Mitigation Plans for Mining in Highly Burst-Prone Ground Conditions at Vale’s Copper Cliff Mine

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Outline

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• Geology
• In-situ stress and rock mass classifications
• Description of occurrence and mechanism of 3.8 Mn seismic events/rock bursts
• Main causes for the damage
• Mitigation strategies to control future seismic risks:
  ➢ Dynamic support requirements
  ➢ Mine design and planning measures
  ➢ Adequate re-entry protocol (beyond this paper)
• Performance of dynamic support system – a case study
• Conclusions and acknowledgments
Introduction:
Location of Copper Cliff Mine

- The mine is located within the Copper Cliff Offset. The Offset extends about 8 kilometers south from the Sudbury Igneous Complex into the footwall rocks.
- Mining commenced in 1960s.
- Approximately 54 million tons of ore has been mined from both surface and underground operations up to the end of 2011.
Ore bodies that are currently being mined
Geology

- The ore deposits predominantly occur within the quartz diorite dyke.
- The country rocks are granite and metavolcanic rocks.
- There are number of ore bodies being mined currently, but this presentation includes only 100 and 900 ore bodies.
- Major structures include: 900 cross fault (striking east-west dipping at 55 degrees North), Trap Dykes (located between 100 and 900 ob striking east-west and dipping steeply towards north), and Olivine Diabase Dyke (striking NW-SE and dipping 80 degrees North).
Major structures - 100/900 ore bodies

- Olivine Diabase Dyke
- 900 X-Fault
- Trap Dyke
- Crown blasted in the 94561 Stope (3050-3200 L) on Sep 11, 2008
In-situ Stress and Rock Mass Classifications

\[ \sigma_1 = 10.828 + 0.041 \times Z \quad 90^0/0^0 \]
\[ \sigma_2 = 8.690 + 0.033 \times Z \quad 0^0/0^0 \]
\[ \sigma_3 = 0.029 \times Z \quad 0^0/90^0 \]

Where Z = depth (meter)

Note: The major principal stress is sub-perpendicular to the strike of 100/900 orebodies.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Q’</th>
<th>UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz Diorite</td>
<td>8 to 12</td>
<td>150</td>
</tr>
<tr>
<td>(ore equivalent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trap Dyke</td>
<td>12 to 17</td>
<td>240</td>
</tr>
</tbody>
</table>
Occurrence and mechanism of 3.8 Mn seismic events/rock bursts

- On September 11, 2008, a crown blast (~14,000 lbs of explosive) was taken in 94561 stope (between 3050 and 3200 L in upper 100 ob).
- Soon after the blast, a series of magnitude events (about 10 events) ranging from 1.2 to 3.8 (Nuttli) were felt within half an hour.
- These magnitude events resulted in 2500 tons of material displaced between 2700 and 3710 L.
- North mine central blast practice prohibits miners underground during any production blasts.
Occurrence and mechanism of 3.8 Mn seismic events/rock bursts (continued)

All external consultants concluded:

- This is a fault-slip induced rock mass shearing.
- This shear movement could occur along the well known active geological structures, including the trap dykes contained in the waste pillar between the 100 and 900 and/or the 900 cross fault.
- Other factors: diminishing pillars (both vertically and laterally).
Occurrence and mechanism of 3.8 Mn seismic events/rock bursts (continued)

- Ground support was relatively light and the support system (i.e. a mix of resin rebars and mechanical bolts) had limited energy absorption and holding capacity.
- Wall support was not extended low enough.
- Damage increased with proximity to the major geological structures, especially the Trap Dyke.
- At some locations, the pillar size (between excavations) was relatively small.
Mitigation strategies to control future seismic risks:

A combination of the following can be implemented to significantly reduce future seismic risks:

- Application of advanced dynamic ground support system,
- Sound strategic mine design and planning, and
- Adequate re-entry protocol after blast and/or major seismic events (beyond the scope of this presentation).
Mitigation strategies to control future seismic risks:

After any major seismic events, mine operators face a few critical questions, which need immediate attention.

Questions include:

- Q1: what types of enhanced support are required for areas, which suffered damage in order to withstand future seismic risks?

- Q2: based on the mechanism of seismic events identified, which areas are likely to be burst prone in the future?

- Q3 (similar to Q1): for future burst-prone areas, what types of dynamic / enhanced support are required?
Mitigation strategies to control future seismic risks – dynamic support requirements:

Q1 - What types of enhanced / burst resistant support are required?
A five-step methodology is developed as follows:

- The first step: to select the site where the most severe damage occurred.
- The second step: to determine the ground motion level in terms of PPV (Kaiser et al, 1996)
- The third step: to calculate the total kinetic energy of any ejected blocks of rock, i.e. the demand on the support. The total energy can be determined (Kaiser et al, 1996): $E_t = \frac{1}{2} m v_e^2 + q m g d$
  Where $d$ = back movement, measured by MPBX
- The fourth step: to determine the energy absorption capacity provided by supports (Kaiser et al, 1996)
- The fifth step: to ensure $FOS = \frac{\text{Support capacity (from step four)}}{\text{Demand (from step three)}}$ is between 1.3 and 1.5.
Mitigation strategies to control future seismic risks –
dynamic support requirements:

Q1 - What types of enhanced / burst resistant support are required?
(continued):

Table 2* Energy absorption (kJ) of various support elements (Kaiser et al., 1996)

<table>
<thead>
<tr>
<th>Description</th>
<th>Energy absorption (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19mm resin-grouted rebar</td>
<td>1 - 4</td>
</tr>
<tr>
<td>Split set bolt (FS46)</td>
<td>5 - 15</td>
</tr>
<tr>
<td>Yielding swellex bolt</td>
<td>8 - 12</td>
</tr>
<tr>
<td>Yielding super swellex bolt</td>
<td>18 - 25</td>
</tr>
<tr>
<td>16mm cone bolt</td>
<td>10 - 25</td>
</tr>
<tr>
<td>16mm cable bolt</td>
<td>2 - 6</td>
</tr>
<tr>
<td>16mm, 2.1m debonded cable bolts</td>
<td>6 - 10</td>
</tr>
<tr>
<td>#4 gauge welded-wire mesh</td>
<td>3 - 6/m^2</td>
</tr>
<tr>
<td>Shotcrete &amp; welded-wire mesh</td>
<td>3 – 5 x mesh</td>
</tr>
</tbody>
</table>

*: Ground support elements being used at Vale Inco’s Sudbury operations.
Mitigation strategies to control future seismic risks – dynamic support requirements:

Q2 – Where (no-damaged) should this enhanced / burst resistant support be applied?

For areas, where the major geological structures intersected the drifts, a simple rating system is developed:

1. Is this area historically seismically active? (1: Low, 2: Medium and 3: High)
2. How is the ground condition? (1: Good, 2: Fair and 3: Poor)
3. How is the existing ground support condition? (1: Good, 2: Fair & 3: Poor)
4. Are there any significantly deteriorated infrastructures, such as raises, in the proximity? (1: distance \(d\) \(\geq\) 30m, 2: 15m \(\leq\) \(d\) < 30m and 3: \(d\) < 15m)
5. Is it anticipated that mining induced stress is likely to change with future mining? (1: not likely, 2: likely and 3: certain)
6. Are there any other geological structures in the proximity? (similar to 4 above)

Back analysis reveals that enhanced support is required only if the total risk rating is greater than 10
Mitigation strategies to control future seismic risks – *Mine design and planning measures:*

- **Eliminate diminishing pillars:** mining should proceed away from the pillar or Dykes between 100 and 900 ore bodies, or mine one first then follow-up with other (this is current plan – mine 100 only).

- **Optimize mining sequence:**
  (sill pillar at 3550 level): mining HW stopes first to cut off the stress, then mining FW stopes.

- **Mining method:**
  A true slot and slash will be used to mine the last lift in 100 O/B instead of VRM.
Mitigation strategies to control future seismic risks – *Mine design and planning measures*: (continued)

- **Development strategies**: for areas crossing any major active geological structures - short rounds, say 2.4 m (8’), de-stressing blasting and enhanced ground support.
- **Local stope de-stress**: De-stress holes have also been drilled along the hanging or footwall in high stressed stopes (6” holes at a 3’ spacing). These holes will generate a slot to cut the stress through stopes.
An integrated approach, incorporating the geology, structures and seismic data is being investigated in the Virtual Reality lab environment to generate seismic hazard maps for both current and future mining zones.

This technique has been successfully used at Creighton mine to locate mine major infrastructure and strategically allocate enhanced support (Malek, 2009).
Performance of dynamic support system – A case study

Case Study:

Inputs:
✓ 2.5 Mn (Nyttli) in the proximity of a section in the main ramp
✓ An average of 2.4 m and 1.8 m thick material were ejected from the wall and back respectively

Outputs:
✓ Kinetic energy from the wall is calculated at 13.51 kJ/m².
✓ Ultimate kinetic energy from the back is calculated 12.62 kJ/m².

Final support recommendation (FOS >=1.5):
✓ Wall support: FS46 friction bolts with #4 gauge WW mesh with 3” thick plain shotcrete, then modified cone bolts with #0 gauge mesh straps as secondary support
✓ Back support: Resin rebar with #4 gauge WW mesh with 3” thick plain shotcrete then modified cone bolts with #0 gauge mesh straps as a secondary support. Depending on the excavation span, longer de-bonded cable bolts are also installed.
Performance of dynamic support system (continued)

**Walls:** 1.95 m long FS-46 split sets on a 1.2 x 0.75 m pattern with #4 gauge welded-wire mesh followed by a minimum 76 mm thick pass of plain shotcrete, and then 2.3 m long modified cone bolts on a 1.2 x 1.8 m pattern with #0 gauge mesh straps. The wall bolting was usually extended to the floor level.

**Back:** 2.4 m resin rebars on a 1.2 x 0.75 m pattern with #4 gauge welded-wire mesh followed by a minimum 76 mm thick pass of plain shotcrete, and then 2.3 m long modified cone bolts on a 1.2 x 1.8 m pattern with #0 gauge mesh straps.

Final product of burst-resistant (dynamic) support system used in one of the drill sills at Copper Cliff Mine.
Performance of Dynamic Support System (continued)

- After introducing the dynamic support system, mining in the 100 and 900 ore bodies was resumed.
- With the resumption of mining in the 100 and 900 ore bodies, we started to experience an elevated seismic activity, particularly while mining the stopes surrounding the Trap Dyke.
- Seven seismic events and/or rockbursts, ranging from Mn 1.2 to 2.9 occurred while mining the 9551 and 9281 stopes.
- These stopes are located in the vicinity of Trap Dyke.
- Out of the seven events, six occurred while mining the 9281 stope between 3710 and 3880 L.
Hole squeezing and shifting while mining the 9281 stope (3710-3880 L)
### Chronology of the events and observations

<table>
<thead>
<tr>
<th>Date</th>
<th>Magnitude (Nuttli)</th>
<th>Ore Body</th>
<th>Level (Stope)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 18, 2009</td>
<td>2.9</td>
<td>100</td>
<td>3710-3880 (9551)</td>
<td>No damage to the mine openings.</td>
</tr>
<tr>
<td>September 30, 2010</td>
<td>1.9</td>
<td>900</td>
<td>3710-3880 (9281)</td>
<td>No damage to the mine openings, but 80-100 tons of trap dyke material was sloughed into the open stope.</td>
</tr>
<tr>
<td>October 2, 2010</td>
<td>1.6</td>
<td>900</td>
<td>3710-3880 (9281)</td>
<td>No damage to the mine openings.</td>
</tr>
<tr>
<td>October 4, 2010</td>
<td>1.4</td>
<td>900</td>
<td>3710-3880 (9281)</td>
<td>No damage to the mine openings.</td>
</tr>
<tr>
<td>October 4, 2010</td>
<td>1.2</td>
<td>900</td>
<td>3710-3880 (9281)</td>
<td>No damage to the mine openings.</td>
</tr>
<tr>
<td>October 5, 2010</td>
<td>1.9</td>
<td>900</td>
<td>3710-3880 (9281)</td>
<td>Some minor surface cracks in the shotcrete.</td>
</tr>
<tr>
<td>October 15, 2010</td>
<td>2.3</td>
<td>900</td>
<td>3710-3880 (9281)</td>
<td>Minor damage to the installed ground support system and some floor heaving.</td>
</tr>
</tbody>
</table>
Damage comparison with reference to event location 
(3.8 Mn vs 2.9 Mn)

PPV:
Taking the source location into consideration, it can be concluded that both 3.8 Mn and 2.9 Mn events would have more or less similar ground movement (ppv) and displacement values.

Damage:
3.8 Mn: Approximately 3000 tons of rock material displaced on different levels between 2700 and 3710 L.
2.9 Mn: No damage was observed even in the immediate vicinity of the source location.
Performance of the dynamic support system (continued)

Personnel were present at these locations (~60 m) when 2.9 Mn event occurred.

Location of 2.9 Mn event (Feb 18, 2009)
Performance of the dynamic support system (continued)

9280 Sill - Minor cracks in the shotcrete along the shoulder of East Wall of 9280 (Surface cracks, possibly due to blast impact itself ($3.4$ M$	ext{N}$) rather than seismic followed by the blast. ($\sim$ 11 ft) (Oct 4, 2010)

9280 Sill - Cracks in the shotcrete and broken wires in the back (central portion of the sill) (Possibly due to blast impact itself ($3.4$ M$	ext{N}$) rather than seismic activity followed by the blast. ($\sim$ 6 ft from the edge of the open hole) (Oct 4, 2010)
Performance of the dynamic support system (continued)

3713 FW Drift - Negligible Damage (~100 lbs contained as baggage) right next to the cone-bolt strapping in the Trap Dyke area on 3710 L (Oct 4, 2010)

9280 Sill - Crack in the shotcrete and broken screen wires in the lower walls (Possibly due to blast impact itself (3.4 MJ) rather than seismic activity followed by the blast. (~ 1.2" wide crack approximately 4 ft long (Oct 4, 2010))
Conclusions:

• A methodical approach is presented in the paper to establish what type of enhanced support is required for both rehabilitation areas as well as for future potentially burst prone areas.

• A simple risk rating system is developed to determine where enhanced support is required.

• Mine design and planning strategies are also presented in the paper to control future seismic risks, including optimizing mining sequence, eliminating diminishing pillars, de-stress practice in both development and stopes as well as an alteration to mining method.

• Even though, many seismic events occurred in the 100 and 900 ore bodies while mining in the burst-prone ground conditions, no significant damage was associated with such events after introducing the burst-resistant support system at Copper Cliff Mine.
Conclusions (continued):

- It was evident from the underground observations that a well designed dynamic support system will cope very well in the event of large and repeated seismic events by sustaining the impact of dynamic loading with no or negligible damage to the underground excavations and/or the installed ground support system.

- Four stopes were mined out successfully without any significant damage after introducing the burst resistant support system in the areas at Copper Cliff Mine.

- All these mitigation measures are being implemented to ensure that the remaining 100 and 900 orebody can be mined safely and efficiently.
Acknowledgements:

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