Rockburst risk management in deep hard rock mines: A multi-tiered approach with dynamic ground support as the last line of defense

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Abstract

Rockbursting around underground excavations continues to be a core risk for many deep mining operations. Numerous advancements in mine design, preconditioning, monitoring, mining equipment, exclusion zones, and ground support have significantly lowered the risk to mine workers. As mining continues in deeper, more challenging environments, a multi-tiered approach to rockburst risk mitigation, starting with mine design, is required. Both the overall mine sequence, for example, avoiding converging mining fronts, and local design "stick handling" can play an important role in risk reduction.

Rockburst case studies dating back to the late 1990s up until 2024 are used to highlight risk factors and risk mitigation (tactical and strategic). Examples from several deep hard rock mines are used, generally in high horizontal stress fields (k ratios 1.5 to 2), and strong brittle rock (> 200 MPa unconfined compressive strength). Mining induced stresses as well as high in situ stress due to depth are discussed. The context is Canadian mining, which typically has highly mechanised operations, large openings and equipment. Examples from a narrow vein mine and shaft sinking are also given because neither environment is simple to mechanise, highlighting the need for other risk mitigations.

A "sieve" analysis based on mine incident reports is used to show how a multi-tiered risk management plan can lower exposure to violent ground failures. A few incidents still make their way through the "sieve," indicating a need for further improvements. Thoughts on future/current developments, and their strategic importance are given.

Ground support is the last line of defence. The proliferation of multiple styles of yielding tendons and support systems has made many choices available to rock engineering professionals. Despite the increased availability of dynamic ground support components, there are still difficulties getting clean load transfer to bolts, determining support demand, monitoring loss of capacity over time/mining, and evaluating true system capacity.

Virgin development in deep high stress brittle rock can result in high strainburst exposure prior to any stoping operations. The mining process must reduce worker exposure to unsupported rockmasses. Successful preconditioning in a shaft sinking operation, the use of high early strength shotcrete, and mechanised equipment are also discussed.

Keywords

rockburst, rockburst risk management, deep mining, dynamic ground support

Introduction

Rockbursts in mining have resulted in safety and production challenges over the last century. As orebodies go deeper, and mining occurs in higher risk environments, mitigations for dynamic rockmass failures become increasingly important. Large magnitude seismic events (Counter, 2014; Jalbout, 2024; Mawson et al., 2022) continue to be difficult to manage. Their source mechanisms are often complex, and damage can be widespread. Many improvements have been made with respect to dynamic ground support systems, mechanised equipment, and mine design. Seismic monitoring systems are becoming better as computing technology improves, and implementation of longhole sensors (Butler, Simser, 2017) allows for early deployment and improved 3D coverage. The focus of this paper is on rockburst risk mitigation and its effectiveness. Robust ground support, and best practice mine design will limit the collateral damage from large seismic events.

The examples shown are from mines that typically record a few events greater than moment magnitude 2 per year, with variable rockburst damage from a few tonnes to a few hundred tonnes.

Mining methods varied from narrow vein cut and fill (underhand, overhand, drift and fill), narrow vein blasthole (upholes or downholes), and sub level open stoping with delayed backfill. Although the specific risk mitigations may not directly apply to all mining methods (for example caving, or narrow reef tabular mining), the principals of using mining strategies both on the global and local scale, reduced exposure, and robust ground support apply to all rockburst prone mines. Tunnel and shaft development examples are also used, which tend to be independent of the local mining method.

A multi-tiered risk mitigation strategy is required for deep mining. For example, even if a dynamic ground support system successfully contains rockburst damage, it is still much better not to have a worker in the area when it occurs. Conversely, even if workers can reliably be kept out of an elevated rockburst risk area, say by tele-remote equipment, the access is still required for removal of ore, or ventilation or other purposes. The exclusion protocol does not negate the need for rockburst resilient ground support.

Mine design is the first line of defence. It is well known that risk increases as mining fronts converge, whether on the scale of two tunnels approaching one another or independent mining fronts used for early ramp up of productive capacity. Underhand mining (top down with accesses under backfill) can create an independent mining front without converging on an existing one. Most of the man entry requirements are in the drilling/loading horizon of a stope; placing the access under engineered material that does not burst (cemented tailings backfill) can dramatically reduce exposure. Section 3 of this paper briefly shows a successful example of a sill pillar extraction between 1320 m and 1355 m below surface at a hard rock mine. Table 1 demonstrates a non-exhaustive list of strategies and tactics for rockburst risk mitigation and several of the items listed have specific examples in the body of the paper.

A simple rockburst model

Although there are many diverse types of rockburst mechanisms (Ortlepp, 1997), the simple model shown in Figure 1 is useful for both understanding risk and risk mitigation. The model represents homogeneous rock in a high horizontal stress field. A zone of stress-fractured material around the excavation is represented by the low stress contours, whereas stored strain energy is represented by the hot colours.

Table 1

Some rockburst mitigation strategies/tactics

Global Mine Design (some factors, not an exhaustive list)
- Overall design impacts risk profile
  - Converging mining fronts (e.g. sill pillars)
  - Yielding pillars (e.g. Primary/Secondary layouts at depth, mine 50% of reserve in low stress)
  - Chevron shape, leads/lags, bad geometries
  - Blast hole/bulk mining (more remote equipment) versus jumbo/hand-held mining (e.g. cut and fill)
- Local Mine Design
  - Mining under backfill
  - Developing through yielded and/or stress shadowed ground
  - Developing in less burst prone rock types, avoiding faults/dykes or crossing at shortest distance
  - Smaller openings less vulnerable than large openings

Exclusion
- Barricading old areas
- Seismic re-entry protocols
- Remotely operated equipment

Pre-conditioning
- Local scale (jumbo holes around development)
- Larger rockmass scale
  - Hydraulic fracturing
  - Choke blast patterns

Last line of defense – Ground Support
- Dynamic capacity
- Timing of installation
  - Earlier generally more effective
  - What portion of the cycle does it protect?
    - E.g. Face screening often only protects loading cycle

Figure 1—A simple model for strain bursts around tunnels. The locally stored energy/stress concentration around the excavation is often the source of the strain burst energy

Figure 2—Left: deep level (2490 m) shaft station excavation. The back was sprayed with rapid set shotcrete shortly after removing the blasted material. Right: view of intense stress fractures that were ahead of the previous advances face, exposed by the next advance (1400 m)

A dilemma for deep mining is that scaling or removal of the stress fractured material, reduces confinement and heads towards high stress concentration. In most cases this leads to more fractures forming, but in some cases, it may lead to violent bursting. The photo shown in Figure 1 initially had a flat back drilled profile, with gravity and bolter scaling resulting in a more stable arched shape. Strainburst risk increases as the confinement is reduced, so the trade-off becomes more dead weight (fractured material) on the ground support versus stored strain energy closer to the skin of the opening. Numerous factors affect the risk level: stronger rock can store more energy; deeper, increased extraction, and converging mining fronts all increase stress; standup time allows the fracture zone to dilate, loosen and more material is likely to fall out or be scaled out. Conversely ground support inhibits dilation, preserves confinement and lowers the strainburst potential.

The depth of fracturing around openings is a function of stress/strength. In strong, hard brittle rock (Figures 1 and 2), the process is time dependent. On the left side of Figure 2, the back was sprayed with rapid set shotcrete prior to bolting and screening. The early application of shotcrete provides confinement to the stress fractures forming around the opening (high horizontal stress, so fractures preferentially form in the back). In many shaft sinking operations, early development off the shaft barrel is completed by hand-held bolting and drilling. If the operator is spending time scaling out loose material, then exposure time increases, and the loss of confinement by removing the fractured ground increases strainburst risk. Although the shotcrete may not be sufficient for final excavation stability, it can contain the stress fractured material and preserve confinement. Field observations also show that if the heading gets hit later by dynamic loading, the shotcrete helps the outer layer of mesh and bolts by spreading the impulse load more evenly.

Although time-dependent failure in soft rock is well known (e.g., salt or potash), there can also be a significant impact in hard brittle rock when under high stress conditions. The right side of Figure 2 shows very intense stress fracturing that was ahead of the previous advances face. The depth and intensity of fracturing becomes more prominent the longer the face sits. In this example, that face was not advanced for approximately ten days 1400 m below surface with rock unconfined compressive strength of 250 MPa, and high stress conditions. Typical observations show limited face fracturing at this depth in similar rock types if the next advance occurs within a few shifts. At greater depths (~2500 m) in similar rock masses, observing increased stress fracture intensity and depth is common when development headings are not advanced for several days (Figure 3).

Figure 3—Fresh development round at 2490 m below surface in high horizontal stress (~1.5 x weight of overburden). Stress fractures from the back have dropped via gravity onto the blasted muck pile. The hanging mesh/friction sets were used to support the face prior to blasting

The case study of the shaft station in Figure 2 was successful because the schedule of shaft sinking is always very tight. The rapid set shotcrete was applied soon after the blasted material had been removed and could be bolted within one hour of application. Lateral development in the same rock types at the same depth has highly variable back overbreak and bolting times. In general, the longer the operators leave the new blast unsupported, the higher the overbreak and the longer the bolting time.

For precondition blasting, a similar model to that of Figure 1 is useful to target the "destress" zone. Hall et al. (2024) used precondition holes ahead of the planned break of a deep shaft sink. The intent was to target the stored strain energy based on the depth of fracturing observations. In the shaft sinking application, observed seismic activity increased as the blasted material was removed. The loss of confinement caused increased frequency of strainburst incidents (Figure 4). With the preconditioning holes and ensuring that the operator did not remove material past the planned break (no excessive scaling), the risk was reduced. The blasting pattern had to be customised for different rock types, as the depth of fracturing increases with weaker rock. Stemming of vertical holes is simple, and effective (gravity + gravel). This is not necessarily the case for lateral development where a lot of the preconditioning blast energy tends to rifle out the hole collar.

Reducing the "coiled spring" of stored energy near the skin of the opening is key to reducing the strainburst potential (Figure 5). However, this only partially addresses other rockburst risks such as fault slip or large-scale pillar bursts. By having an increased

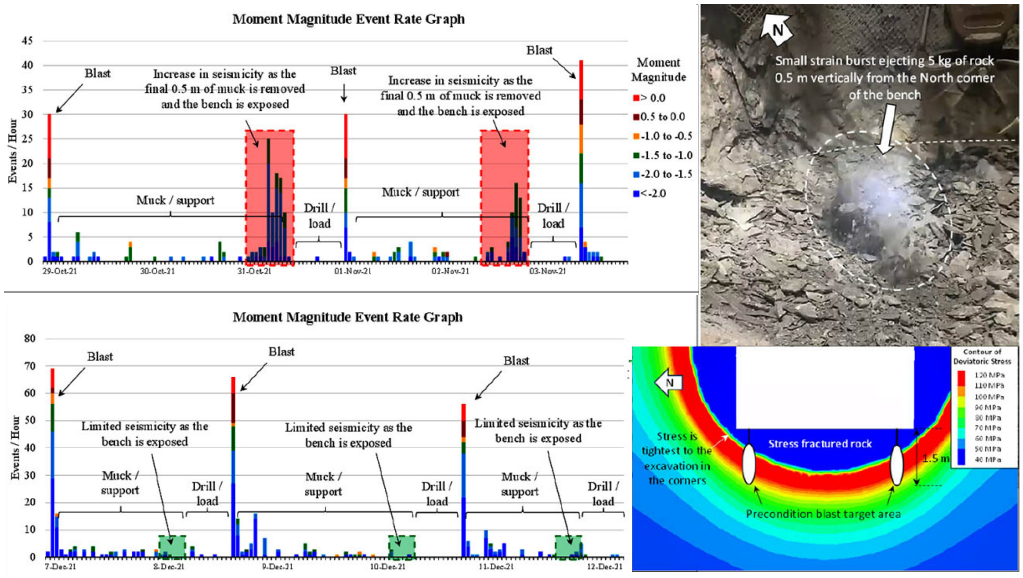

Figure 4—Top left shows seismic monitoring records for a deep shaft development cycle. Small magnitude events increase in frequency when the blasted rock is removed from the bench face (loss of confinement). This is when workers are normally checking for misfires and prepping for the next advance. By adding preconditioning blast holes, targeting the high stress zone ahead of the bench, and by NOT over scaling/mucking, the situation was alleviated. The lower left seismic records show no increased activity after the blasted muck was removed indicating successful preconditioning (Hall et al., 2024)

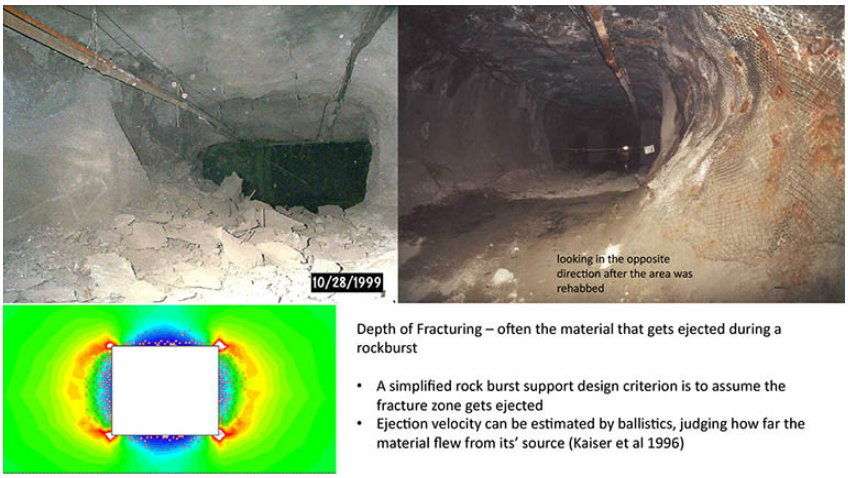

Figure 5—Left: wall burst material consisting of brittle rock, shotcrete and rebar. Shotcrete as the outer later has low deformation capacity. Right: same area after rehabilitation. This wall burst fits the simple model of the strain energy beyond the fracture zone being suddenly released (Simser, 2017)

"cushion" around the opening, knitted together by ground support, the impact of far field events may be dampened, but not necessarily eliminated. The far field event is often a good trigger to release the coiled spring (Simser, 2019).

Underhand mining

The use of excavations in backfill does not fit the simple model used in the aforementioned section. Backfill simply cannot store enough strain energy to generate rockbursts. Well engineered fill can be a safe place to be in the event of large magnitude seismicity (no coiled springs). The practice of underhand mining has been around for a long time (Pigott, Hall, 1961) and remains an effective risk mitigation for high stress mining.

Following, an example is shown from a sill pillar extraction at 1355 m below surface. The orebody was wide enough for three panels in the transverse direction (90 m total), with floor to floor spacing of 30 m. The original crosscut from the overhand mining was re-accessed by benching the floor and coming under cemented tailings backfill (hydraulic fill with unconfined compressive strength of about 2 MPa). Ground support consisted of fibre reinforced shotcrete, welded wire mesh, and expandable rockbolts.

During the mining of the third panel below the backfill, a large (moment magnitude 1.5) seismic event occurred in the stope crown after the first blast was taken. The standard practise at the mine was to take a ~30 000 tonne stope in two blasts using a 1.2 m raisebore as a slot. The first blast ("toe shot") trims the bottom of enough holes to get sufficient void for a final stope blast. For deep mining, the in-stope blasting sequence may need to be further altered to avoid shrinking an in-stope pillar, by daylighting to the overcut and slashing into the void for the final blast. This example highlights why that is a better method. Fewer blasting steps equate to lower worker exposure and better fragmentation. In this case the toes of the holes were fired first, creating a pillar between the overcut and the undercut (Figure 6).

The narrow span of the overcut (5 m) combined with ground support, and the ground motion dampening/attenuation role of the backfill reduced the potential rockburst damage. Some lower

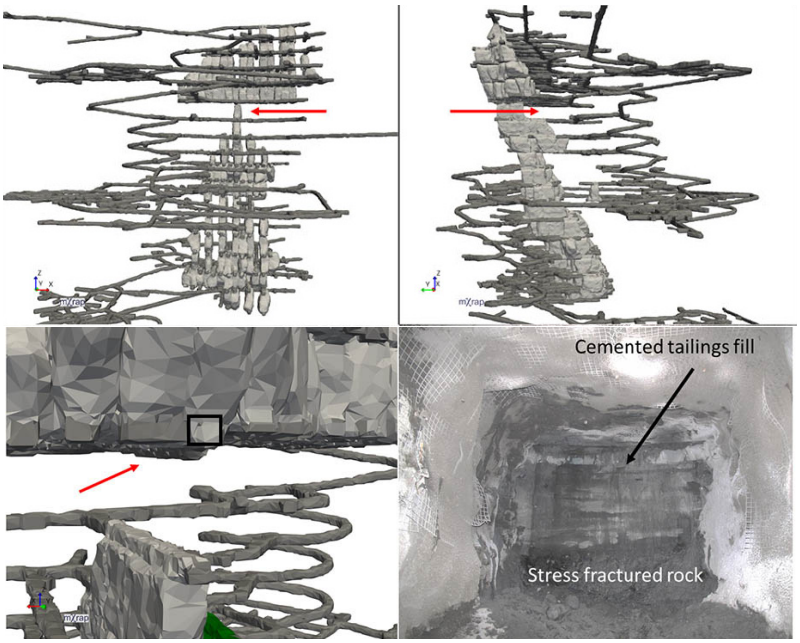

Figure 6—Sill pillar extracted 1355 m below surface (red arrow). The mined-out stopes above were filled with cemented hydraulic tailings. The sill pillar overcut was established by benching under/through the fill about 5 years after the original stope above was mined. The tunnel profile is 5 m x 5 m and mine sub level spacing was 30 m

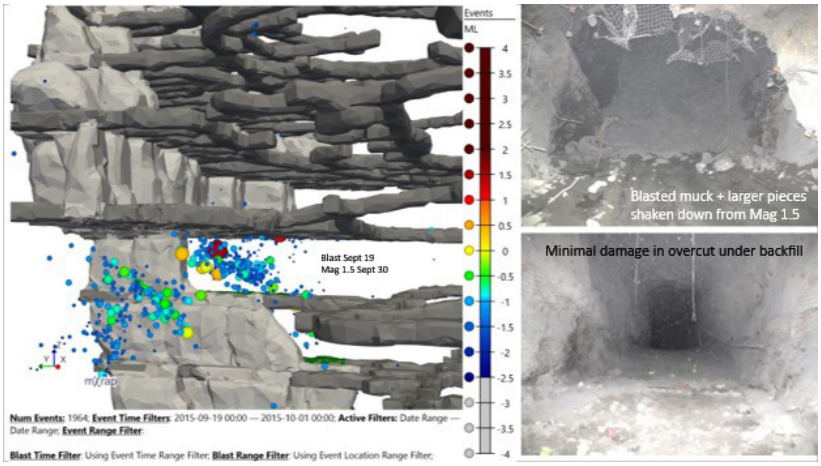

Figure 7—Left: Cross-section of stoping area showing seismicity in the crown (top portion) of the stope after the void blast (lower portion or "toes" of the blastholes fired). A moment magnitude 1.5 event occurred eleven days after the blast. Damage consisted of open stope slough onto the original blasted material. The overcut under backfill had minimal damage

wall shakedown occurred (Figure 7) but only required minor cleanup and check scaling. Fill undercut on the scale of a mined-out stope (12.5 m W x 30 m L in this example) can be prone to failure, however this stage is an open stope with no personnel access allowed.

Hierarchy of controls/control effectiveness

At great depth, in hard brittle rock, there may be sufficient high stress to make every development round a bursting risk. From experience, most advances do not burst but are prone to spalling and small magnitude seismic activity. This seismicity is a record of inelastic rockmass damage. The safety implications of a rockburst require that protection be in place, because even if a small percentage of rounds experience more violent failure, the consequences can be severe. In this type of environment, a robust process is required, because the uncertainty of which round might burst can not be easily resolved. High areal coverage, high deformation capacity (mesh on the outside), and dynamic bolts are applied. Equally important is the selection of mechanised equipment, to lower worker exposure to unsupported ground. There are several choices available such as the Australian style jumbo bolting, platform bolters with robotic arms, and Scandinavian style boom bolters (Figure 8).

Mine design plays a significant role in controlling rockburst risk, especially for larger seismic events. Simser et al. (2024) describe how overall increasing mine extraction leads to increased abutment stresses, and more seismicity, as well as faults becoming more mobile with time/extraction. Fault resistance to slip breaks down as asperities and/or rock bridges break down by repeated seismic activity and fault creep (inelastic deformation). As mining advances, the structures are pierced by more stopes, giving them increased freedom to displace. Ideally the mining advance would be away from the fault zone, however this is not always possible when there are multiple faults. Recognising the stress trapping between the fault and the mining front is also important. Appendix 1 shows an example of elevated seismicity under these circumstances.

Figure 8—Mechanised bolting with hollow core dynamic bolts and pumpable resin. The machine has a mesh handling arm and carousel/drill boom so that all ground support can be completed with the operator in the enclosed cab Left image is a close-up view of the bolting carousel/drill, right image is the same machine with the mesh transportation holder in the foreground

The figures depict a high stress abutment mining area with an underhand mining configuration, primary/secondary stopes and a seismically active fault zone. There were several design "stick handling" manoeuvres that were required to safely extract the area, which are alluded to in the image.

Converging mining fronts are well known stress raisers and elevate rockburst risk. Pillar failures, both on the converging mining front scale and local scale (e.g., draw point pillars, stope pillars, etc.), are also a well-known seismic source. In the mining layout shown in Figure 6, primary/secondary stopes were used. The secondary stopes are ore pillars that are mined after the adjacent primary stopes are extracted/backfilled. The pillars are left with slender width/height ratios (Jalbout et al., 2014) so that they do not build excessive confinement in the core and yield out benignly. The exact width/height ratio will be a function of both rockmass strength and stress. Slender pillars need to have an approximate W/H < 2/3 for hard rockmasses. Pillars that start to have W/H ratios > 1 will tend to build up enough confinement that the core of the pillar still carries load. Irrespective of the exact ratio, in narrow tabular deposits and narrow vein deposits it is difficult to design yielding pillars, as most mining geometries will result in squat pillars, and low W/H ratio pillars are likely to spall excessively (Andrews et al., 2019).

The following Figures 9a to 9j show a progression of annual mining steps in a narrow vein copper mine. The veins have an overall dip of about 45⁰ but locally range from flat to near 90⁰. Most of the mining was done by cut and fill, with some longhole extraction in converging mining fronts to reduce man entry requirements. The longhole method was optimised for stopes to be extracted in two steps: slot (void blast) and final blast. The final mucking access was typically positioned midway along strike, perpendicular to the vein. This process requires camera mucking left/right but keeps the remote stand outside of the plane of high stress, shadowed by the veins' extraction. Cut and fill mining practise varied to account for local dip, flat areas using drift and fill (mine a cut, cemented tailings backfill, mine adjacent to the backfill), overhand cut and fill (work on top of previous cuts backfill), and underhand (work below previous cuts backfill).

The mining progression shown was from 2015 to 2024, however historic extraction in the general area started in 1983. Rockburst incidents are shown with a "sieve" analysis (Table 1), indicating the effectiveness of controls. A few incidents were not controlled (leak through the sieve). No injuries occurred in any of the examples, but the potential existed. The complex network of veins created many geotechnical risks:

- Converging mining fronts (sill pillars).
- "Island pillars" where isolated waste blocks were formed by surrounding cut and fill mining.
- Mining towards a major fault zone. In this case the fault zone acted as a stress flow barrier, pinching stress between the mining front and the fault.

Typical cut dimensions were 3 m x 3 m or 4 m x 4 m, so most pillars left behind have high W/H ratio (squat). For converging mining fronts, empirical experience at the mine required a minimum of four cuts left (12 m) to safely switch to longhole mining. Numerical model back analysis thresholds were also determined, but in general the rule of thumb worked well. Some flatter dip areas could not be mined via longhole methods, and the last few cuts in a convergence zone were left unrecovered.

Figures 9a to 9j represent a small volume of the mine, approximately 300 m x 350 m x 150 m and 1400 m below surface.

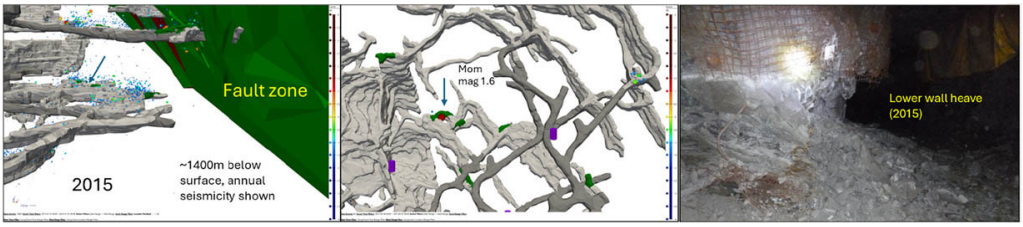

Figure 9a—Series of annual seismicity plots for a portion of an underground copper mine. Left image shows a long sectional view where drift and fill mining gradually approached a prominent fault zone, advancing from left to right in the image. The central image is a plan view of the same general area, where both converging mining fronts and isolated "island" pillars form. Right photo shows damage observed from the seismic event highlighted in the centre image

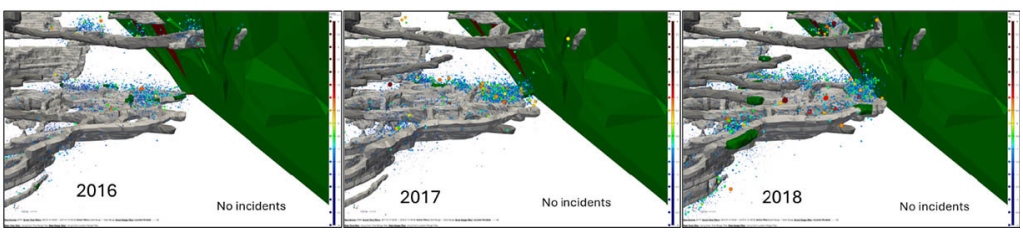

Figure 9b—Continuation from figure 9a left, showing annual seismicity plots as the drift and fill mining of a relatively flat vein advances toward the fault zone. The curvature of the vein in plan view meant that some portions were closer to the fault, the grey tunnels are 3 m x 3 m for scale

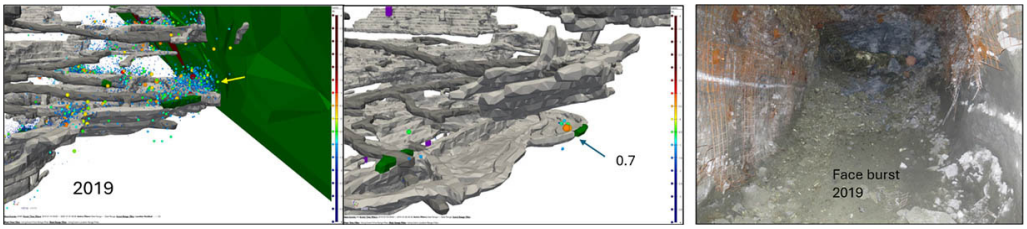

Figure 9c—By 2019 the outer flank of the curving vein was close enough to the fault zone that increased seismicity occurred. A strainburst happened prior to the face ground support being installed (seismic event associated with the burst indicated in the central image)

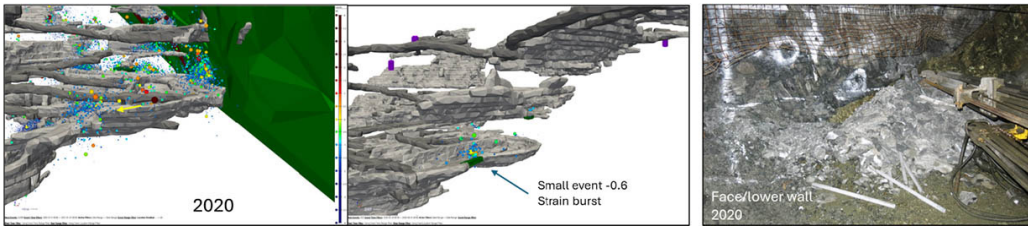

Figure 9d—The seismicity spread more vertically in line with the fault zone trapping stress between the mining front and the fault. Another strainburst incident occurred

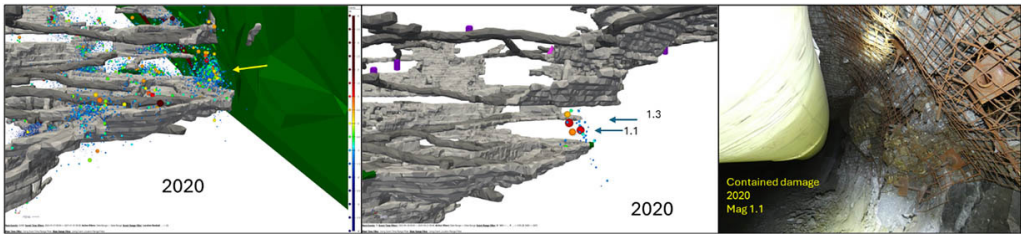

Figure 9e—The drift and fill mining was also approaching the mined-out vein above. Relatively large seismic events shown in the central figure (moment magnitude) had contained rockburst damage as shown on the photo

Figure 9f— The sill pillar vertically below the one forming in figure 9e experienced a moment magnitude 1.8 seismic event with some face and lower wall heave as well as contained damage, as shown in the photographs

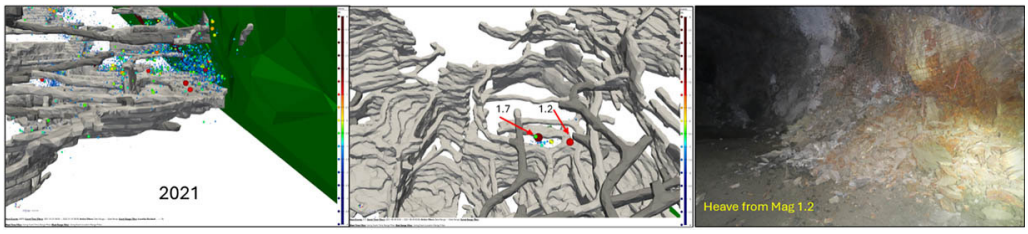

Figure 9g—An interior "island" pillar, which formed in the general region had two large events, damage shown was from the moment magnitude 1.2 event while the magnitude 1.7 event only caused local shotcrete cracking/mesh bagging

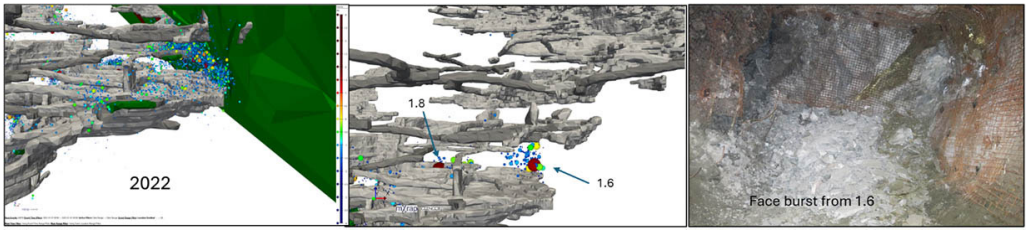

Figure 9h—A moment magnitude 1.6 seismic event caused a face rockburst in the drift and fill heading, again before the face bolts and screen could be installed

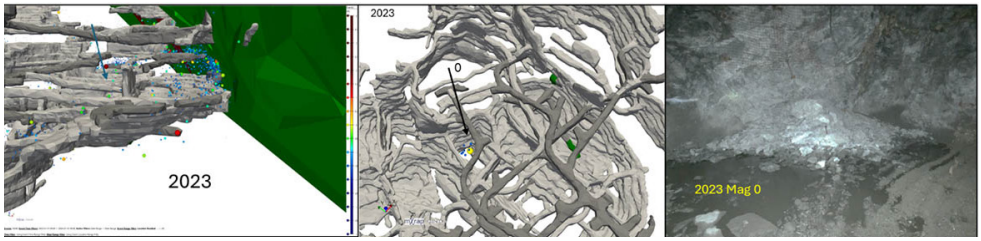

Figure 9i—A local interior "island" pillar experienced a moderate magnitude seismic event (magnitude 0 shown in the central figure) causing damage to the unsupported area in a longhole overcut heading

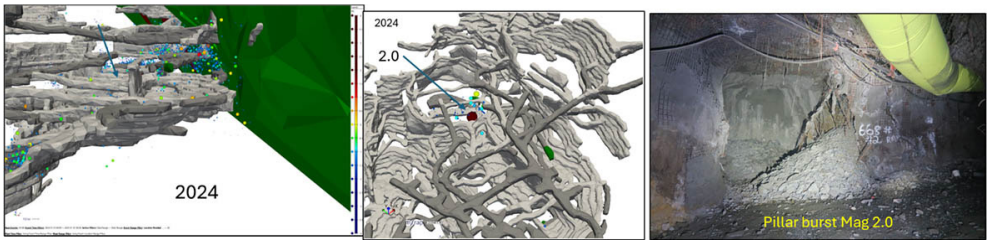

Figure 9j—The same "island" pillar shown in Figure 9g experienced another large seismic event (moment magnitude 2 shown in the central image), which had significant damage (photo)

Table 2

Summary of the 9 incidents shown in Figure 9. Although no injuries occurred, the red text highlights where the risk was not fully mitigated. This can be seen as a sort of "sieve" analysis to determine where controls that were in place were not sufficient to eliminate risk to workers

Incident	Mining geometry	Precursory seismic activity	Blast within 48 hours	Hindsight remedial measure
1	Island pillar	none	no	Support to floor
2	Sill pillar	Normal local seismicity	no	Remote load/wire/fire
3	Sill pillar	Normal local seismicity	26 hours	Re-entry worked
4	Sill pillar	Large event 1 hour before	8 hours	Re-entry worked
5	Sill pillar	none	no	contained by support
6	Island pillar	Large event 3 hours before	no	contained by support
7	Sill pillar	Large event 20 hours before	27 hours	Re-entry worked
8	Island pillar	Normal local seismicity	41 hours	Re-entry worked
9	Island pillar	none	no	Heavier support

The host rocks are granitic with high strength and complexity (breccias, gneisses > 250 MPa unconfined compressive strength). The copper veins are much weaker (~100 MPa u.c.s.) and the large strength contrast was a contributing factor to observed ground conditions. All seismic events are coloured/sized according to moment magnitude.

An exhaustive study of each incident is not included here but the overall summary in Table 2 that follows can be thought of as a "sieve", where multiple controls were in place. Seismic re-entry, rockburst prone support, and equipment selection were all part of the controls. Limited ability to predict the incidents in exact time and space was present, although risk factors, converging mining fronts, approaching the fault zone, and "island" pillars were all present. Narrow vein mining has fewer mechanised equipment options than say, bulk mining, which typically has 5 m x 5 m tunnels, allowing for larger jumbos, bolters, LHDs and other equipment. The early mining in the area used handheld drills for bolting (jacklegs and stopers) and was later switched to mechanised bolting. The mechanised bolter was a scissor deck style rig that required cut and fill profiles to increase from 3 m x 3 m to 4 m x 4 m for operating clearances.

Ground support varied from older rebar/mesh systems to yielding bolts and straps over mesh (75 mm aperture with 4.1 mm wire sheets and mesh strapping with 100 mm aperture and 8.4 mm wire stands). Development faces were supported by mesh and 1.8 m friction sets. An important aspect of that is areal coverage and timing of the face support. The advancing face is going to be blasted, so the temporary face support only protects a portion of the development cycle (loading). The practise at the mine was to bolt and mesh the walls and back first, then install face support. Several face bursts occurred before the face support was fully installed.

This specific area had high overall extraction, and several converging mining fronts. Removing one sill pillar would add load to other sills in the region. A blanket 48-hour seismic re-entry protocol was used after all longhole blasts. This, in principle, could be replaced by tele-remote equipment, eliminating risk to workers by accepting potential equipment damage.

Ground support (the last line of defense)

There are many inconvenient truths about rockburst resistant ground support (Hadjigeorgiou, 2024). Most support testing is based on axial loading, whereas a significant amount of shear loading exists in the field, load transfer to small cross sectional area tendons can be difficult, especially if fly rock is from small fragments. The source region of a large seismic event may not be supportable. Fortunately, the source region of most large fault slip events is often offset some distance from excavations. Despite limitations, there have been many improvements since the pioneering work and guidance of people like Ortlepp and Stacey (1997). The following section uses a few sample photographs to illustrate a few key points regarding dynamic ground support. In the authors' opinion there is still room for improvement despite the proliferation of multiple yielding bolt types available to industry (Simser, 2018).

It is useful to visualise the effect of catching a fast ball or a line drive off a cricket bat. This is best done by giving a little, rather than using a stiff arm. Shotcrete on the outside does not have sufficient deformation capacity, even if reinforced with mesh or fibres, it can only deform a few centimetres, whereas a few decimetres are required for strong bursts (Figures 5, and last visual in Figure 9).

Differential displacement occurs as large magnitude low frequency seismic waves pass through. The shotcrete post in Figure 10 failed during a Richter magnitude 3.7 event, the floor and back momentarily came closer, the stiff post in between did not survive unscathed. Falls of ground can also occur where the wave passing through momentarily interrupts clamping stress, for example, a steep wedge in high horizontal static stress.

A major design dilemma is what capacity to use for any individual tendon. Dynamic testing in the lab usually represents excellent load transfer, and maximum dynamic capacity (Li et al., 2024). Li et al. (2021) also highlighted the fact that an individual testing rig may have repeatable results for a specific bolt type, but there are inconsistencies between different test facilities. In situ it is difficult to get clean load transfer to the tendon, and many rock bolts do not fail during a burst or simply have a thread failure/plate tearing off, which occurs at lower loads than a split tube lab test.

In contrast to Figure 12, where joint dilation improved load transfer to the tendons and accommodated significant displacement during the seismic loading, the examples from Figures 5, 10, and 11 are more like the "simple model" that was discussed earlier on. Strain energy being suddenly released around the opening can eject the stress fracture zone into small fragments, which can easily fly out around the tendon.

Conclusions/discussion

The examples used in this paper are biased by experience in hard, brittle rock in high horizontal stress conditions. Other bursting types exist in mines, buckling of thin stiff layers, coal outbursts, dykes exploding, and faults/joints slipping. Ground support is the last line of defense, if possible no one wants to experience the trauma of a large ground motion close by. Exclusion, either by remotely operated equipment, barricading off old areas, central blasting, or seismic re-entry protocols should always be part of the risk mitigation strategy.

Mine design improvements clearly are required as more challenging conditions are encountered. For example, it is common practise to work multiple mining fronts to improve overall productive capacity. The later convergence of these mining fronts invariably increases stress, and rock bursting risk. At shallow depths this may be fine, at great depth the use of diverging mining fronts such as overhand/underhand lowers risk.

Some mining environments have inherently high strain burst risk due to depth/rock types. Focus on the process, keeping workers away from unsupported ground, becomes a critical control. Future

Figure 10—Deformation capacity is required to contain significant rockbursting. Mesh (left) can deform several decimetres if a weak link does not fail. Common weak links are sharp edged plates guillotining the wire strands, and seams between sheets peeling open. Bigger, stronger, more capacity does not work if there is insufficient deformation capacity (right shotcrete post with capacity > 1000 tonnes crunched by a seismic wave passing through the area)

Figure 11—Left: "naked tendons", a phrase coined by Ortlepp (1997) where the rockbolt does not break but the rock unravels around it, sometimes tearing of the face plate, sometimes leaving the bolt intact. Right: successful containment of a strain burst, the shotcrete on the inner layer promotes more even loading to the outer layer mesh. Despite using yielding tendons, there is still a deformation incompatibility between the highly compliant mesh and the stiff bolts. Rubber conveyor belt pieces were used to back the steel face plates to prevent guillotining

Figure 12—Blocky ground fares better than massive ground during a burst. The area shown had a seismic episode including moment magnitude 1.4, 1.8., and 1.9 seismic events. A substantial amount of deformation was absorbed by joint dilation, and dilating joints with smooth steel bars between them achieved good load transfer, allowing the yielding tendon to work closer to the lab testing result. See also Simser (2018)

improvements would include remote load/wire/fire. The practise of face screening in development is limited by the use of temporary support capacity and only protects the loading cycle. The ensuing blast-damaged face mesh and bolts are difficult to dispose of in new mining projects with limited development.

The simple model of stored strain energy around the opening as being the main source of rockburst energy is not universally applicable. It does apply in many instances and shows the need to target preconditioning holes to where the stored strain energy is. This seems obvious, but many preconditioning patterns are designed around where future bolt holes might intersect potentially unexploded powder. The model also explains why over-scaling at depth can create a hazard by removing confinement, and why rapid application of shotcrete to lock in stress fractures can be effective.

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References

Andrews, P.G., Butcher, R.J., Ekkerd, J. 2019. The geotechnical evolution of deep level mechanised destress mining at South Deep. *Deep Mining 2019 Conference*. Muldersdrift, 24-25 June 2019. The Southern African Institute of Mining and Metallurgy.

Butler, T., Simser, B. 2017. Microseismic Monitoring Strategy for Glencores's Nickel Rim Deep and Onaping Depth Projects. *Rasim9. 9th International Symposium on Rockbursts and Seismicity in Mines*. Santiago, Chile.

Counter, D.B. 2014. Kidd Mine – dealing with the issues of deep and high stress mining – past, present and future. *Deep Mining 2014* – M. Hudyma and Y Potvin (eds). Australian Centre for Geomechanics, Perth.

Hadjigeorgiou, J. 2024. Inconvenient truths about ground support in deep and high-stress mines. *Deep Mining 2024* – P. Andrieux and D. Cumming-Potvin (eds). Australian Centre for Geomechanics, Perth.

Hall, A., Simser, B., Cai, M., Lindsay, J. 2024. Preconditioning blasting for rockburst control in a deep shaft sink. *International Journal of Rock Mechanics and Mining Sciences*, vol. 181, 105841.

Jalbout, A. 2024. Geotechnical strategies to resume mining at Westwood mine following a Mn3.7 seismic event: part 1 – the investigation. *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*.

Jalbout, A. 2024. Geotechnical strategies to resume mining at Westwood mine following a Mn3.7 seismic event: part 2 – the mitigation plan. *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*.

Jalbout, A., Simser, B. 2014. Rock Mechanics tools for mining in high stress ground conditions at Nickel Rim South Mine. *Deep Mining 2014* – M Hudyma and Y Potvin (eds). Australian Centre for Geomechanics.

Kaiser, P.K., Tannant, D.D., McCreath, D.R. 1996. *Canadian Rockburst Support Handbook*. Geomechanics Research Centre, Laurentian University, Sudbury, Ontario.

Li, C., Hadjigeorgiou, J., Mikula, P., Know, G., Darlington, B., Royer, R, Pytlik, A., Hosp, M. 2021. Performance of identical rockbolts tested on four dynamic testing rigs employing the direct impact method. *Journal of Rock Mechanics and Geotechnical Engineering*.

Li, C., Mikula, P., Hadjigeorgiou, J., Simser, B., He, M. Canbulat, I, Joughin, W. 2024. I*SRM* Suggested Method for Determining the Properties of Rock Bolt Assemblies by Mass Freefall Impact Testing in the Laboratory. *Rock Mechanics and Rock Engineering*. 2024.

Mawson, M. Dahner-Lindkvist, C.R., Anderson, U.B., Thomas, A, Backstrom, A. 2022. The Kiruna seismic event: important insights from the geotechnical model. Caving 2022 – Y. Potvin (ed.). *Australian Centre for Geomechanics*.

Ortlepp, W.D., Stacey, T.R. 1997. Testing of Tunnel Support: Dynamic Load Testing of Rock Support containment systems. SIMRAC GAP Project 221. South Africa.

Ortlepp, W.D. 1997. *Rock* Fracture and Rockbursts, an illustrative study. *The South African Institute of Mining and Metallurgy*, Johannesburg, Monograph Series M9.

Pigott, J.A., Hall, R.J. 1961. Undercut-and-fill mining at the Frood-Stobie Mine of the International Nickel Company of Canada, Limited. Canadian Institute of Mining, annual General Meeting, Quebec City.

Simser, B. 2019. Rockburst Management in Canadian Hard Rock Mines. *Journal of Rock Mechanics and Geotechnical Engineering*. Jrmge. 2019.07.005

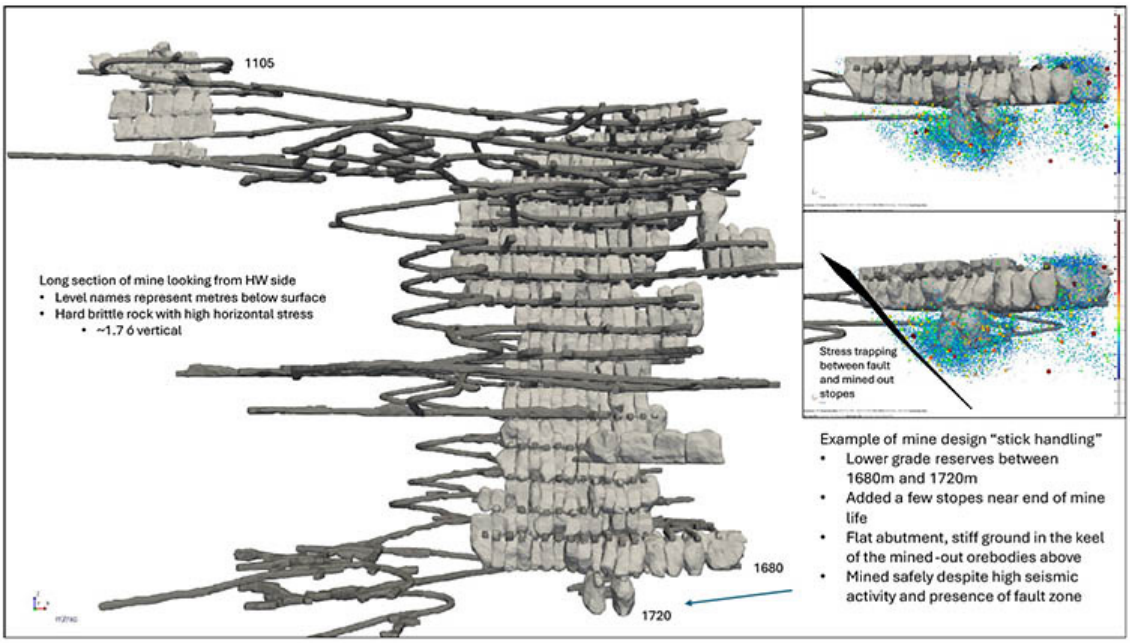
Simser, B. 2017. Design of Rockburst Support Systems for Deep Hard Rock mines. *Rock Mechanics and Engineering Volume 4: Excavation, Support and Monitoring*. CRC Press, April 2017.

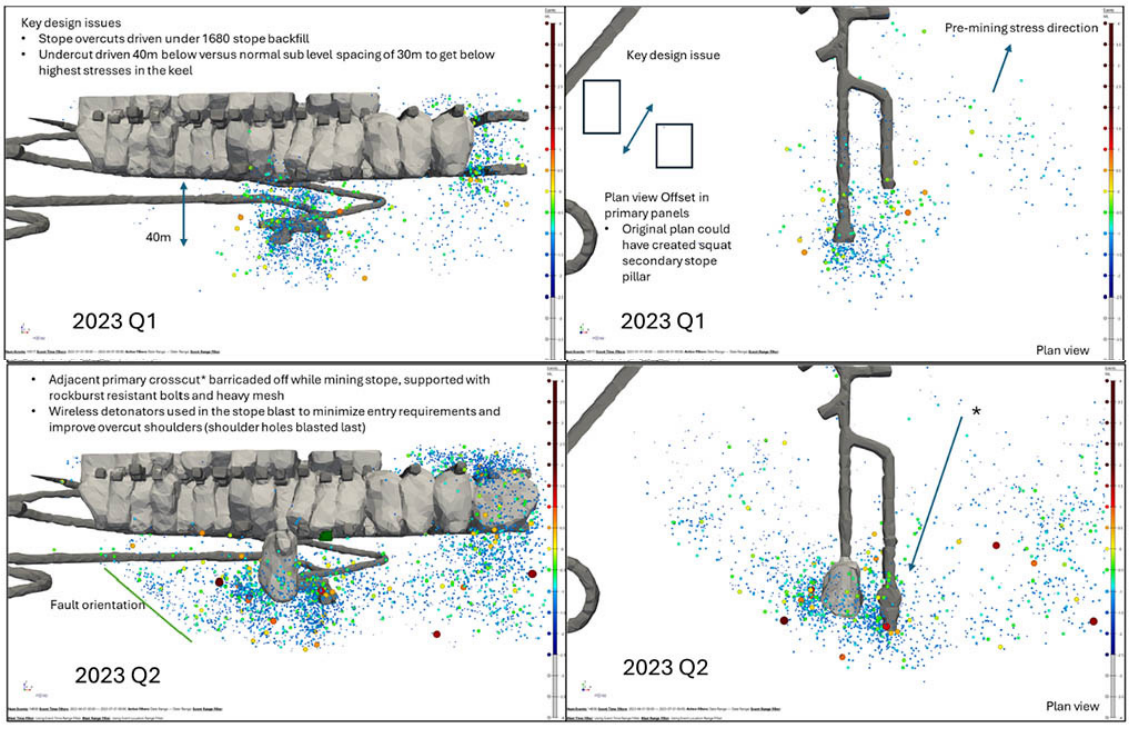
Simser, B., Yadav, P., Butler, T. 2024. Evolution of fault-related seismic behaviour at Nickel Rim South Mine. Deep Mining 2024 – P. Andrieux and D. Cumming-Potvin (eds). *Australian Centre for Geomechanics*, Perth.

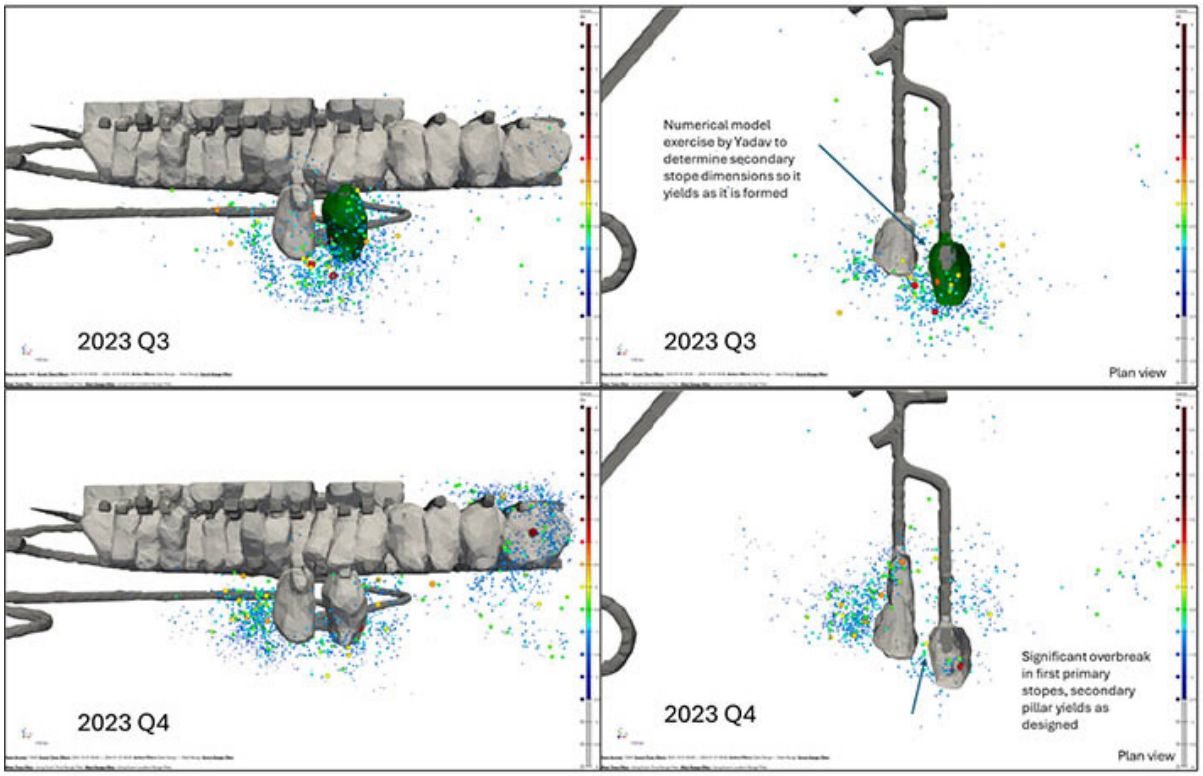
Simser, B. 2018. Rock burst Observations from hard rock mines: failures, successes, lessons learned. Rock Dynamics – Experiments, Theories and Applications – C. Li, X. Li, & Z-X Zhang (eds). 2018 Taylor & Francis Group, London. ◆

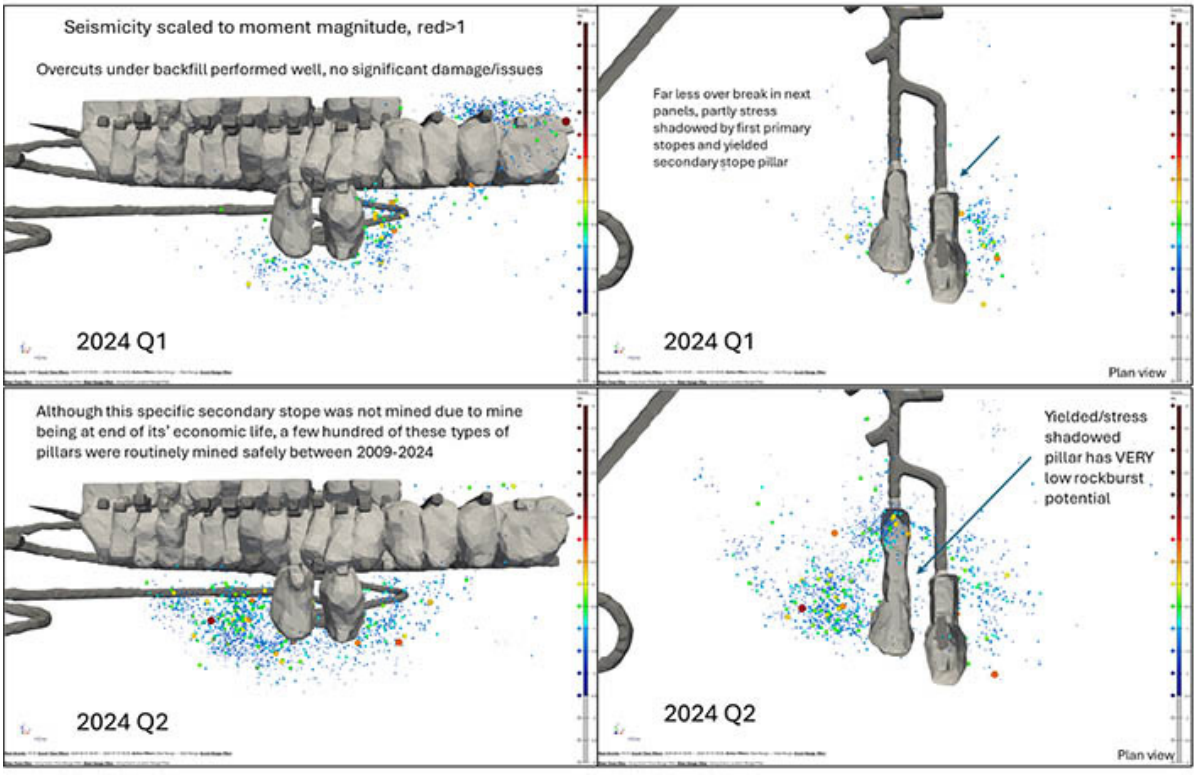
Appendix 1

Example of mine design lowering rockburst risk, overall approach and local "stick handling"






2023 Q3
Numerical model exercise by Yadav to determine secondary stope dimensions so it yields as it is formed
2023 Q3
Plan view
2023 Q4
2023 Q4
Significant overbreak in first primary stopes, secondary pillar yields as designed
Plan view


Seismicity scaled to moment magnitude, red>1
Overcuts under backfill performed well, no significant damage/issues
2024 Q1
Far less over break in next panels, partly stress shadowed by first primary stopes and yielded secondary stope pillar
2024 Q1
Plan view
Although this specific secondary stope was not mined due to mine being at end of its' economic life, a few hundred of these types of pillars were routinely mined safely between 2009-2024
2024 Q2
Yielded/stress shadowed pillar has VERY low rockburst potential
2024 Q2
Plan view