Voisey’s Bay Nickel Mine:  
A unique approach to mine rock management in the 1990s with a follow-up assessment in 2017

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W.A. Napier  
*Argonaut Gold*
The Players

• INCO acquire Voisey’ Bay deposit in 1996 for $4.3B

• INCO’s Voisey’s Bay Nickel Company (VBNC)

• Vale acquires INCO in 2006 and operates the Voisey’s Bay mine
The Context

• Discovery of 32 Mt Ovoid Massive Sulphide Ni-Cu deposit
• Identification of significant underground resource
• EIS completed between 1996 – 1999 with a Mine Rock Management plan
  – Using PAG identification of 0.2%S or greater
• Project on hold for due to incomplete negotiation with stakeholders
• Negotiations with stakeholders on necessary agreements concluded in 2002
• Started Mining the Ovoid (open pit) in 2005
  • 0.2%S used in start of operation from 2005 to present
• 2016 Plans expansion to mine underground
• Request from regulator to review mine rock management criteria and plans
The EIS (1996-99)

- Recognized early that this deposit is sulphide rich and appropriate waste rock management will be required

- Need to identify:
  - non-reactive mine rock that can safely be deposited on-land, and;
  - potentially reactive mine rock that should be stored underwater as a mitigative measure

- All tailings to be stored underwater (PAG)
Precautionary Principle

- Adopted a precautionary principle regarding PAG rock:

  Assume all mine rock is potentially reactive until proven otherwise
1996-1997 Test Program

- Extensive analyses and testing provided confidence
- Static Tests - more than 500 analyses for:
  - Metal Content
  - Acid Base Accounting (ABA-includes Sulphur)
- Kinetic tests (assess reactivity)
  - 22 Humidity Cells / 18 Column tests
  - 58 Oxygen Consumption Measurements
Mine Rock Investigation
Flow Chart

Phase I

Chemical and Mineralogical Characterization

Ovoid
Western Extension
Overburden

No Sulphide

Phase II

Kinetic Tests

Underground
Open Pit

Reactive
Not Reactive

Underwater
On Land
Summary of Key Results (1997 EIS)

- Relatively simple geology with two main types of mine rock that are easy to recognize
  - Low-Sulphur “Gneiss” (light colored)
  - Sulphur-bearing “Intrusive” (dark colored)

- Sulphur content is the KEY indicator of available metals and of reactivity
Frequency Analysis of Sulphur in Gneiss

Number of Gneiss Samples

Sulphur %

B.C. ARD Cutoff
Frequency Analysis of Sulphur in Intrusive Rock

Number of Intrusive Samples

Sulphur %

B.C. ARD Cutoff
NP/AP Ratio vs. Total Sulphur in Gneiss

Voisey’s Bay Proposed Cutoff

B.C. ARD Cutoff (Price, 1997)

NA/AP Ratio = 1
Conclusions of 1997 Study

• Overburden is non-reactive

• **Intrusive** rock is assumed to be reactive and all will be placed underwater

• The non-reactive **Gneiss** represents more than 90% of the mine rock from the open pit that can be safely deposited on-land
Conclusions of 1997 Study (cont.)

• Results show that a **0.2% sulphur content** is a conservative cut-off value to separate reactive and non-reactive mine rock.

• Segregation procedures and protocols based on sulphur content are practical and achievable during mining.
Recommendations of 1997 Study

- Humidity cells and columns continuing
- Underwater testing of:
  - Mine Rock
  - Tailings
  - Potential surface barriers
Current Operating Parameters

- Use of 0.2%S to identify non-PAG
- Assays blast holes and classify material prior to blasting
- Define non-PAG allowing 5 m buffer from 0.2%S zones
- All PAG material is placed sub-aqueously for final storage
- Non-PAG material to the CRD pile adjacent to the pit
- Approximately 10 Mt of non-PAG rock with an average of 0.06 %S in 2017
2016 Review of Mine Rock Management

- Development Plan for underground expansion submitted in 2015
- Request from regulator to review mine rock management criteria and plans
The 2016 Review

• Original document by BEAK (1997) and follow up studies
• Reviewed in the context of more recent guidance (Price, 2009; GARD Guide, 2009) and EXPERIENCE since 1997

• Found criteria of 0.2% is reasonable
• Questioned “effectiveness” of NP (Sobek) used in the assessment
• Suggested additional assessment of “effective” NP
The 2016 Review

• Sobek and Carbonate NP values available in the database

• New samples collected and characterized

• Effective NP assessed in the lab
Neutralization Potential Ratio (NPR)

- Effective NP likely between Sobek and Carbonate values
## NP Concepts Overview

<table>
<thead>
<tr>
<th>NP Method</th>
<th>Method Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sobek-NP</td>
<td>• Excess HCl addition (down to pH &lt; 2.0), digestion &amp; back-titration with NaOH to pH 8.3</td>
</tr>
<tr>
<td></td>
<td>• Includes carbonates &amp; other potential buffers &quot;outside&quot; relevant environmental of pH &lt; 6.0 (e.g. aluminosilicates); <em>typically overestimate</em></td>
</tr>
<tr>
<td>Carbonate-NP</td>
<td>• Based on Inorganic Carbon analysis (as % CO$_2$) converted to (%CO$_3$) &amp; Carbonate-NP; <em>typically conservative</em></td>
</tr>
<tr>
<td>Assessing</td>
<td>Operationally, “readily available” NP able to maintain pH~ 6.0</td>
</tr>
<tr>
<td>“Effective-NP”</td>
<td>• Bracket an Eff-NP using two approaches</td>
</tr>
<tr>
<td></td>
<td>(1) Titrations with Acid</td>
</tr>
<tr>
<td></td>
<td>(2) Batch Phased Acid Additions</td>
</tr>
</tbody>
</table>
Recommendations from 2016 Review

- Asses effective NP “available” to maintain pH of 6.0 or greater
- Reassess cut-off criteria based on effective NP
- Test program initiated in 2016, using core samples and rock from open pit
Results 1: Titration-Effective NP

- Rates very slow – not practical to define an Eff-NP
- At 1200 h, sporadic pH increases occur (pH >6.0)
- Enderbite Titration NP at less than 15% Sobek-NP
## Results 1: Titration-Effective NP

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>ABA Analysis</th>
<th>Titration Experiments</th>
<th>Titration Experiments</th>
<th>Total Experiment Time</th>
<th>pH Status From Last Acid Addition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carb-NP</td>
<td>Sobek NP (kg CaCO₃/t)</td>
<td>Titration Effective NP</td>
<td>*pH From Last Acid Addition</td>
<td>Last pH Reading</td>
</tr>
<tr>
<td></td>
<td>kg CaCO₃/t</td>
<td>%</td>
<td></td>
<td>Days</td>
<td></td>
</tr>
</tbody>
</table>

| Enderbite   | 0.4          | 15                    | 2.0                   | 14                    | 5.74                            | 6.26 |
| Enderbite   | 0.6          | 15                    | 1.7                   | 12                    | 5.74                            | 6.00 |
| Enderbite   | 0.8          | 17                    | 1.5                   | 9                     | 5.70                            | 6.30 |
| Enderbite   | 1.3          | 15                    | 3.5                   | 23                    | 5.78                            | 6.44 |
| Paragneiss  | 1            | 6.3                   | 2.2                   | 35                    | 5.86                            | 6.18 |
| Paragneiss  | 4.3          | 8.8                   | 1.5                   | 17                    | 5.80                            | 6.25 |
| Paragneiss  | 0.5          | 7.9                   | 3.3                   | 41                    | 5.85                            | 6.30 |
| Troctolite  | 0.4          | 24                    | 3.1                   | 13                    | 5.83                            | 6.26 |
| Troctolite  | 2            | 25                    | 1.9                   | 8                     | 5.76                            | 5.89 |
| Troctolite  | 2.6          | 22                    | 3.2                   | 15                    | 5.78                            | 6.26 |
| Troctolite  | 0.8          | 29                    | 2.7                   | 9                     | 5.85                            | 6.11 |

*Last acid addition done within the last 400 hours (17 days)
Results 2: BPAA-Effective NP

- 2 phase Bulk Acid Additions
- Only able to recover (pH > 6.0) from 1\textsuperscript{st} bulk acid addition; plateaued (pH < 6) after 800H
- \textit{Enderbite} pH vs. Time sample plot
# Results 2: BPAA Eff-NP

- Batch Phased Acid Eff-NP (as % Sobek-NP)

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Sample Location</th>
<th>ABA Analysis</th>
<th>1st Phase Batch Acid Addition</th>
<th>2nd Phase Batch Acid Addition</th>
<th>Terminal pH (Within approx. last 200 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Carb-NP</td>
<td>Sobek-NP</td>
<td>BPAA - ENP</td>
<td>Recovered to pH&gt;6?</td>
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<tr>
<td></td>
<td></td>
<td>kg CaCO₃/t</td>
<td>kg CaCO₃/t</td>
<td>%</td>
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<tr>
<td>ENDERBITE</td>
<td>SE Extension</td>
<td>0.4</td>
<td>15</td>
<td>4.8</td>
<td>32</td>
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<tr>
<td></td>
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<td>0.6</td>
<td>15</td>
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<td>4.8</td>
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<tr>
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<td>RB Ramp</td>
<td>0.8</td>
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<tr>
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<td>1.3</td>
<td>14</td>
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<td>ED Conveyor</td>
<td>0.8</td>
<td>17</td>
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<tr>
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<td>2.0</td>
<td>17</td>
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<tr>
<td>PARAGNEISS</td>
<td>RB Ramp Churchill Province</td>
<td>4.3</td>
<td>9</td>
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<td>TROCTOLITE</td>
<td>Reid Brook</td>
<td>1.6</td>
<td>43</td>
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<td>1.9</td>
<td>25</td>
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Batch Acid Titrations - Paragneiss

- Batch acid addition of a portion of the Sobek-NP – 6 Paragneiss Tests

![Graph showing NP (Kg CaCO3/tonne) for different tests. The graph is labeled "PARAGNEISS: NP." It shows bars for Sobek-NP, Carb-NP, and Effective-NP for tests 1 to 6.]
Sobek-NP to Effective-NP

• Enderbite
  – 30% of Sobek-NP is effective
• Paragneiss
  – 30% of Sobek-NP is effective
• Troctolite
  – 20% of Sobek-NP is effective

• Further investigations can use Sobek-NP to estimate Effective-NP
Neutralization Potential Ratios

![Graph showing neutralization potential ratios based on total sulphur percentage. The graph compares Non-PAG, PAG, and Uncertain categories with different markers for Sobek-NPR, Carb-NPR, and Effective-NPR. The x-axis represents total sulphur percentage, ranging from 0.001 to 1, while the y-axis represents NPR, ranging from 0.001 to 100. The graph includes a vertical line at 0.1% sulphur concentration.]
Effective-NPR and Sulphur

- **PAG**: $S > 0.2$
- **Uncertain**: $0.1% > S > 0.2$
- **Non-PAG**: $S < 0.1$

![Graph](image-url)
Mine Rock Management Conclusions

• Total sulphur content used as a standalone predictor of ARD

• The sulphur content of 0.2% S appears reasonable based on effective NP

• A 0.1%S value to identify PAG and non-PAG materials will be more conservative

• Carbonate content not a reliable predictor of Effective-NP at Voisey’s Bay

• Should assess metal leaching characteristics to confirm low risk for rock with less than 0.1%S
The Work Continues

- Field investigation in progress to evaluate the behaviour of the non-PAG rock in the CRD

- Confirmation of S criterion and investigation of metal leaching within the field “kinetic test cell”