

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

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ABSTRACT: While mining the approved stope sequence in the 100/900 ore bodies at the North Mine in Sudbury Basin of Vale Inco Ltd and following a crown blast in one of the stopes in 100 orebody in a sill pillar area, several major seismic events, with the highest magnitude of 3.8 Mn (Nuttli), occurred in both the Trap Dyke, which is located between 100 and 900 ore bodies, and in the sill pillar itself. This paper describes the mechanism of these events and the methodology of designing highly yielding ground support for rehabilitation areas with a view to withstand future seismic impact. A risk-based systematic approach was developed to determine where enhanced support is required in any other areas to be exposed by future seismic activities.

Numerical modelling undertaken for the low part of the 100 ore body reveals that a future sill pillar, having similar geometry to the one in the upper, will be subjected to even higher mine induced stress conditions. This paper discusses the mitigation plans to control seismicity in this highly burst-prone ground conditions, which include: modifying mine plans to eliminate the narrow sill pillar, an introduction of high yielding ground support, such as de-bonded cable bolts, Modified Cone Bolts and FS-46 friction sets etc, and installation of field instrumentation as well as the utilization of de-stressing techniques in both development drifts and around stopes, which has been successfully implemented at other mines of Vale Inco's Sudbury basin.

1 INTRODUCTION

Copper Cliff North Mine is located within the Copper Cliff Offset (Figure: 1). The Copper Cliff Offset extends about 8 kilometres south from the Sudbury Igneous Complex into the footwall rocks. Since commencement of mining in 1960 to the end of 2008, about 51.8 million tons of ore have been milled from surface and underground operations.

The Copper Cliff Offset begins as a funnel shaped embayment and then thins to a quartz diorite dyke. The ore deposits of the North Mine environment predominantly occur within the quartz diorite dyke. The quartz diorite dyke strikes north-south with an approximate width of 50 m, and dips vertically or steeply west.

The country rocks west of the dyke are predominantly granite and granodiorite rocks of the Creighton Pluton. The country rocks east of the dyke are metavolcanic and metasedimentary rocks of the Elsie Mountain, Stobie and Copper Cliff formations of the Huronian Supergroup. Sudbury Breccia predominantly occurs east of the dyke and is widespread at breaks (Cochrane, 1984) in the dyke.

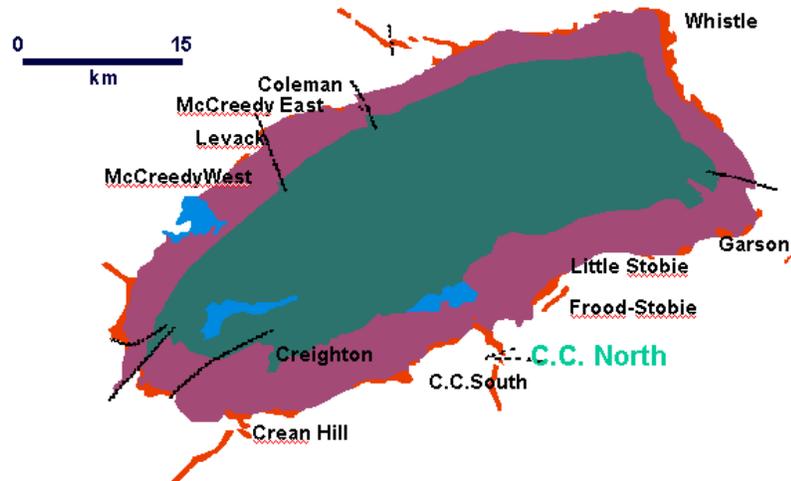


Figure 1: Location of Copper Cliff North Mine in Sudbury Basin of Vale Inco Ltd.

There are a number of major geological structures present at the Copper Cliff North Mine. At the southern end of the North Mine, the Creighton Fault displaces the quartz diorite dyke approximately 700 meters. The Creighton fault strikes east-west, and dips steeply towards north. The 900 orebody cross fault strikes east-west and dips 55 degrees north and it does not appear to displace the quartz diorite dyke. The Number 2 Mine cross fault strikes northeast, and dips 55 degrees northwest. The Number 2 Mine fault displaces the quartz diorite dyke 70 meters to the west. The Number 1 cross fault displaces the quartz diorite dyke 65 meters west. This fault strikes east-west and dips 40 degrees north. Apart from the above major faults, two dykes namely Quartz Diabase Dyke (Trap Dyke) and Olivine Diabase Dyke are present in the close proximity of 100/900 ob. The Trap Dykes are located between 100 and 900 ob striking east-west and dipping steeply towards north.

Historical data revealed that 900 cross fault was very seismically active and caused significant seismic events/rock bursts in and around 100/900 ob in the past. Recent seismic activity in the middle and lower 100/900 ob revealed that even trap dykes are known sources of major seismic activity.

Figure 2 shows simplified geology on the 3200 level with microseismicity superimposed in the 100/900 ore body.

On September 11, 2008, a major rock burst occurred following a series of magnitude events immediately after a crown blast in the middle 100 ob between 3050 and 3200 L. The magnitudes of the events ranged from 1.2 to 3.8 on the Nuttli scale. The 3.8 Nuttli magnitude event, in association with other significant events, caused an enormous amount of damage. The damage was so widespread that it was extended from 2700 L to 3710 L around the 100/900 ob region. In total, more than 2500 tons of material was displaced at different locations on different levels. Most of the damage was observed to be associated mainly with major geological structures such as Trap Dyke, Olivine Diabase Dyke and 900 X-fault. This paper describes the mitigation plans that were employed to control seismic risks in the future, including:

- A simple risk rating system was developed to determine where enhanced support is required;
- A methodical approach was developed to establish what type of enhanced support is required for the rehabilitation areas as well as for future potentially burst prone areas identified above;

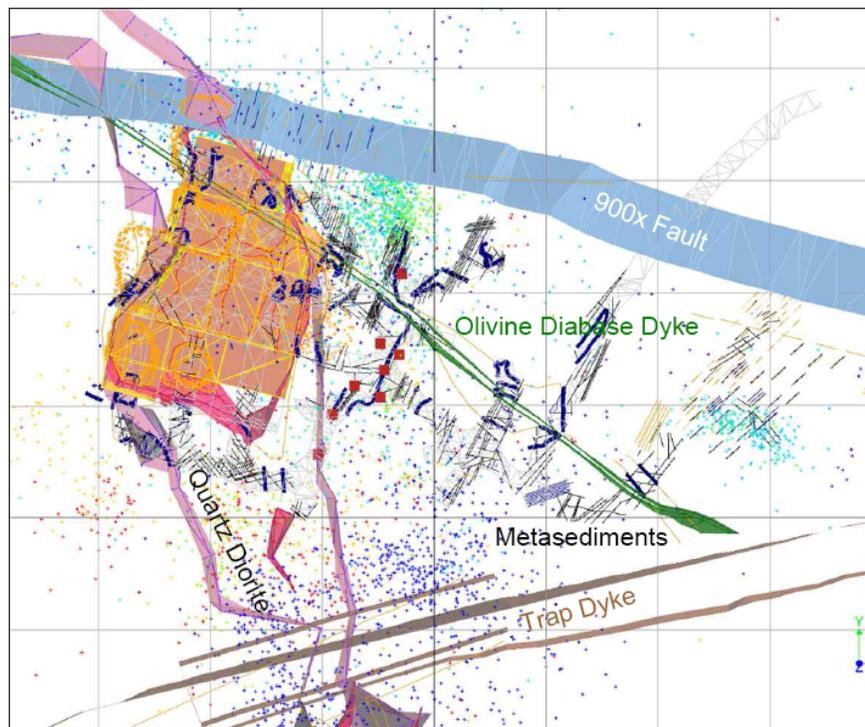


Figure 2: Simplified geology on the 3200 level with microseismicity.

- Mine design and planning strategies are also described in this paper, including eliminating narrow sill pillar formation, de-stress practices in development and stoping as well as the introduction of field instrumentation to monitor ground movement and ground support effectiveness.

2 DESCRIPTIONS OF OCCURRENCE AND MECHANISM OF THE ROCK BURST

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) at around 7:21 a.m. Soon after the blast, a series of magnitude events (about 10 events) ranging from 1.2 to 3.8 (Nuttli) were felt between 7:21 and 8:06 a.m. These magnitude events caused an enormous amount of seismic activity in different work places between 2700 and 3710 L. North mine central blast practice prohibits operators underground during any production blasts. The Long section (Figure 3) depicts the locations of the major events, associated damage and their proximity to major geological structures.

It is concluded by all external consultants (Itasca, Golder and Mirarco, 2009) that 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 contributing factors may include:

- Proximity to the trap dykes, the 900 cross fault as well as quartz diorite (QD) contacts, possible excessive stress concentration and stored energy due to the stiffness contrast between the structures and the host rock;
- Diminishing pillars (both vertically – sill pillars and laterally – pillar between two orebodies) generating concentration of high stress;
- Mining induced stress changes resulting in the loss of confinement to these major geological structures.

Underground observation reveals that damage was attributed to a combination of the follows:

- The level of ground support is relatively light and support systems (a mix of resin rebars and mechanical bolts) have limited energy absorption and holding capacity;
- Damage increase with proximity to the major geological structures, especially the trap dyke;
- Wall support was not extended long enough;
- At some locations, pillar between excavations is relatively small, and this pillar failed during this rock burst.

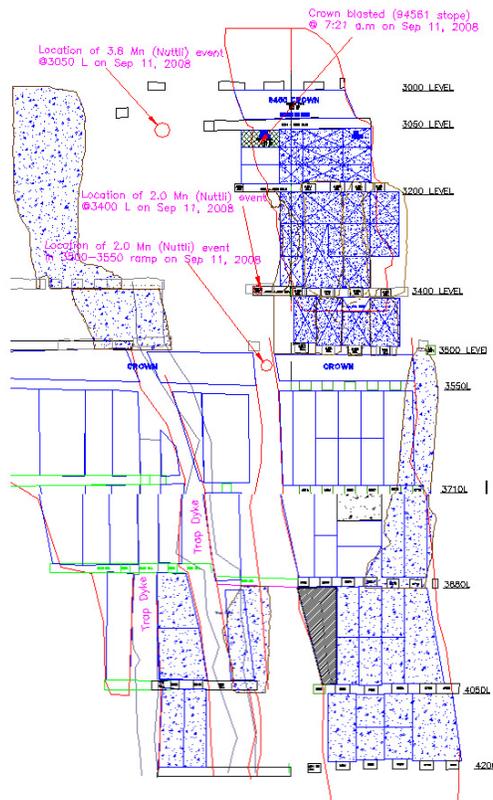


Figure 3: Long section showing the locations of the major events on different levels (3000-3710 L).

Both the recent and historical rock bursts in 100/900 orebody clearly demonstrate that the areas, which most likely suffer damage from any major seismic events, are the sections, where the major geological structures, including trap dyke, 900 cross fault and Olivine Diabase Dyke, intersects the drifts. It should be noted that enhanced support discussed in this paper is applied to these areas only.

3 MITIGATION PLANS TO CONTROL SEISMIC RISKS

Although seismic risks cannot be totally removed in operations, which have highly stressed ground and seismically active geological structures, application of advanced dynamic ground support system, sound strategic mine design and planning as well as adequate re-entry protocol after blast and/or major seismic events can be implemented to significantly reduce seismic risks. This paper will focus on the former, but re-entry protocol, which is being successfully implemented in Vale Inco’s Sudbury operations using a combination of Seismic Watch (energy level) and events rate (Malek, 2006), will not be discussed in this paper.

After the occurrence of major events, mitigation plans must be put in place to ensure that the remaining ore bodies can be mined safely and efficiently. There are a few steps mine operators are taking to accomplish this task. First, the mine operators need to determine what types of enhanced support are required. This will form rehabilitation plans for the areas, where damage occurred. Secondly, a common question faced to mine operators is “are there any other non-damaged areas, where this type of enhanced support should be applied?” Last, the mine operators need to investigate any long-term measures of modification to mine design, mining method and practices to reduce future seismic risks. This paper will clearly demonstrate how these issues are addressed at Vale Inco’s Sudbury operations following any major seismic events.

3.1 Dynamic support requirements

Although there are a wide variety of ground support elements, such as rockbolts, mesh/straps, shotcrete, cable bolts and modified cone bolts, some of these elements are specially designed to absorb energy when rock bursts occur. Even with dynamic support elements, each has different level of energy absorption. Generally speaking, dynamic support elements are much more expensive than the support elements designed for static loading. It is not economic to apply the dynamic support systems throughout a mine. A systematic approach is developed to determine where the dynamic support, i.e. enhanced and burst resistant support, is required and what types of combined dynamic support elements should be designed to sustain future seismic risks.

3.1.1 Where is dynamic support, i.e. enhanced support, required?

As discussed in section 2, most of the damage occurred in areas where drifts crossed the major geological structures, including trap dyke, OD dyke and 900 cross fault or drifts in close proximity to these structures. It is obvious that enhanced support (section 3.1.2) is required for areas, where damage occurred. But for areas, where the major geological structures intersected the drifts but no damage occurred from these seismic events, a rating system (see Table 1) is developed to determine whether an enhanced support is required or not.

Table 1 A risk rating system to determine where enhanced support is required in the major geological structure zones, including trap dyke, 900 x- fault and OD dykes.

1 - Is this area historically seismically active? – this can be done by examining historical data in the last 2 years
 Low - None or $M_n < 1.0$, and/or base line $>$ Number of micro-seismic events, Risk Rating = 1
 Medium - $1.0 < M_n < 2.0$, and/or base line \leq Number of microseismic events $<$ base line by 20% Risk Rating = 2
 High - $2.0 \leq M_n$, and/or number of microseismic events \geq base line by 20%, Risk Rating = 3

2 - How is the ground condition?

Good - $RMR \geq 60$, Risk Rating = 1

Fair - $60 > RMR \geq 40$, Risk Rating = 2

Poor - $RMR < 40$, Risk Rating = 3

3 - How is the existing ground support level?

Good - standard support, shotcrete and additional secondary support, such as cable bolts. Risk Rating = 1

Fair - standard support plus shotcrete. Risk Rating = 2

Poor - standard support, or no support or support damaged. Risk Rating = 3

4 - Are there any significantly deteriorated infrastructures, such as raises, in the proximity?

Distance $\geq 100'$, Risk Rating = 1

Distance = 50' to 100', Risk Rating = 2

Distance $< 50'$, Risk Rating = 3

5 - Is it anticipated that mining induced stress is likely to change with future mining?

Not likely - outside of influence zone, Risk Rating = 1

Likely - within the influence zone, Risk Rating = 2

Certain - high stressed pillars or abutment zone, Risk Rating = 3

- 6 - Are there any OTHER geological structures in the proximity?
 Distance >= 100', Risk Rating = 1
 Distance = 50' to 100', Risk Rating = 2
 Distance < 50', Risk Rating = 3

A total risk rating is calculated in the range from 6 to 18. Back analysis of a number of areas indicates that for any concerned area, enhanced support (section 3.1.2) is required only if the total risk rating is greater than 10.

3.1.2 What types of enhanced support are required?

A five-step methodology is developed to determine what types of enhanced support are required to sustain future seismic events.

- The first step is to select the site, where the most severe damage occurred. Commonly, the largest seismic events take place in the proximity of this site.
- The second step is to determine the ground motion level in terms of peak particle velocity (PPV), that can be generated at the drift surface when the largest events occurred. Kaiser et al. (1996) presents average predicted PPV as a function of distance and seismic event magnitude (Figure 4).
- The third step is to calculate the total kinetic energy of any ejected block of rock, i.e. the demand on the support. The total energy can be determined by (Kaiser et al, 1996):

$$E_t = \frac{1}{2} m v_e^2 + q m g d \tag{1}$$

Where m = the mass of ejected rock = one unit area (1 m^2) x rock/ore density x average thickness of the ejected blocks (back or wall); v_e = the ejection velocity (PPV determined above); $q = 1, 0$ for ejection from the back and wall and d = a distance the block has traveled (wall or back movement by a remote seismic event). Figure 5 provides a preliminary assessment of the anticipated wall movement with standard support caused by a remote seismic event (Kaiser et al, 1996). This movement can be measured from field instrumentation, such as multi-point bore extensometers, if they are available.

- The fourth step is to determine the integrated support system consisting of various support elements (Table 2, Kaiser et al, 1996), which is currently being used at Vale Inco's Sudbury operations to achieve a support energy absorption capacity (energy absorption of any support element/bolt pattern) that exceeds the demand.
- The fifth step is to calculate factor of safety (FS) = Capacity (from step four)/Demand (from step three). The required FS must be at least 1.3 and 1.5 respectively for temporary and permanent openings.

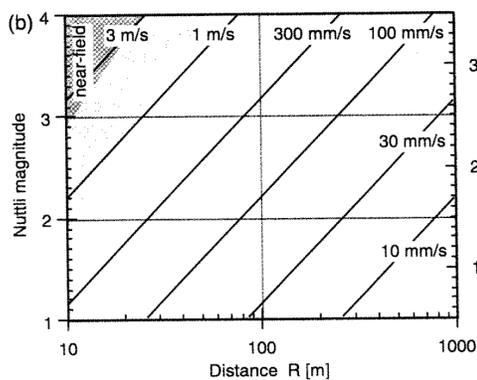


Figure 4. Peak particle velocity (PPV) for Recommended design conditions (Kaiser et al. 1996)

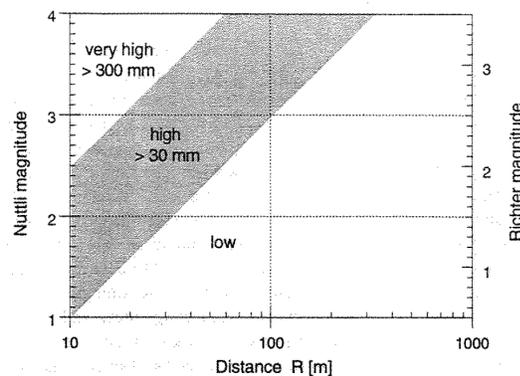


Figure 5. Typical wall displacements in openings with standard support caused by a remote seismic event (Kaiser et al. 1996)

3.1.3 Case study

The section of the main ramp from 3500 to 3550 level suffered the most severe damage with seismic event magnitude of 2.5 Mn (Nuttli) in the proximity. PPV at the drift surface is predicted to be 2.0 m/s by using Figure 3. Underground observation reveals that an average of 2.4 m (8') and 1.8 m (6') thick block was ejected from the wall and back respectively. By using equation (1), kinetic energy released from the wall is calculated at 13.51 kJ/m².

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

Description	Energy absorption (Kj)
19mm resin-grouted rebar	1 - 4
Split set bolt (FS46)	5 - 15
Yielding swellex bolt	8 - 12
Yielding super swellex bolt	18 - 25
16mm cone bolt	10 - 25
16mm cable bolt	2 - 6
16mm, 2.1m debonded cable bolts	6 - 10
#4 gauge welded-wire mesh	3 - 6/m ²
Shotcrete & welded-wire mesh	3 - 5 x mesh

*: Ground support elements being used at Vale Inco's Sudbury operations.

Multi-point bore extensometer at one of Vale Inco's operations measures approximately 50 mm ground movement at a draw point where a 2.3 Mn seismic event occurred in the proximity (Punkkinen, 2009). Ultimate kinetic energy with 50 mm movement in the back is calculated in the order of 12.62 kJ/m².

To meet a factor of safety of at least 1.5 for these permanent openings, the following combined support elements are proposed for the wall and the back:

For walls – 6'6" FS46 friction bolts on a 4'x2.5' pattern with #4 gauge welded-wire mesh followed by a minimum of 3" thick plain shotcrete and 7'8" long modified cone bolts on 4' x 6' pattern with #0 gauge mesh straps (being parallel to the drift) as a secondary support.

For the back - 8' resin rebars on a 4' x 2.5' pattern with #4 gauge welded-wire mesh followed by a minimum of 3" thick plain shotcrete and 7'8" long modified cone bolts on 4' x 6' pattern with #0 gauge mesh straps (being parallel to the drift) as a secondary support. If excavation span is greater than 6 m (20') and/or adverse structures are identified, 6 m (20') long double cable bolts are installed on a 7' x 7' pattern. Alternative of having one cable with a 7' de-bonded section at the collar is being investigated to gain additional energy absorption capacity.

Figure 6 shows the installed enhanced support in areas predicted to be burst-prone in the future. Recently, a 2.9 Mn (Nuttli) seismic event occurred in this area, all enhanced support performed extremely well without any damage.

3.2 Mine design and planning measures

In addition to implementation of the enhanced support, mine design and planning strategies play an important role in controlling seismic risks, and these include: eliminating diminishing pillars (both vertically and laterally), de-stress practice in both development headings and stopping areas as well as a change of mining method in burst prone conditions.



Figure 6: Enhanced support installed in burst prone areas

Prior to mining two remaining stopes in the top sill pillar area (from 3050 to 3200 level), in addition to installation of the required enhanced support, instrumented cable bolts and multi-point borehole extensometers are to be installed to monitor ground movement and ground support effectiveness. Monitoring results will be used as an important part of decision-making on re-entry protocol after each major blast. This process has been successfully implemented at South mine while mining in similar ground conditions (Punkkinen, 2009).

To eliminate the lateral pillar, i.e. the pillar between 100 and 900 ore body, it has been decided that the 100 ore body will be mined first then follow-up with the 900 orebody. This will generate stress shadow in the pillar when 900 orebody is mined. Numerical modeling indicates that the initially proposed sill pillar between 3500 Level and 3550 Level (Figure 2) will be highly stressed (Figure 7). Risk assessments are ongoing to assess the safest and most reliable alternatives to avoid this 15m (50') sill pillar, which is considered to be inadequate in size (in terms of thickness) to withstand the high stress and burst prone conditions. One of the options is to generate a top sill underneath backfill either at 3500 level or 3550 level. This will increase the sill pillar to 50 m (160') thick.

At the development stage, a mining practice has been standardized for areas crossing any major active geological structures, including the trap dyke, 900 cross fault and OD dyke, etc. This mining practice includes: short rounds – 2.4 m (8'), de-stressing and enhanced ground support. De-stress holes have also been drilled along the hanging or footwall in high stressed stopes (6" holes at a 3' spacing, Figure 8a and 8b). These holes will generate a slot to cut the stress through stopes, and this will reduce the squeezing of blast holes as well as seismic activity during mining the stopes.

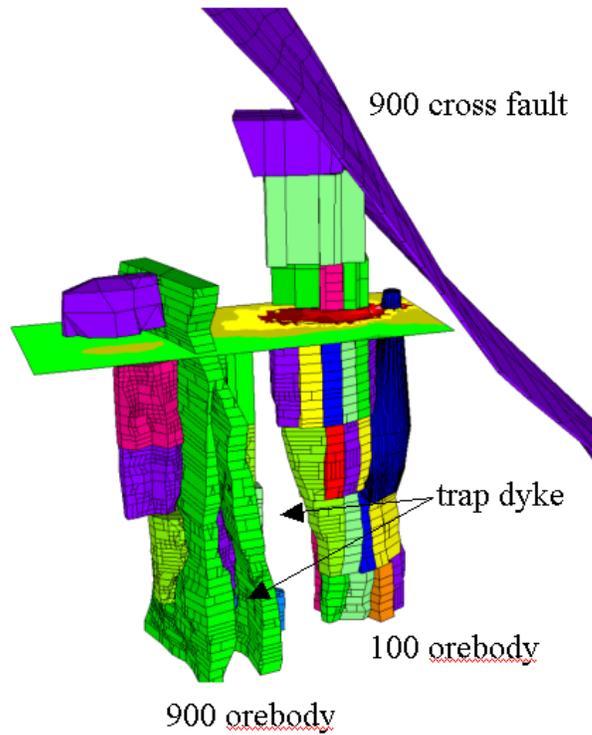


Figure 7: High stress concentrations in the initially proposed sill pillar between 3500 level to 3550 level ($\sigma_1/UCS = 0.7$)

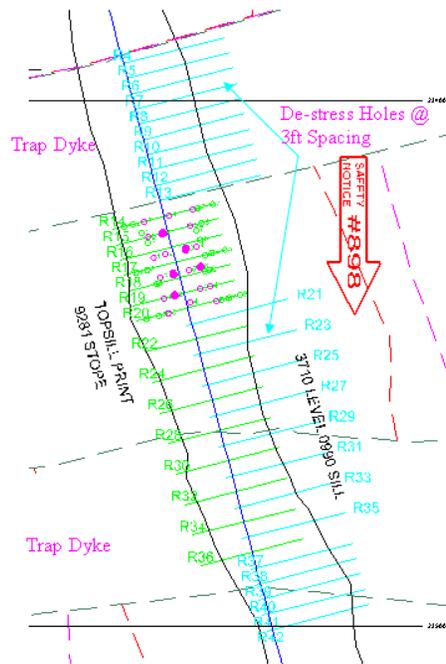


Figure 8a: Plan showing de-stress holes laid out in trap dykes and the stope on 3710 L.



Figure 8b: Section showing de-stress holes laid out in trap dykes and the 9281stope (3710-3880 L).

Mining at North Mine has been predominantly Vertical Retreat Mining (VRM). Squeezing holes in ore at the stresses anticipated below 3500 Level will result in problems in loading and blasting. Slot Slash is being successfully implemented in the high stress environment in other Vale Inco Sudbury operations. Normally, a 1.2 m (4') raise bore hole slot is reamed at one end of the stope. Blast holes are slashed into the raise bore slot. In extremely highly stressed ground, one row of holes can be drilled and then slashed into the slot. This row of holes is in the stress shadow of the slot. This method also necessitates having the ITH drill left at the top sill for drilling rings and re-drilling squeezed holes.

An integrated modelling approach incorporating the geology, structures and stress models together with a comprehensive up to date seismic database is being investigated. The goal of this approach is to generate seismic hazard maps for both current and future mining zones. A seismic hazard map is a surface of over layered predicted seismically induced factors showing zones of hazard severities (Figure 9). All data can be integrated into one common model by using the Virtual Reality lab environment. This technique has been successfully used at Creighton mine to safely and economically locate mine infrastructure and strategically allocate enhanced support (Malek, 2007).

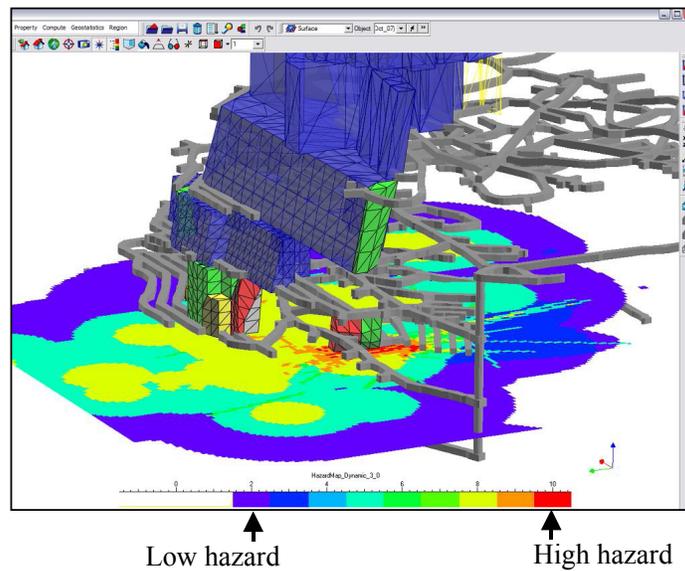


Figure 9: Hazard maps generated in Virtual Reality lab for Creighton Mine (Malek, 2007)

4 CONCLUSIONS

After any major seismic events, mine operators face a few critical questions, which need immediate attention. Questions include: what types of enhanced support is required for areas, which suffered damage in order to withstand future seismic risks? Considering the occurrence of these events, which areas are likely to be burst prone in the future thus enhanced support being required? This paper describes a simple risk rating system to determine where enhanced support is required. A methodical approach is also presented to establish what type of enhanced support is required for both rehabilitation areas as well as for future potentially burst prone areas. In addition to implementation of enhanced support, mine design and planning strategies to control seismic risks are also discussed in this paper, including eliminating diminishing pillars, de-stress practice in both development and stopes, alteration to mining method as well as the introduction of field instrumentation to monitor ground movement and ground support effectiveness. All these mitigation plans are implemented to ensure that the remaining 100 and 900 orebody can be mined safely and efficiently.

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