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Lessons learnt from a pillarburst at a development heading in one of Vale's deep mines: a case study

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Abstract

Over the last decade, Vale's Sudbury Operations have experienced an increase in the occurrence of significant seismic events. Common contributing elements identified through seismic event investigations include:

- *high quality rock mass conditions combined with high strength and brittle material properties*
- *elevated stress levels associated with increased mining depths (up to 2.5 km below surface)*
- *unfavourable mining geometries, such as sill and diminishing rib pillars*
- *higher extraction ratios, reflecting the maturity of mining operations*
- *interaction with seismically active geological structures (joints, faults, dykes and shear zones, etc.).*

Mitigation strategies focused on these contributing factors have been developed within Vale's Mining Operations, to manage and control the risks associated with seismicity and rockbursting.

This paper presents a unique rockburst event that occurred in a development breakthrough pillar in the 5220 Ramp at Garson Mine that resulted in injuries to two employees. This event triggered a comprehensive investigation to identify the failure mechanism, contributing factors and lessons learned; forming the basis for additional mitigation strategies, focused on minimising and/or preventing future re-occurrence of similar rockbursts. The investigation results are presented in this paper, and the more recent 5300 Level 1210 Level access breakthrough is presented as an example to demonstrate the successful implementation of a new design methodology and process. It is hoped that by sharing this case study with the industry, ground control professionals can be made aware of when rockbursts may occur, and what mitigation strategies can be adopted when a similar mining scenario is encountered at their operations.

Keywords: *pillarburst, deep mines, breakthrough, development headings, seismicity and rockburst*

1 Introduction

As shown in Figure 1, Garson Mine is located in the Southeast quadrant of the Sudbury Igneous Complex, located in Ontario, Canada. Garson Mine Complex consists of a series of orebodies, that are extracted by two mines with separate accesses that share some services and operate with independent crews. The surface ramp is accessed by a ramp from the surface and has active operations from near surface to an approximate depth of 300 m. The main mine (where this case study takes place) is accessed through the #2 Shaft, with the majority of active areas ranging from approximately 1,000 to 1,650 m in depth. A general arrangement of the main mine ramps and shaft accesses is included in Figure 2. There are three main levels within the active portion of the main mine that connect to the #2 Shaft: 3400 Level, 3800 Level, and 4000 Level (at Garson Mine the name of mining levels corresponds to the approximate depth below surface in feet). The 3800 Level shaft access is a track drift that is used for moving supplies from #2 Shaft to the main mine ramp while the 4000 Level shaft access is a track drift used for tramming ore and rock from the passes to the crusher and bins.

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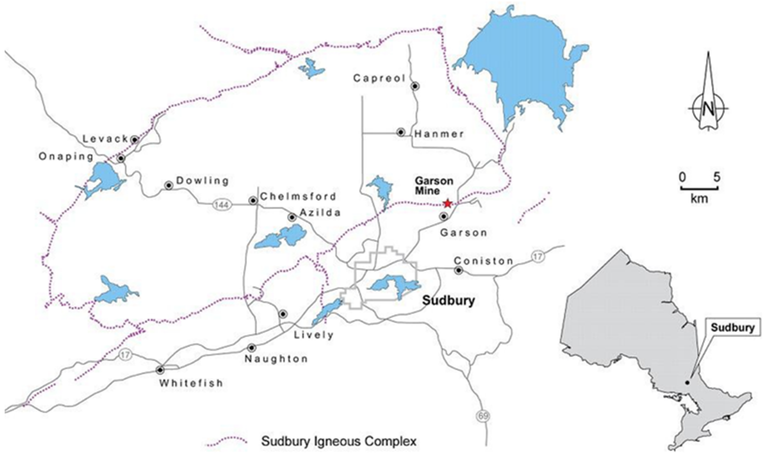


Figure 1 Location of Garson Mine within the Sudbury Igneous Complex

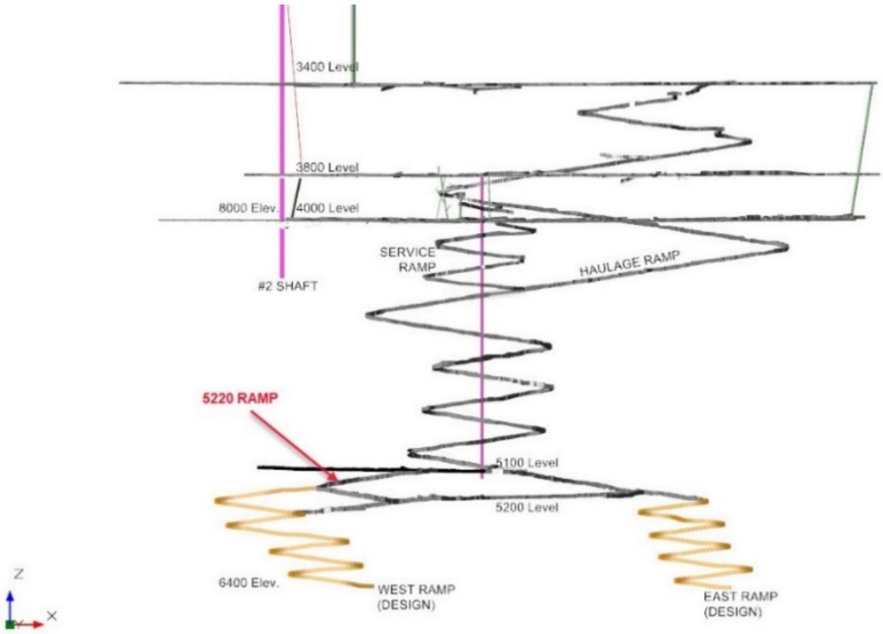


Figure 2 Main mine general arrangement: longitudinal view (looking north)

Off the three shaft access levels, the main mine ramp system provides access to all other Main Mine workings between 3400 Level and 5300 Level. The primary haulage ramp system down to 5100 Level is in the footwall norite rock. Below 5100 Level, the ramp system is divided into two branches: the east ramp and the west ramp. Garson development is currently advancing both the east ramp and the west ramp at depth, approaching 5400 Level design elevation.

2 Background

The 5220 Ramp is an access ramp that was advanced on the west side of the mining zone, between 5100 Level and 5200 Level. An access ramp on the east side of the mining zone between 5100 Level and 5200 Level enabled the 5220 Ramp to be developed from two access points concurrently; the 5220 down ramp was driven downwards toward 5200 Level, while the 5220 up ramp was driven from 5200 Level advancing upwards towards 5100 Level. The 5220 down ramp and the 5220 up ramp required a breakthrough to create a single continuous ramp (the 5220 Ramp). Therefore, by design, the 5220 Ramp excavation necessitated a development breakthrough pillar, as shown in Figure 3.

The 5220 up ramp development was stopped, following several unusual ground control occurrences, including two rockbursts in the up ramp. The mine technical services and operations teams undertook an evaluation of the ground conditions and completed a risk assessment, which resulted in the development and implementation of additional controls, including a new face support design that extended the face support to within 0.6 m (rather than 1.5 m) of the floor, and stopping the advance of the up ramp heading and developing the remainder of the 5220 Ramp from the down ramp side.

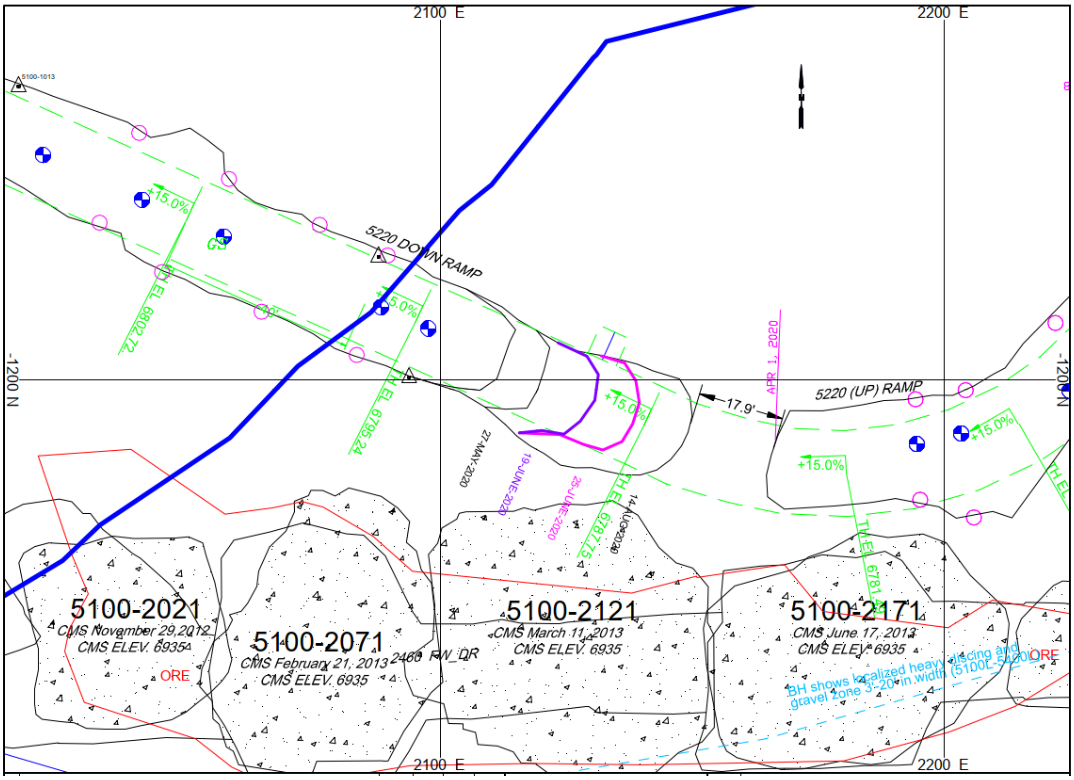


Figure 3 Plan view of the last survey of the 5220 Ramp before the breakthrough pillarburst

The last development round in the 5220 down ramp was blasted with 5.5 m left to breakthrough into the 5220 up ramp heading. After the blast, the round was mucked out and bolted, without incident. After one week, the Operations team initiated face bolting, as per ground support standards. During this task, a MN1.95 seismic event and pillarburst occurred resulting in the ejection of approximately 40 tonnes of material from the down ramp development face, and approximately 180 tonnes of material from the up ramp development face. At the time of the pillarburst, two employees were delivering additional materials to the down ramp to complete face bolting, and unfortunately both employees were injured by the ejected material.

Given the severity of the incident, a comprehensive investigation and analyses were completed to identify the failure mechanism, contributing factors, and lessons learned; which formed the basis for additional mitigation strategies focused on minimising the likelihood of similar events and mitigating the potential consequences of future breakthrough pillarbursts.

3 Seismic history of the 5220 Ramp

Three cumulative frequency plots of the seismicity leading up to and just beyond the rockburst incident are provided in Figure 4. The time periods are:

a. the five-month period prior to the incident

b. the month of August up to the day of the incident

c. the 48-hour period prior to the incident.

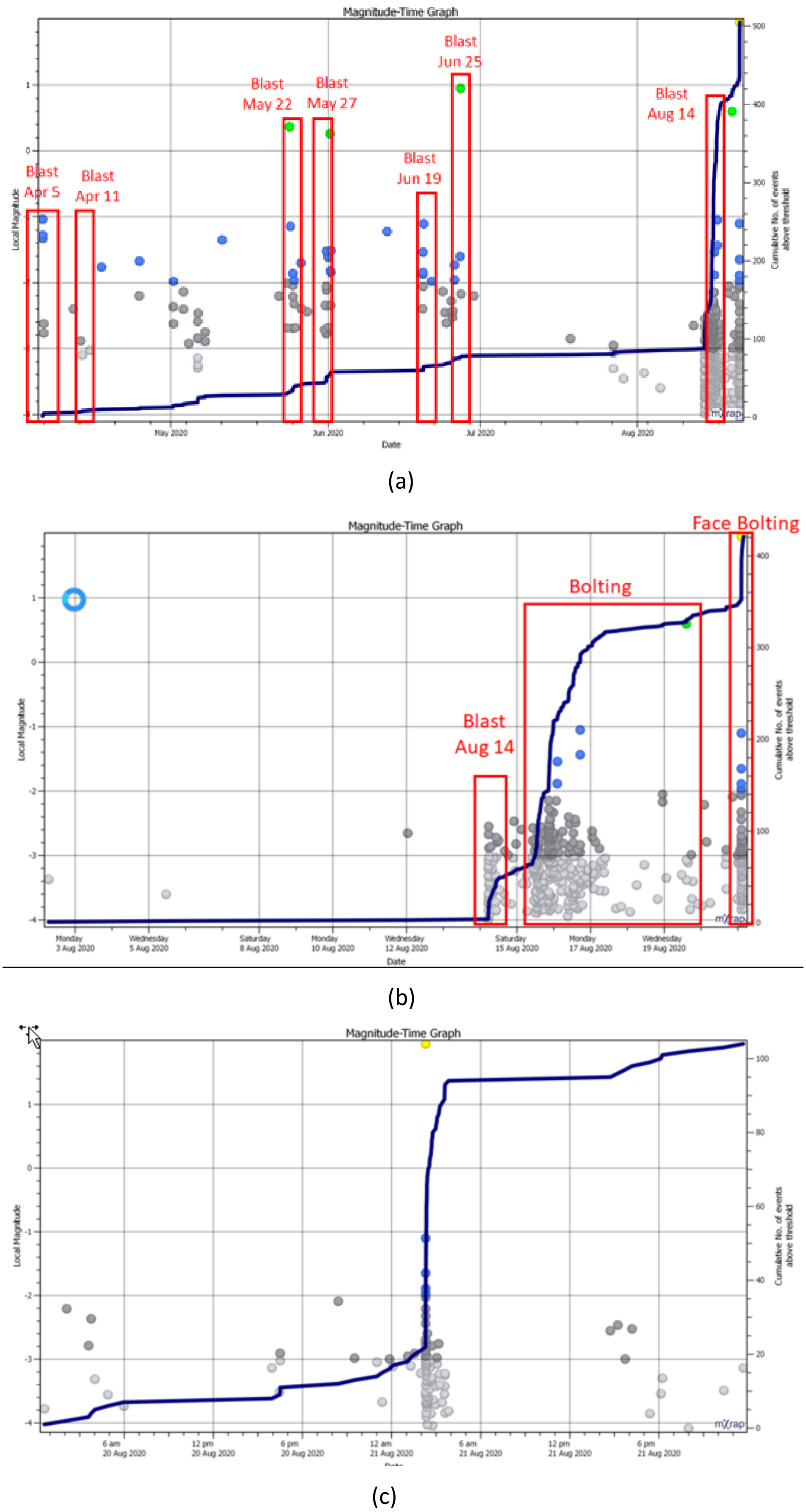


Figure 4 **Local magnitude versus cumulative number of events for three time periods of (a), (b) and (c)**

It is clear from these plots that very little seismicity occurred following the natural decay in the immediate period after the development rounds. Aside from random low magnitude seismic events occurring during these time periods, the only large cluster of events unrelated to development rounds occurred within the breakthrough pillar following the rockburst event. It is concluded that the microseismic response to the previous development rounds did not provide an indication that a large event was imminent (Ruest & Yao 2020).

It should be mentioned that additional seismic sensors were commissioned in the concerned area between 25 June and the final blast on 14 August 2020. As a result, the cumulative frequency plots indicate an elevation of microseismicity following the 14 August 2020 development blast (Figure 4b). However, this elevation in seismicity is attributed to an increase in seismic system sensitivity rather than serving as evidence of increased seismic response in the heading.

4 5220 Ramp risk mitigation measures

The controls that were in place to mitigate the risk of seismicity in the 5220 Ramp included the following:

- seismic monitoring system and re-entry protocol – Garson Mine has a re-entry protocol in place for seismicity and this was followed for the 5220 Ramp
- de-stress development blasting – Garson Mine procedure (Figure 5) was followed for the 5220 Ramp (Yao & Moreau-Verlaan 2010)
- de-stress relief holes in the pillar – at 15 m to breakthrough, de-stress relief holes were drilled as follows (Figure 6):
    - holes were 7.3 m long, and aligned with drift grade and azimuth
    - nine 63.5 mm diameter holes were collared into the 5220 down ramp face
    - nine 63.5 mm diameter holes were collared into 5220 up ramp face.
- enhanced dynamic support – primary support system consists of 2.4 m long PAR1 dynamic bolts (1.2 × 0.76 m pattern) with #4 gauge welded-wire mesh overlain with #0 gauge mesh straps secured with 2.4 m long PAR1 dynamic bolts (1.5 × 1.5 m pattern) at a 1.5 m spacing in the back and walls along the drift (Figure 7)
- face support – consists of 2.0 m long, 46 mm diameter friction sets (1.2 × 1.5 m pattern) with #4 gauge welded-wire mesh, and the face support extended to within 0.6 m (rather than 1.5 m) from the floor (Figure 8).

The purpose of the de-stress relief holes in the pillar was to precondition the rock mass by allowing the holes to squeeze and thus providing pressure relief points. Though the effectiveness of these ‘pressure-relief’ de-stress holes have not been categorically demonstrated, underground observations indicate they have provided some form of de-stressing in previous applications. However, this strategy proved inadequate in the 5220 Ramp breakthrough pillar.

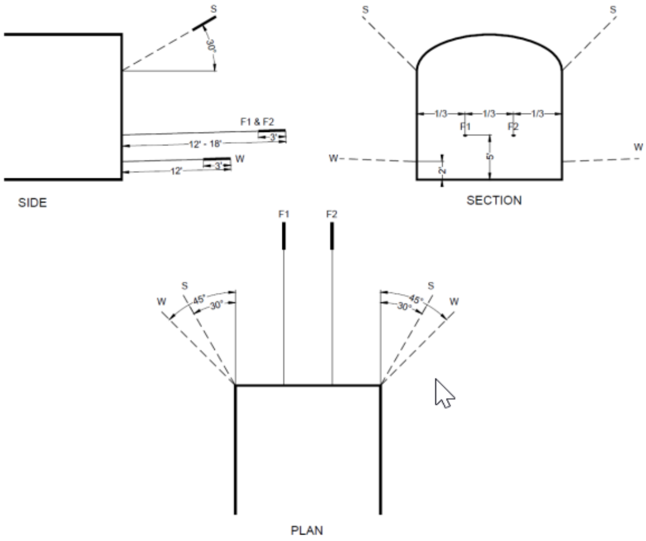
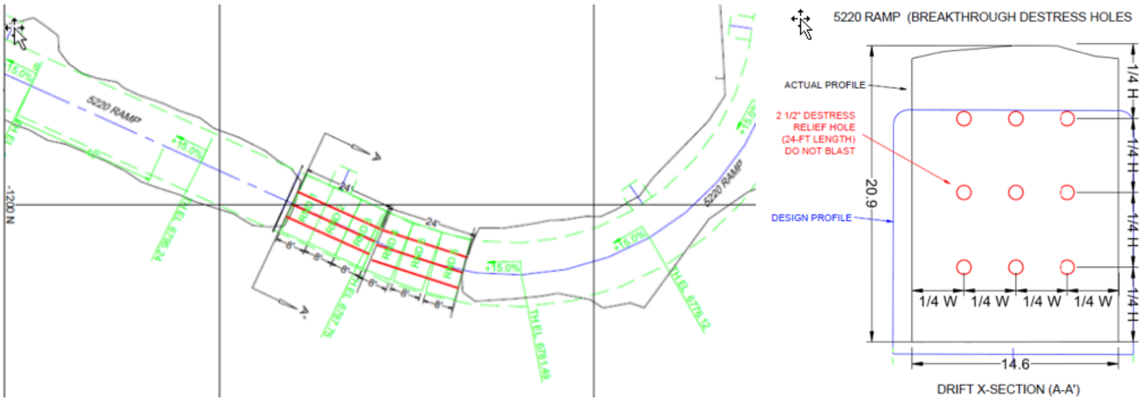


Figure 5 Garson's development de-stress layout



(a) (b)

Figure 6 De-stress relief holes in the pillar presented on (a) plan view and (b) section view

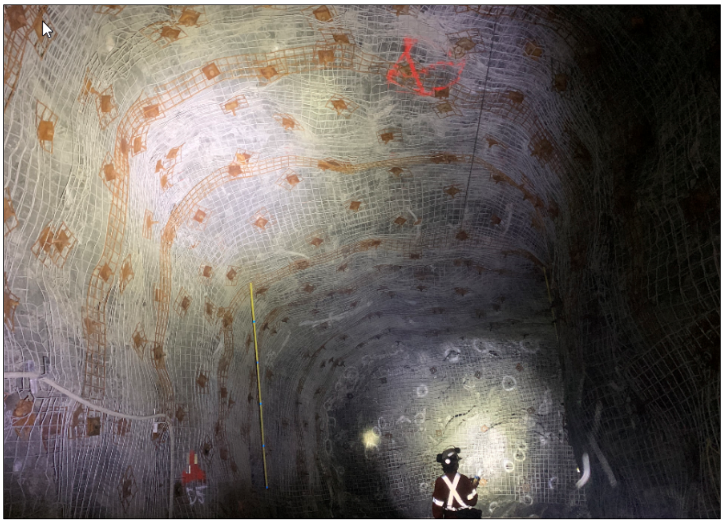


Figure 7 Dynamic support system

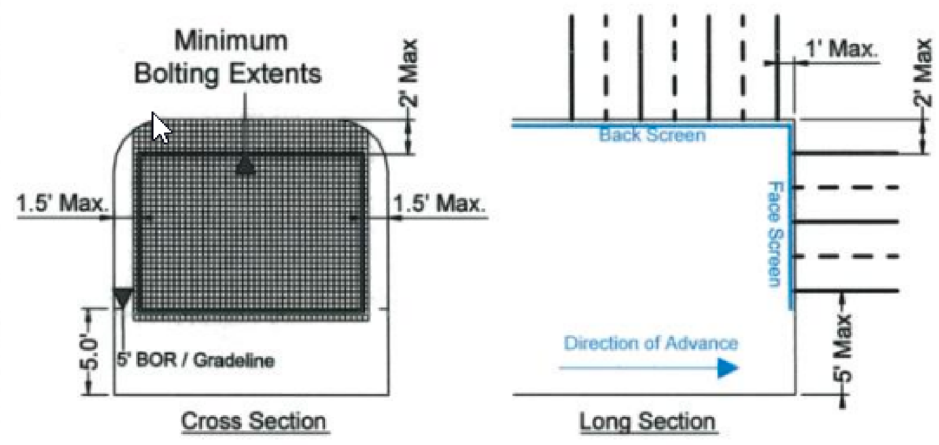


Figure 8 **Face support system**

5 Back-analysis of 5220 Ramp diminishing pillar performance

A back-analysis was performed on the development advance in the 5220 Ramp, focusing on the final rounds leading to the rockburst incident. This back-analysis was completed using FLAC3D (ITASCA n.d.), and geometry in the modelling environment included nearby stope mining, adjacent development, and the last surveys of development rounds in the 5220 Ramp.

The 5220 Ramp is situated primarily in the meta-basalt unit (MTBS), a common lithology at Garson Mine. At this location, the MTBS is characterised by silica veins making it stronger, stiffer, and more brittle than usual. It should also be mentioned that some major joint sets were observed in the failed pillar but weren't taken into account in the numerical modelling analysis.

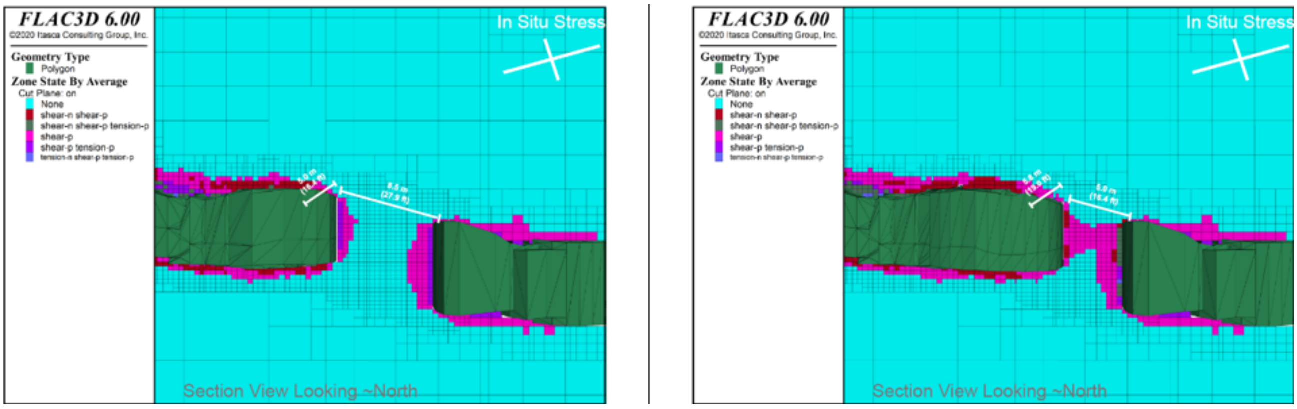
The following assumptions were made during the back-analysis regarding strength and stiffness based on rock property data collected at the mine:

- Uniaxial compressive strength (UCS) = 180 MPa
- Young's modulus (E) = 122 Gpa.

The principal stress assumptions were consistent with previously calibrated Garson numerical stress models, and are as follows:

- σ_1 (psi) = 1,543 + 1.80 × depth (ft) (075°/00°)
- σ_2 (psi) = 1,343 + 1.07 × depth (ft) (165°/00°)
- σ_3 (psi) = 1.20 × depth (ft) (000°/90°).

Yielded elements from the stress model output, shown in Figure 9, are contoured at a breakthrough pillar thickness of 8.5 m (consistent with the face position one round before the rockburst) and when the pillar has a thickness of 5.5 m, after the final round had been taken before the rockburst. These results show that at 8.5 m, the pillar core is intact while at 5.5 m, the core has yielded in a classic shear mechanism.



(a) (b)

Figure 9 **(a) Yielded elements in 8.5 m thick pillar; (b) Yielded elements in 5.5 m thick pillar**

Table 1 summarises empirical thresholds, quantified as deviatoric stress ratio (DSR), for predicting rock spalling and bursting potential. DSR is the ratio between the deviatoric stress ($\sigma1$:$\sigma3$) and the UCS; typically used as a damage or failure criterion for brittle rock. The thresholds have been found to correlate well with past seismic hazards. The contour plot in Figure 0 shows DSR contours for the breakthrough pillar at 5.5 m width. The plot shows that the core of the pillar has a DSR in the range of 0.5–0.6 which is considered a 'high' seismic hazard. It should also be mentioned that extensive stress induced fracturing was evident in the back, which resulted in significant overbreak.

Table 1 **Anticipated seismicity for ranges of Deviatoric Stress Ratios**

Deviatoric stress ratio	Damage/failure criteria	Seismic hazard
≤ 0.3	No damage or failure	Low
0.3–0.5	Potential damage initiation	Moderate
0.5–0.7	Potential moderate rock mass failure with low to moderate seismicity	High
> 0.7–1.0	Potential sudden rock mass failure with moderate to intense seismicity	Very high

Pillar width:height (W:H) ratio has also been found to correlate well with seismic hazard in the mining industry. Pillars with a W:H ratio between 0.5 and 2.0 are relatively squat and have historically demonstrated greater seismic activity as compared to slender pillars. Figure 10 shows a plan view of secondary stopes (pillars) bounded by previously mined primary stopes and measured seismicity (Brad Simser, pers. comm., 2020). Because the main driving stress is horizontal and roughly perpendicular to the orebody, the relevant W:H ratio is the ratio of the stope strike length to the orebody thickness. As can be seen in Figure 11, there is significant seismicity in the squat pillars (2.0 > W:H > 0.5) and there is very little seismicity in the slender pillars. It is noted that the Garson breakthrough pillar had a W:H ratio of 5.5:5.8 m or 0.95.

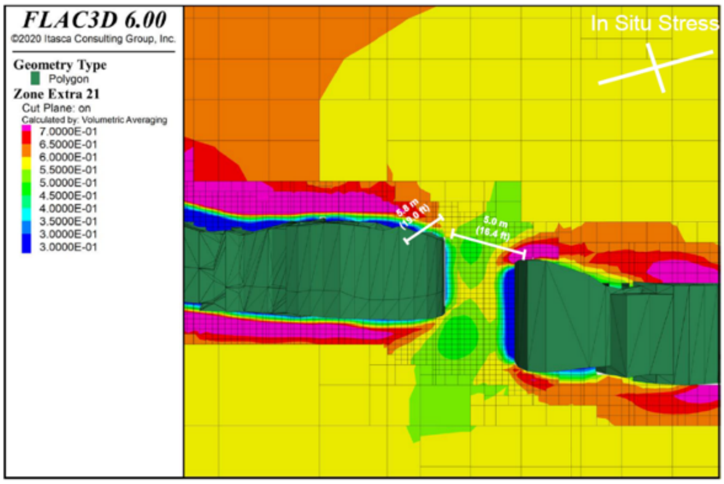


Figure 10 Deviatoric stress ratio at 5.5 m wide pillar

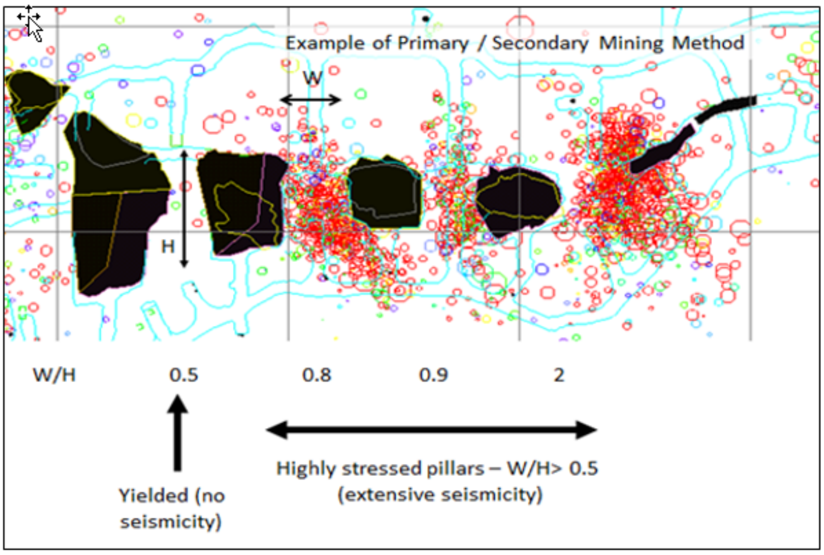


Figure 11 Example of seismicity for various weight:height (W:H) ratios (Brad Simser, pers. comm., 2020)

6 Methodology for the design and mining of breakthrough pillars in development headings

One of the key recommendations from the investigation into the 5220 Ramp rockburst is the formulation of a design and mining methodology for the management of diminishing pillars, including:

1. a methodology to assess seismic hazard for development breakthrough pillar
2. formalise a design review process (Vale North Atlantic Rock Engineering Group 2020).

6.1 Seismic hazard assessment

Based on internal knowledge and experience, many factors must be considered when assessing seismic hazard in a development breakthrough pillar. As shown in Figure 12, these factors include, but are not necessarily limited to: excavation method, anticipated stress level, previous knowledge and experience on rock mass behaviour in the area, local geology and geological structure, rock mass conditions and seismicity trends. For each factor, a rating of 1, 2 or 3 is assigned for Low, Medium, or High hazard respectively. In order to define the seismic hazard level, a simplistic approach was used and a numerical value of 12 (cumulative total if all parameters were rated as moderate) was selected to differentiate between a low to moderate seismic hazard and a high to very high seismic hazard. It is important to note that had this methodology been in place prior, the breakthrough pillar at the location of the 5220 Ramp, the pillarburst would have been classified as a 'high to very high' seismic hazard. This methodology will be further reviewed to identify opportunities for improvement in the future.

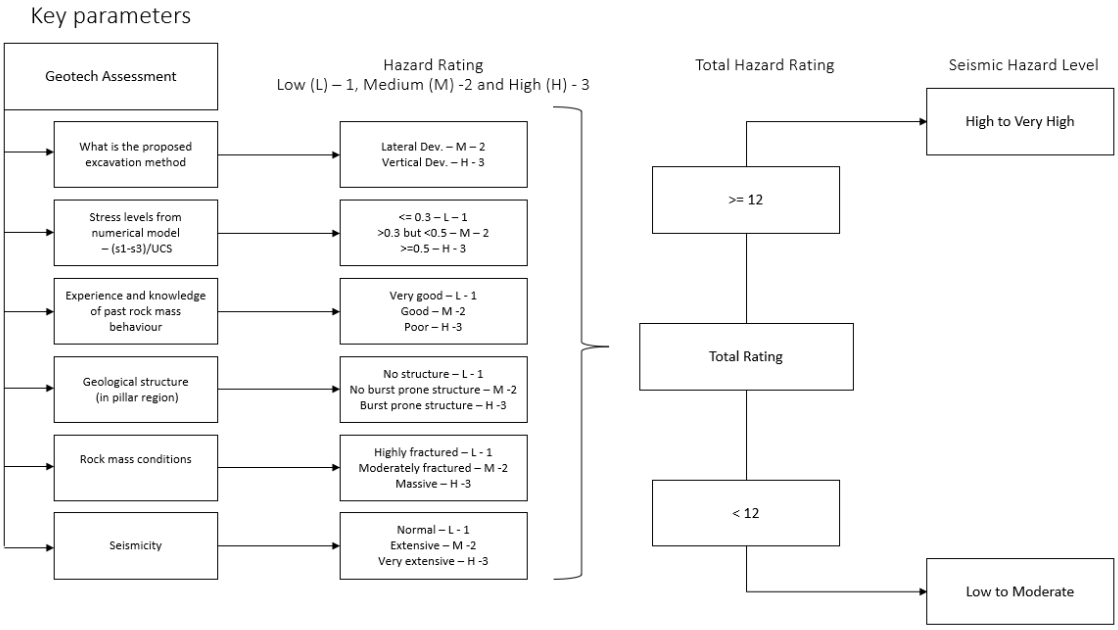


Figure 12 A rating system to assess seismic hazard for breakthrough pillars

6.2 Design review process

As shown in Figure 13, all development breakthroughs with 'high to very high' seismic hazard automatically trigger a formal risk assessment, including review and approval by an independent qualified individual is required and the development of a job hazard assessment with all key stakeholders, while all breakthroughs with 'low to moderate' seismic hazard follow normal development mining practice.

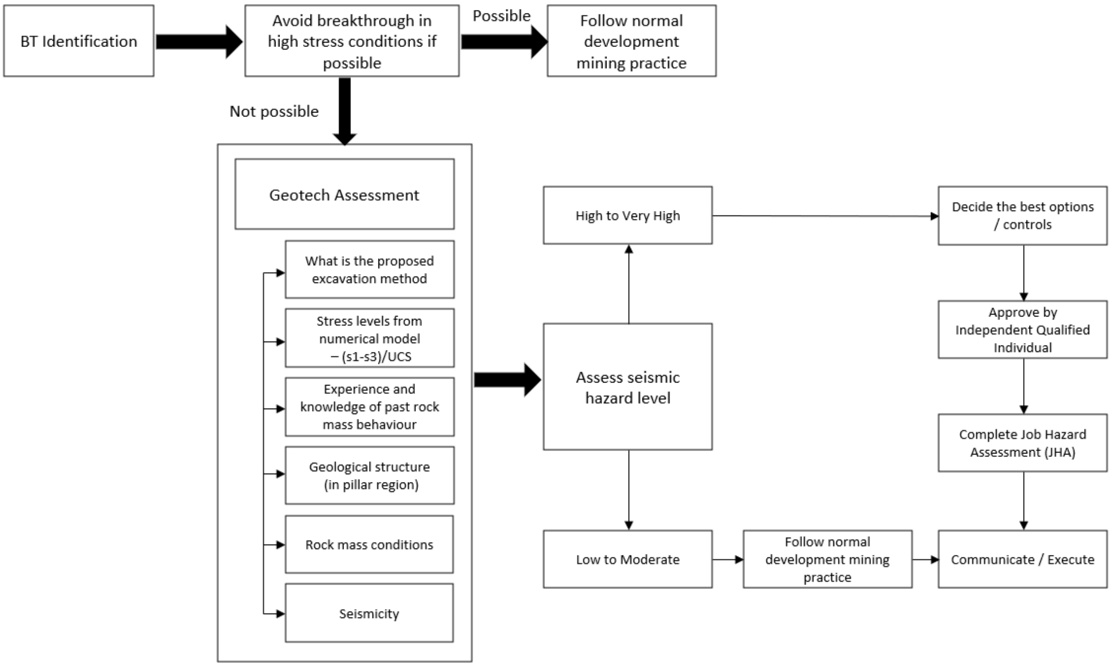
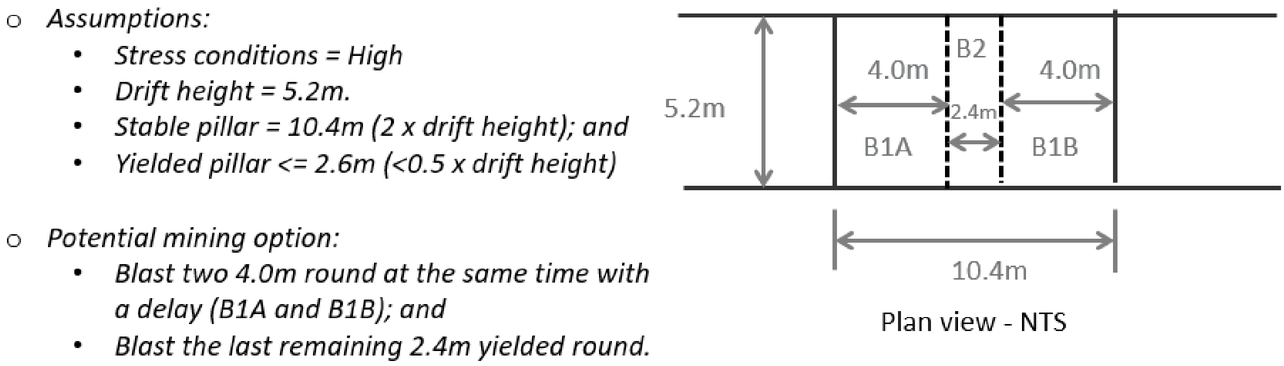


Figure 13 Design review process flow chart

6.3 Potential control measures

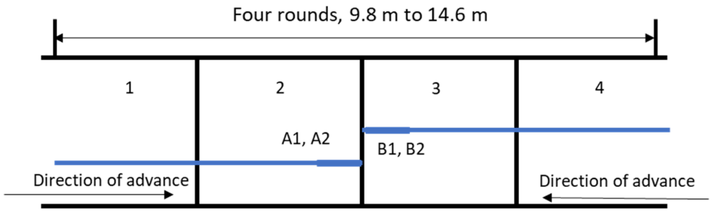
One of the most effective control measures is to blast and mine the remaining pillar from stable to yielded in a single step, i.e. from W:H > = 2 (likely stable) to W:H < = 0.5 (likely yielded). An example is given in Figure 14 to demonstrate this design.

Additionally, de-stress blasting may be implemented to alter the stiffness of the pillar, thus reducing high stress in the pillar, as shown in Figure 15. Similarly, preconditioning, including closely spaced drillholes, could be used to reduce the ability of the pillar to carry high stress.

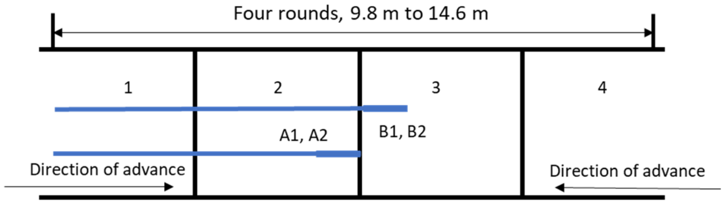


- *Assumptions:*
  - *Stress conditions = High*
  - *Drift height = 5.2m.*
  - *Stable pillar = 10.4m (2 x drift height); and*
  - *Yielded pillar <= 2.6m (<0.5 x drift height)*
- *Potential mining option:*
  - *Blast two 4.0m round at the same time with a delay (B1A and B1B); and*
  - *Blast the last remaining 2.4m yielded round.*

Figure 14 Blast design aimed at creating a yielded pillar state



(a) Drill from both faces



(b) Drill from one face only

Figure 15 De-stress blasting of the core of breakthrough pillar (drift height of 4.9 m, not to scale)

7 Successful implementation of the new design methodology for the 5300 Level 1210 Level access breakthrough

Since the pillarburst in the 5220 Ramp occurred, Garson Mine has designed more than 20 development breakthroughs using the new design methodology. To date, only two have been classified as 'high to very high' seismic hazard, both of which have been successfully developed without incident. The more recent of the two was the 1210 Level access on 5300 Level which connects the west side of 5300 Level to the west ramp (referred to as the 5210 Ramp at this location) as shown in Figure 16.

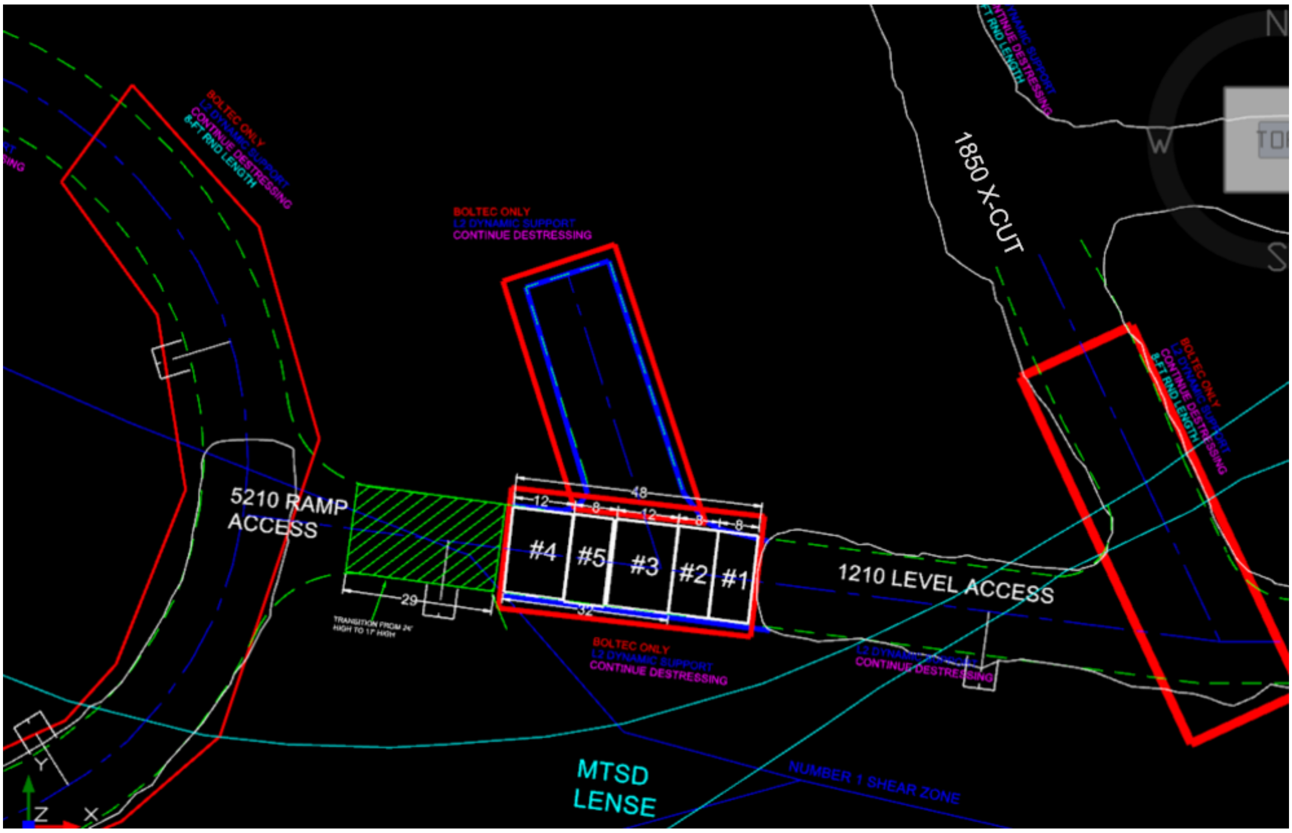


Figure 16 Plan view of the breakthrough in the 1210 Level access on 5300 Level

The 1210 Level access breakthrough was considered more hazardous than many other breakthroughs because it was planned to be developed in one of the more challenging areas of the mine. The west ramp to the west, and the 1850 Crosscut and connected infrastructure to the east; both experienced a number of strain bursts while being developed. This area of the mine is situated primarily in MTBS interlaced with east–west trending, steeply dipping metasedimentary lenses. As previously mentioned, the MTBS is very stiff and relatively strong and can be moderately jointed in some locations. The metasedimentary lenses are less stiff, and this stiffness contrast may explain why the mine has noticed that strainbursts often occur near the contact between these two lithologies.

The first step in designing a development breakthrough is to select a location. In some cases, practical and operational constraints may dictate the location; however, whenever this isn't the case, careful consideration is given to selecting a location. In the case of the 1210 Level access breakthrough the location was chosen to be as far from the nearby metasedimentary lens as possible (albeit not very far), to be in a length of drift that is not larger than usual either in height or span, and to be in a drift that is approximately aligned with the major principal stress (075°/00° at Garson Mine).

Next the anticipated stress conditions associated with various development strategies were assessed. Map3D's Fault Slip package (Wiles n.d.), which is a boundary element method tool that models the rock mass as being linearly elastic was used for the assessment. Figure 17 shows the development that was modelled, and the vertical grid plane that was used to view results. Mined out areas and the metasedimentary lens were included in the model but are omitted from Figure 17 for clarity. The breakthrough location was divided into 1.2 m lengths of drift advance, that were sequenced such that they were excavated sequentially so that the stress conditions in the pillar could be assessed in increments to determine when it was anticipated to transition from a stable pillar with an undamaged core to a yielded pillar.

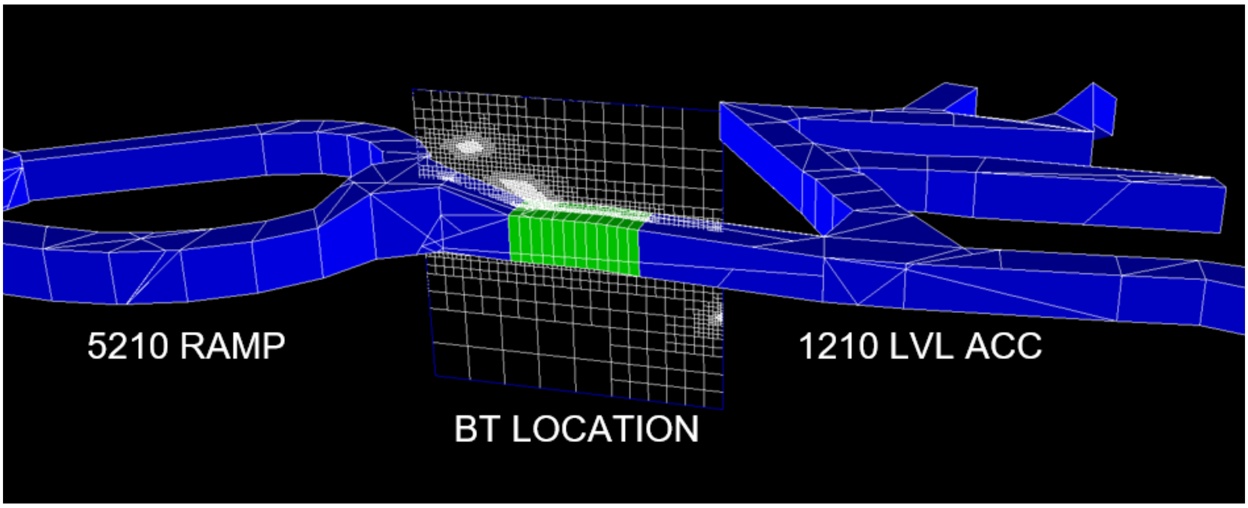
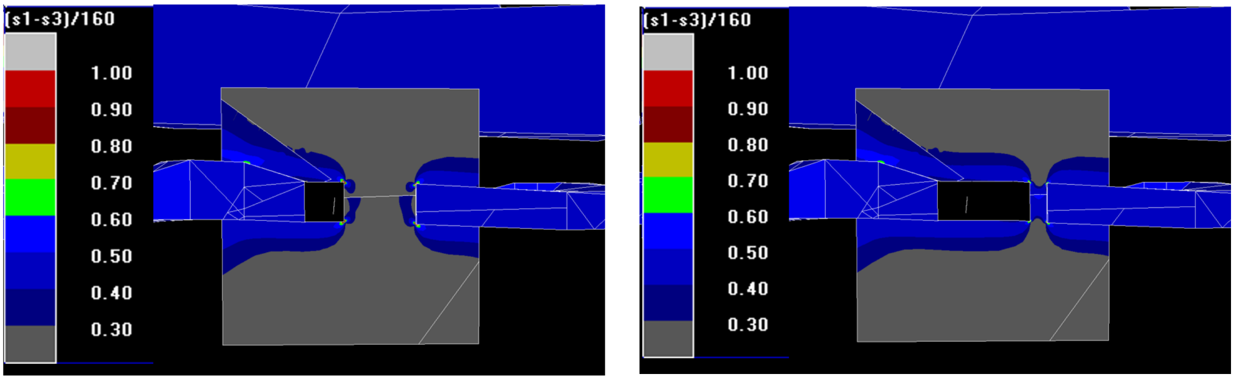


Figure 17 **Isometric view looking approximately north showing the geometry of the 5300 Level 1210 Level access that was modelled and the vertical grid plane that was used for viewing results**

Figure 18 presents the modelling results in terms of DSR for when the 1210 Level access is 9.75 m from breaking through (left) and when it is 2.4 m from breaking through (right). It should be mentioned that due to additional data collected, a UCS of 160MPa was used in this model compared to 180MPa being utilised in the previous model. The solids that make up the breakthrough pillar are not shown in Figure 18 to allow for an unobstructed view of the modelling results on the grid plane. The modelling results suggested that at 9.75 m there may be some stress induced damage in the face, which is common for all development in this area; however, the core of the pillar was anticipated to be intact. At approximately 7.30 m the pillar core was anticipated to begin to experience stress induced damage, and by 4.88 m the pillar was anticipated to begin to yield. These results suggested that it would be relatively conservative to develop the pillar to a thickness of 9.75 m, and to then blast a 3.66 m round from either side, leaving a 2.43 m yielded pillar that could be safely excavated. Figure 16 shows how this plan was executed, by numbering the rounds in the plan view. Rounds #1 and #2 were developed sequentially as 2.44 m rounds, then rounds #3 and #4 were excavated simultaneously as 3.66 m rounds, then round #5 was excavated as the final 2.44 m round.



(a) (b)

Figure 18 **Isometric view facing north showing deviatoric stress ratio displayed on a vertical grid plane when the 1210 Level access breakthrough pillar is (a) 9.75 m and (b) 2.43 m**

The execution of the breakthrough development plan was completed without incident. The seismic response to the development was modest, with the largest recorded seismic event being MN0.7. A number of tactical controls were also put in place:

- Personnel were only allowed near the face to check and mark bootlegs in order to limit personnel exposure, and only immediately after the ground control department had confirmed that no unusual seismic activity was occurring.
- The face was surveyed after every round.
- After the first two rounds were excavated, a test hole was drilled through the pillar to confirm the thickness reported by the survey results.
- A 24-hour seismic standoff was put in place after each round.
- De-stress blasting techniques were employed.
- A boom bolter (Boltec) was used to bolt the rounds and to bolt the face of each round.
- An enhanced face support pattern was employed that used a denser than usual bolting pattern of 1.2 × 0.76 m bolt spacing and the bolting was extended to a maximum of 0.9 m above the floor.

Ultimately, the success of this breakthrough as well as many of the other breakthroughs that have been recently executed was dependant on support from various work groups. The plan developed by the Garson Mine Ground Control team was reviewed and supported by an independent qualified individual, as is specified in the design review process. The plan was also supported by the Garson Mine Operations team and executed by DMC Mining Services. Leading up to the execution of the breakthrough plan, the Garson Ground Control team carried out a campaign of presentations and discussions with the various crews involved to ensure everyone was informed regarding the risks, the plan, and the reasoning for how various aspects of the plan had been established. Although a lack of clear communication had been identified as being a contributing factor leading to the pillarburst that occurred in the 5220 Ramp, effective communication is now considered an important control for development breakthroughs.

8 Conclusion

A detailed technical investigation into the 5220 Ramp rockburst has revealed that this was a classic pillarburst, where stress in the remaining pillar reached a critical (and unstable) state at 5.5 m to breakthrough. Lessons learned from this pillarburst can be summarised as follows:

- Although seismic monitoring in the period leading up to the incident failed to indicate elevated rockburst potential, historical experience while driving the ramp did indicate the presence of a seismic hazard.
- Having identified the seismic hazard through a risk assessment, additional controls, including stopping the advance of the up ramp heading and developing the remainder of the 5220 Ramp from the down ramp and a new face support design that extended the face support to within 0.6 m (rather than 1.5 m) of the floor, were demonstrated to be successful in reducing the severity of the incident.
- The effectiveness of 'pressure-relief' de-stress holes proved inadequate in mitigating the 5220 Ramp rockburst.
- This breakthrough pillar had a W:H ratio of 5.5 m:5.8 m or 0.95 being in the range between 0.5 and 2.0, which is relatively squat and has historically demonstrated greater seismic activity as compared to slender pillars.
- Back-analysis of the diminishing pillar via numerical stress modelling indicates that pillar yield was anticipated for a 5.5 m thick breakthrough pillar.

This paper presents a design and mining methodology for the management of diminishing pillars, including:

1. A methodology to assess seismic hazard for any development breakthrough pillar.
2. Development of a design review process.
3. Control strategies from a design perspective, which may include, but not necessarily be limited to; de-stress blasting, precondition the core of the breakthrough pillar and/or excavate the remaining pillar from a stable to yielded state.

The 5300 Level 1210 Level access breakthrough was used as an example to demonstrate how the new design methodology and process have been successfully implemented following the 5220 Ramp pillarburst.

It is hoped that by sharing this case study with the industry, ground control professionals can be made aware of when rockbursts may occur, and what mitigation strategies can be adopted when a similar mining scenario is encountered at their operation.

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