-2}) = 13.4 + 83.1 \sin(2\pi t/365 - 1.30)\)

- **Ground surface heat flux:**
  - Maximum: 20.4 W m\(^{-2}\) in July
  - Minimum: -28.6 W m\(^{-2}\) in mid Dec.
  - The fitting curve: \(G = -4.1 + 24.5 \sin(2\pi t/365 - 1.35)\)

- The mean annual heat flux across the bottom of the till: -1.78 W m\(^{-2}\) which is 43 % of mean annual surface heat flux

- Negative heat flux through the till means that heat is removed from the underlying Type III waste rock
Full-Scale Thermal Regime

- 3 drill holes
  - 32, 31 and 40 m deep
Results: Ground temperatures

- Initial 0°C isotherms are at about 11 m below the surface.

- Initial depth affected by the drilling processes and temperature disturbances at the drill holes.

- The temperatures at the drill hole locations are usually warmer than undisturbed ground temperatures.
Results: Simulation

- Two cases:
  - Case 1: 1-D heat conduction:
  - Case 2: 1-D heat conduction with 1.5-m till and 3-m Type I rock.

- Boundary conditions are no flux at the base and surface temperature.

- Surface temperature

\[
T_s = -6.3 + 20.3 \sin \left( \frac{2\pi t}{365} \right) + \frac{0.056t}{365}
\]

- Warming rate of surface temperature is 5.6°C over 100 years.
Results: Simulation (Case 1 – Uncovered)

- Active layer thickness dynamically changes with time and is at 7m after 100 years due to the warming climate.
- It reaches its minimum value of 4 m in 2020 and then increases steadily to 7 m in 2110.
- Maximum ground temperatures at 4m and 7m reach 0°C in 2040 and 2110 respectively.
- Below 20m, ground temperatures show no annual variations and the changes are due to warming climate.
- At greater depths, the impacts of warming climate come later.
Results: Simulation (Case 2 – Covered Pile)

- Active layer is at 3m (top of the till) for the period between 2020 and 2040, however, its thickness increases to 3.9m (within till layer) in 2110.

- Maximum ground temperature at 3m (top of the till) is above 0°C after 2040 due to warming climate.

- Ground temperatures below 20 m are similar to the case 1
Results: Simulation (Case 2 – Covered Pile)

- Trumpet curve of ground temperatures of the waste dump indicates:
  - Active layer is at 3.9 m depth which is 0.9 m into the till
  - Without warming climate, the active layer will be contained within the Type I rock.
  - The Type III rock below the till stay below 0°C (about -2.5°C) under the proposed climate change.
Research Highlights

Geochemistry
Uncovered Test Pile Geochemistry

- **pH**: 4, 5, 6, 7, 8
- **Alkalinity (mg/L CaCO3)**: 0, 20, 40, 60, 80
- **SO4²⁻ (mg/L)**: 0, 1000, 2000, 3000

<table>
<thead>
<tr>
<th>Year</th>
<th>1Bxxd13</th>
<th>3BSxxd15</th>
<th>3BNxxd15</th>
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<tr>
<td>2007</td>
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<tr>
<td>2011</td>
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<td></td>
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</tr>
<tr>
<td>2012</td>
<td></td>
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</table>
Uncovered Test Pile Geochemistry

Ni (mg/L)

Co (mg/L)

Fe (mg/L)

2007 2008 2009 2010 2011 2012
Uncovered Test Pile Geochemistry

Cu (mg/L)

Zn (mg/L)

Cd (mg/L)

2007 2008 2009 2010 2011 2012

1Bxxdrrn13
3BSxdrn15
3BNxdrn15

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Covered Test Pile Geochemistry

- **pH**
  - pH values range from 4 to 7.

- **Alkalinity (mg/L CaCO3)**
  - Alkalinity values range from 0 to 25 mg/L CaCO3.

- **SO₄²⁻ (mg/L)**
  - SO₄²⁻ concentrations range from 0 to 5000 mg/L.

Data points for the years 2007 to 2012 are plotted.
Covered Test Pile Geochemistry

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Ni (mg/L)

Co (mg/L)

Fe (mg/L)

2007 2008 2009 2010 2011 2012

CBxdrn13
Sulfide Mineral Weathering: Full-Scale Dump

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Sulfide Mineral Weathering: Full-Scale Dump
Sulfide Mineral Weathering: Full-Scale Dump

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Research Highlights

Scale-up
Scale-up Calculations

- Reactive transport modelling of humidity cell experiments
  - Develop robust conceptual model of sulfide mineral oxidation and geochemistry to be applied to larger scales
  - Calibrate model to sulfide content, mineral surface area and temperature effects
  - Only measurable parameters adjusted in input files
  - Additional calibrations underway
Scale-up Estimates

- Concentration calculations based on:
  - Reaction rates from humidity cell experiments
  - Rates scaled to weathering age of rock
  - Estimated residence time
- Estimates normalized to
  - Mass of rock
  - Mass of solid phase sulfur
  - Estimated surface area of solid phase sulfur
- No temperature correction
- Simple residence time estimate
Concentration Estimates
Type III Upper Collection Lysimeters - Nickel

- Estimated by Kg Rock
- Estimated by Kg Sulfur
- Estimated by Surface Area Sulfur
- Type III West UCL
- Type III East UCL

Date:
- 28/Apr/2007
- 14/Nov/2007
- 01/Jun/2008
- 18/Dec/2008
Concentration Estimates
Type III Upper Collection Lysimeters - Iron

Probable Solubility Control
Supersaturated with respect to Goethite

Date
Thank You!

Questions?