doi:10.36487/ACG_repo/2435_G-06

Structural models, a weak link in managing the risk from large seismic events

Y. Potvin and D. Cumming-Potvin
Australian Centre for Geomechanics, University of Western Australia

ABSTRACT

In caving and stoping mines, very large seismic events (i.e. moment magnitude 3.0+ events) are an important risk in terms of safety and production loss. A significant portion of these very large events are fault-slip type events. In spite of this, many seismically active mines do not have a good understanding of their structural geology from a seismic standpoint. Structural models are typically developed in the early project stages and focused on structures controlling orebody formation and mineralisation, rather than being created with a focus on the potential for generating seismicity. Commonly, the structural models available to the geotechnical team are out of date and can include hundreds of structures which do not influence seismicity, making the interpretation of fault-slip seismicity extremely challenging. Structural geology resources at mine sites are almost entirely focused on exploration and orebody delineation. Geotechnical departments rarely have access to structural geologists before seismicity becomes a major problem. When they do, these personnel often dedicate only a fraction of their time to update the structural model and they lack training or experience in mine seismicity. This paper details the importance of well-constructed, targeted structural models when managing seismicity and analysis methods that can be used to better understand the character and risks of fault-slip seismicity.

1 INTRODUCTION

Mine seismicity is a major risk in deep underground mines. Seismic risk mitigation methods can be strategic by managing stress redistribution from extraction sequencing or tactical, by using ground support with high energy absorption capacity as well as reducing personnel exposure by exclusion and automation.

Strategic mitigation is typically implemented at the design stage. For example, the choice of block/panel caving methods enable limitation of exposure of personnel to the extraction level, while the stress (and seismic) front is migrating upward with the cave. In open stoping mines, the stoping sequence can drive stress concentrations and seismicity towards the mine's abutments. Strategic mitigations require long lead times for implementation and as such, they provide little opportunity for implementation when a mine is producing.

Due to these limitations, tactical mitigation methods are the most commonly used methods during extraction. Modern dynamic ground support systems are typically efficient for events up to approximately Moment Magnitude (M_W) 2.0, with a general trend of decreasing performances for larger magnitudes. Mikula and co-authors have empirically demonstrated this trend at four Australian mine sites. **Error! Reference source not found.** is a plot of seismic events (local magnitude) versus support damage (SD scale after Kaiser et al. 1995), based on 361 data points from Flying Fox and Spotted Quoll mines (Graham et al 2023). These data points include all event types (both slip and crush-type events). The damage levels of S4 and S5 are classified as intolerable. The data suggests that for heavy seismic support systems (red lines), the ground support experienced tolerable damage for events approximately up to magnitude 2. Similar results were obtained from

Mount Charlotte (Mikula 2012) and Hamlet mine (Mikula and Gebremedhin 2017).

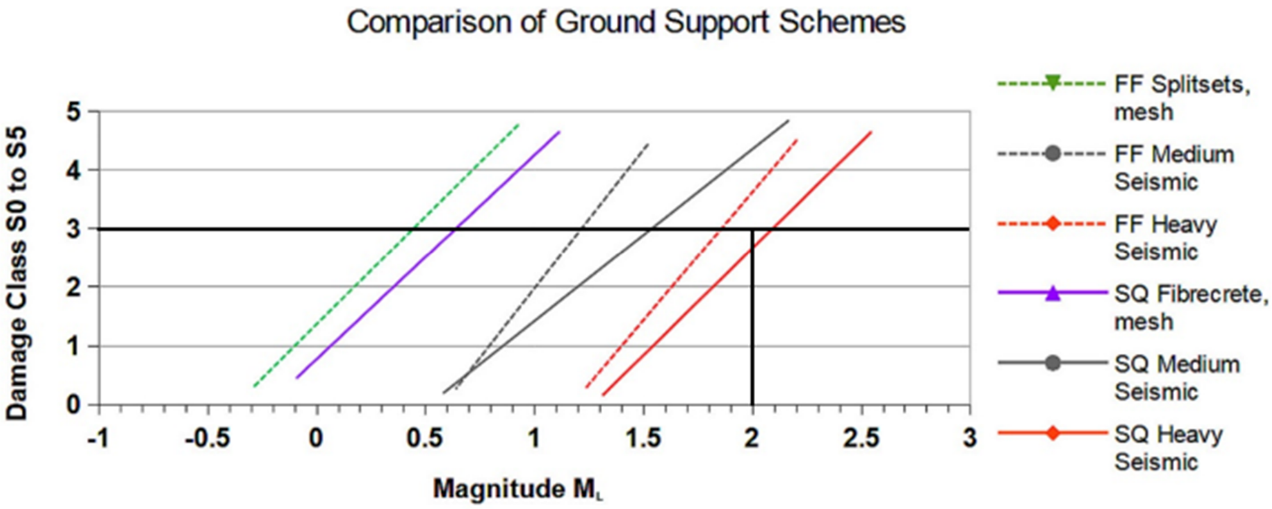

Figure 1 An example of the Empirical Charting Method from Graham et al (2023) showing that heavy seismic support at two Australian mines have been reliable for seismic events up to local magnitude 2.

Predicting when and where the next large events will happen is beyond the capability of current technology, but exclusion strategies following blasting or large events can further reduce the likelihood of personnel being exposed to seismic hazard.

Seismic risk management has been relatively successful over the last decade with very few fatal seismic events reported from mechanised mines. Nevertheless, large and destructive events exceeding M_W 3.0 are still occurring in both caving and open stoping mines. The potential consequences from such events can, in the worst case, cause significant loss of ore reserves, mine closure or multiple fatalities. Such extreme consequences motivate the need for continuously improving seismic risk management.

Understanding the source and mechanisms producing large events at mine sites can provide an excellent advantage to target tactical seismic risk mitigation in the right areas of the mine. Ortlepp (1992) provided useful guidelines regarding the range of magnitudes associated with different failure mechanisms (**Error! Reference source not found.**). He proposed that events greater than M_L 2.5 are typically either the result of a newly formed shear rupture through intact rock or a slip along an existing fault. In the authors' experience, large new shear ruptures are rare, and many of the very large events (M_W 3.0+) are fault slip related.

Table 1 Five mechanisms of damaging Rockbursts, modified after Ortlepp (1992)

Seismic Event	Postulated Source Mechanism	First Motion from Seismic Records	Richter Magnitude M_L
Strain-bursting	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	–0,2 to 0
Buckling	Outward expulsion of larger slabs pre-existing parallel to opening	Implosive	0 to +1.5
Pillar or face crush	Sudden collapse of stope pillar, or violent expulsion of rock from tunnel face	Implosive	+1.0 to +2.5
Shear rupture	Violent propagation of shear fracture through intact rockmass	Double-couple shear	+2.0 to +3.5
Fault-slip	Violent renewed movement on existing fault	Double-couple shear	+2.5 to +5.0

From more than half a century of seismic monitoring in mines, it is well known that the relationship between the frequency and magnitude of events from seismic sources (i.e., fault slip) approximately follow a power law (Gibowicz, J & Kijko 1994). Therefore, prior to event larger than Magnitude 3 occurring on a fault, one would expect approximately 10 Magnitude 2 and 100 Magnitude 1 events in the proximity of the seismically active fault (assuming a b-value of 1).

The implication is that the occurrence of significant numbers of smaller seismic events along a fault in the past can be a warning of the potential for large events to occur – enabling a pro-active local tactical dynamic ground support mitigation campaign. There are two key elements to implement this approach:

- To have a microseismic monitoring system capable of locating events with sufficient accuracy (+ or - 10 m is common target for high accuracy of source location).
- To have a functional structural model adapted to seismic response monitoring.

Seismic systems tend to evolve with time and increasing seismic activity and as a result, mines experiencing high seismic hazard often operate sufficiently accurate seismic monitoring systems. However, in the opinion of the Authors, the absence of a functional structural model is often a weak link in the implementation of seismic risk management plans at many mine sites. This is further discussed in the following section.

Identifying the trigger of large fault slip seismic events can be difficult. They often occur concurrent to, or within a short time after nearby blasts, or they can also happen days or weeks after a local blast (Woodward & Wesseloo 2015). They can also be triggered by another smaller seismic event. The long, time-dependent responses of faults slip events is likely due to faults being at limit equilibrium, where any small change in conditions can trigger a large event. This makes tactical exclusion protocols less efficient against fault related seismic hazards. Nevertheless, knowing the location of the seismic source (the seismically active fault) is helpful in defining the local volume of exclusion as well as areas that may require intense energy absorption ground support systems. The role of a good quality structural model for the tactical management of seismic risk is therefore critical.

2 STRUCTURAL MODELS IN UNDERGROUND MINES

Structural models are generally developed at the exploration stage of mining projects to define orebodies and establish mining resources and reserves as part of the scoping and feasibility studies. Once mines reach production, these structural models are updated periodically, typically with a focus of extending current ore reserves and resources. When created for this application, structural models can be very complex and may include hundreds of structures at scales varying from regional to mine wide, to local (drive) scales. The "ownership" of the structural model can lie with the exploration or the mine geology group but are often distant from daily mining and geomechanics activities.

Mine seismicity generally manifests itself progressively and becomes more intense with increasing depth and extraction of ore. Seismic events of larger magnitude often occur after many years of production in mature underground mines. By that time, the structural models are frequently "disconnected" from the operation. In many cases, the model in the area of interest has not been updated for many years because the area is no longer of interest to exploration work, or in other cases, the model comprises so many structures in a range of scales that it becomes impractical to relate structures to seismic activities.

A survey of 23 seismically active mines from around the world was conducted to gain a better understanding of how structural models are currently used to manage seismic risk in the industry. Figure 2 gives a breakdown by region of the surveyed mines.

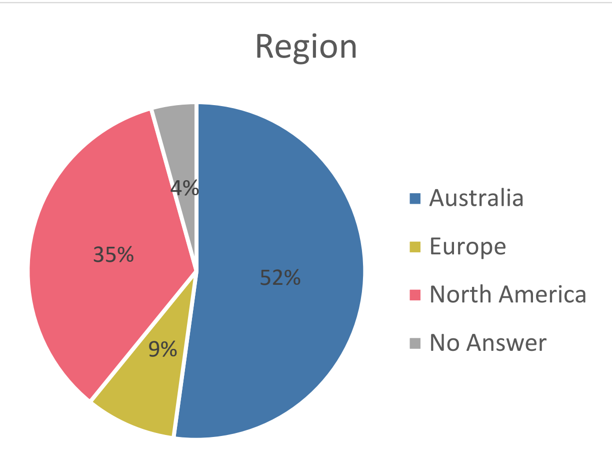

Figure 2 Breakdown of surveyed mines by region.

The rate of seismic activity for the surveyed mines is given in Figure 3. The definitions for the different categories were based on event rates above M_W 0 and were arbitrarily defined as:

- Low: Less than 50 events/year
- Medium: 50 to 100 events/year
- High: 100 to 1000 events/year
- Very High: More than 1000 events/year

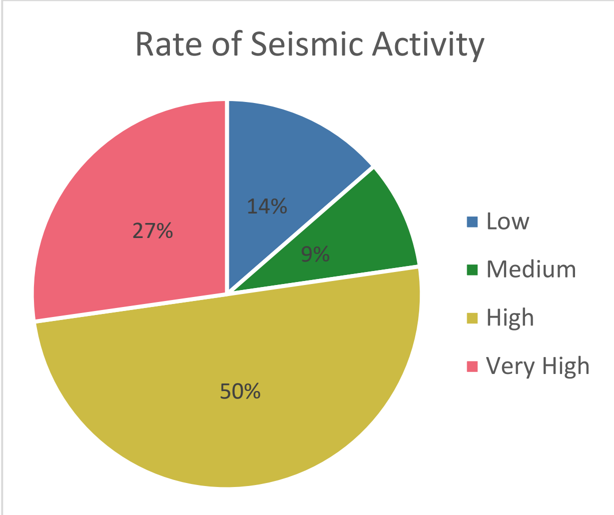

Figure 3 Rate of seismic activity of mines included in survey.

Despite the fact that more than three quarters of the mine surveyed experienced high to very high seismicity, only 26% of mines said that their structural geologist was moderately or highly experienced in dealing with mine seismicity and 43% had no structural geologist at all (Figure 4). The survey results show that the industry has a serious lack of structural geologists with experience in mine seismicity.

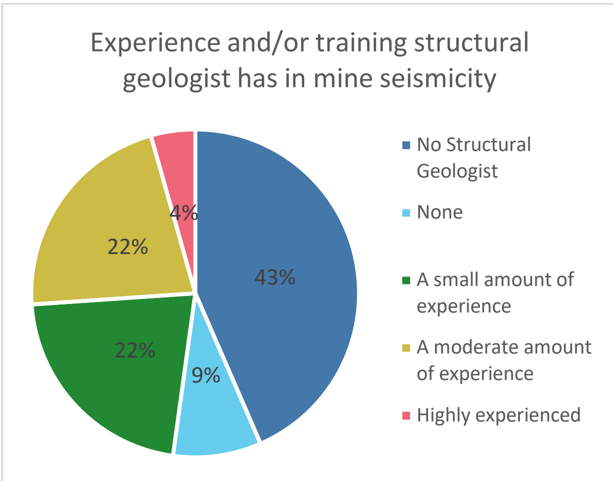

Figure 4 Structural geologist experience in mine seismicity.

In addition to the lack of experienced structural geologists, operating mines tend to receive very little help in this area. Almost three-quarters (74%) of mines either had no structural geologist, or one that spent 20% or less of their time on seismicity (Figure 5). A majority of mines (59%) had either no structural geologist, or one that interacted with mine operations only once per year (Figure 6).

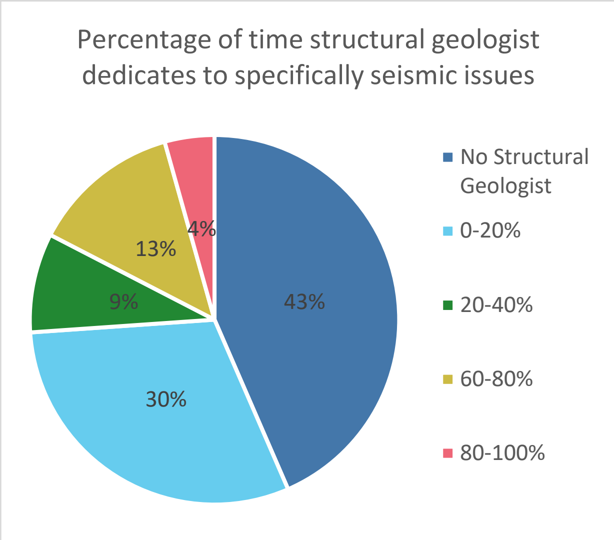

Figure 5 Percentage of time structural geologist dedicates to seismicity.

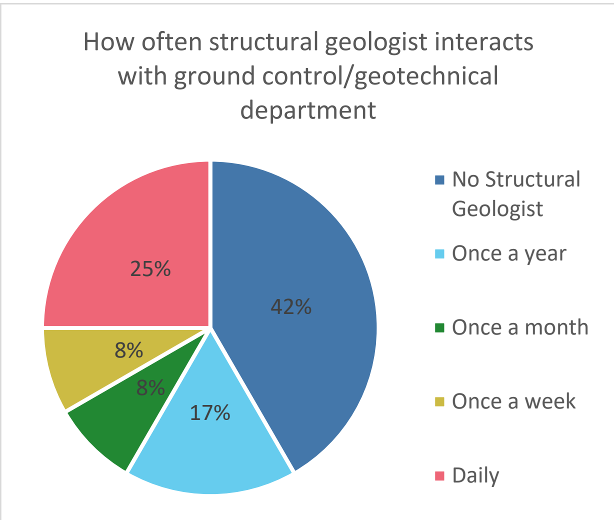

Figure 6 How often structural geologists interact with ground control /geotechnical department.

The lack of experienced structural geologists interacting with ground control engineers comes in spite of many of these mines having significant seismic activity (77% High or Very High seismic activity). The usability of the structural models that engineers have access to is also limited at many mines. Almost half (48%) of mines had structural models that were updated at most once per year (Figure 7). A significant portion had extremely few structures included, or so many as to no longer be useful (Figure 8). This is reflected in the engineers' opinions of the structural models, with only 35% rating their structural model a 7 or higher on a 1 to 10 scale (Figure 9).

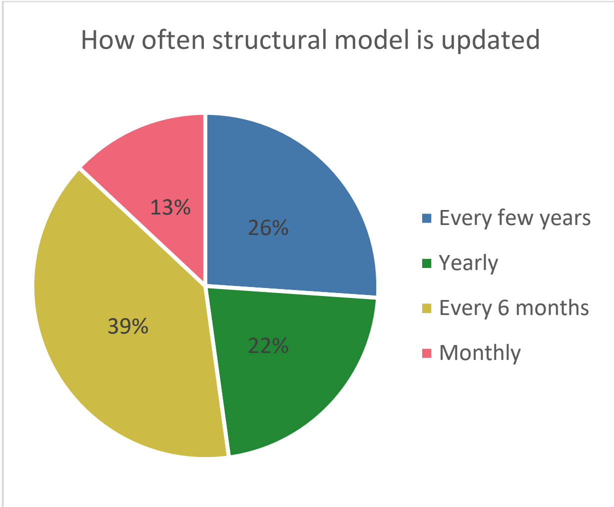

Figure 7 How often structural model is updated.

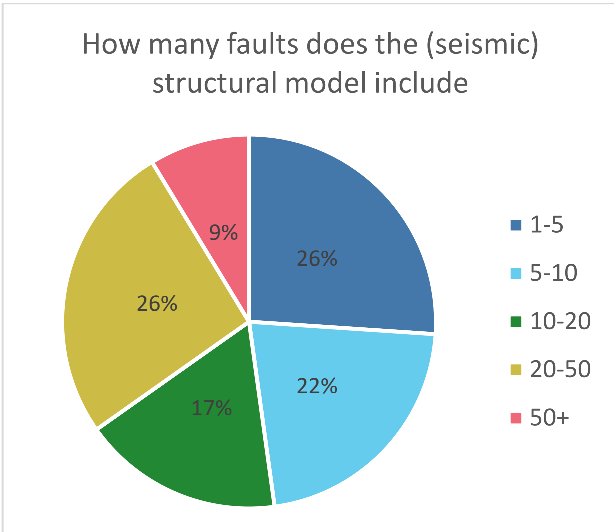

Figure 8 How many faults included in structural models.

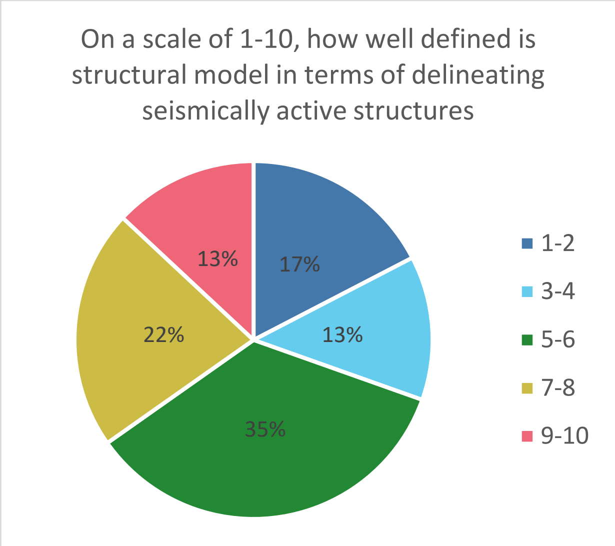

Figure 9 Rating of structural models in terms of delineating seismic structures (1 being poorly delineated and 10 very well delineated).

3 USING STRUCTURAL MODELS TO MANAGE LARGE SEISMIC EVENTS

One premise of this paper is to demonstrate that a functional and accurate structural model is a key tool to identify the source of most large events and understand their mechanisms, and as such provide powerful information to manage seismic risks. The likelihood of rockburst damage is generally significantly higher where highly seismically active structures intersect excavations. Therefore, although it is not possible to predict when the potentially damaging event will occur, locations that may be prone to rockburst damage can be identified ahead of time and tactical dynamic ground support can be installed pro-actively where highly seismically active structures intersect excavations. This requires a functional, up to date and accurate structural model.Managing large seismic events in open stope mines

Connecting large seismic events to specific structures is also important for the purposes of understanding the mechanism and root cause of large events. Mine induced seismicity is instigated by the redistribution of stresses around openings created by mining. More specifically, when the redistributed stresses result in an increase of the driving (shear) stress along faults and/or the reduction of the normal stress which is confining faults, it may re-activate fault slip movement. By understanding the cause (stress change due to mining) of large seismic events on a given fault, it may be possible to implement strategic mitigation by designing a favourable mining sequence that minimises shear stress increase and normal (confining) stress decrease on critical faults. It is important not only to focus on shear stress increases on structure, as the de-confining effect is often as much, if not more significant with respect to causing fault slip events. This is further discussed below. It is also noted that for complicated mine geometries, numerical modelling can assist in understanding shear stress increase and unconfining of faults, but for simple tabular deposit geometry, it is easy to understand stress redistribution qualitatively without any sophisticated models. Furthermore, there is very limited value in undertaking complex modelling analyses if the structural model is not adequate. In this case, quantitative assessment of seismic hazard from numerical modelling can be misleading.

To achieve a good understanding of the cause (stress change on seismically active structure) and effect (large seismic events), one needs to examine the historical stope extraction sequence in conjunction with the seismic responses and the structural model for periods that have led to large seismic events (e.g. larger than M_W 2). This has been identified as Step 7 "Measurements and Observations Trends for Forensic Analysis" in the Seismic Risk Management Process (**Error! Reference source not found.**).

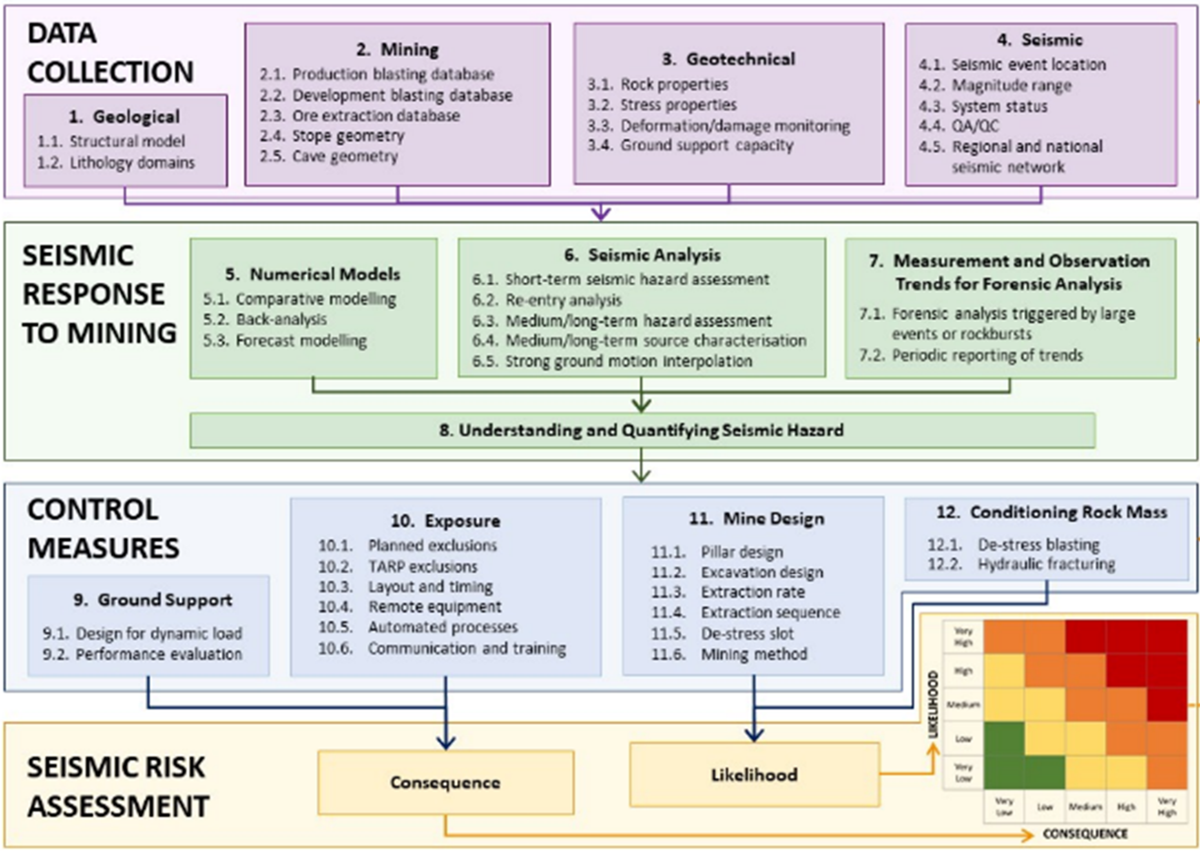

Figure 10 Seismic risk management process (Potvin et al, 2019).

It is reiterated that an adequate structural model (Step 1 of the process) and the identification of problematic structures are an essential prerequisite before undertaking analyses (Step 5 to 8) to achieve a good understanding of the seismic response to mining. More specifically in Step 7, one should be looking at time history of the seismic responses to individual stope extractions (and even individual blasts) during the weeks leading to large events and relate this to the stress changes (increase in driving stress/or decrease in confining stress) on the structures identified as the source of large events. Some of the common causes of large events on faults in open stopes observed at several mines include:

- Blasting of secondary stopes often unconfine structures sub-parallel to the orebody.
- Blasting primary stopes can increase abutment shear stress on structures perpendicular to the orebody.
- For thick orebodies, blasting footwall panel stopes can increase shear stress on structures sub-parallel to the orebody.
- Creation and shrinking of pillars containing major structures can increase shear stress and unconfine structures.

These are further discussed below.

The seismic moment and energy, and therefore the magnitude of fault-slip events is related to the area of slip along the fault. Consider the common case of a fault sub-parallel to a sub-vertical tabular orebody where σ1 is perpendicular and σ2 is parallel to the orebody. Extracting stopes shadows the confining stress originally acting perpendicular to the fault. The area extracted will grow with time and will produce a growing unconfined area on the surface of the fault. This means a larger potential slip area and potential for generating larger events. This principle is illustrated in **Error! Reference source not found.**.

A primary/secondary sequence will keep the fault confined by the stress going through the secondary stopes until they are extracted. This is temporarily a favourable situation but will have consequences in the longer term, as secondary stope mining will rapidly expand the unconfined area on sub-parallel faults. For example, the first secondary stope extraction connects the unconfined areas from the adjacent primary stopes and triples the unconfined area on the structure. Mining the second secondary connects two more primaries and results in an unconfined area equivalent of five stope widths, and this increase continues to expand significantly with secondary stope extraction. This is illustrated in **Error! Reference source not found.**.

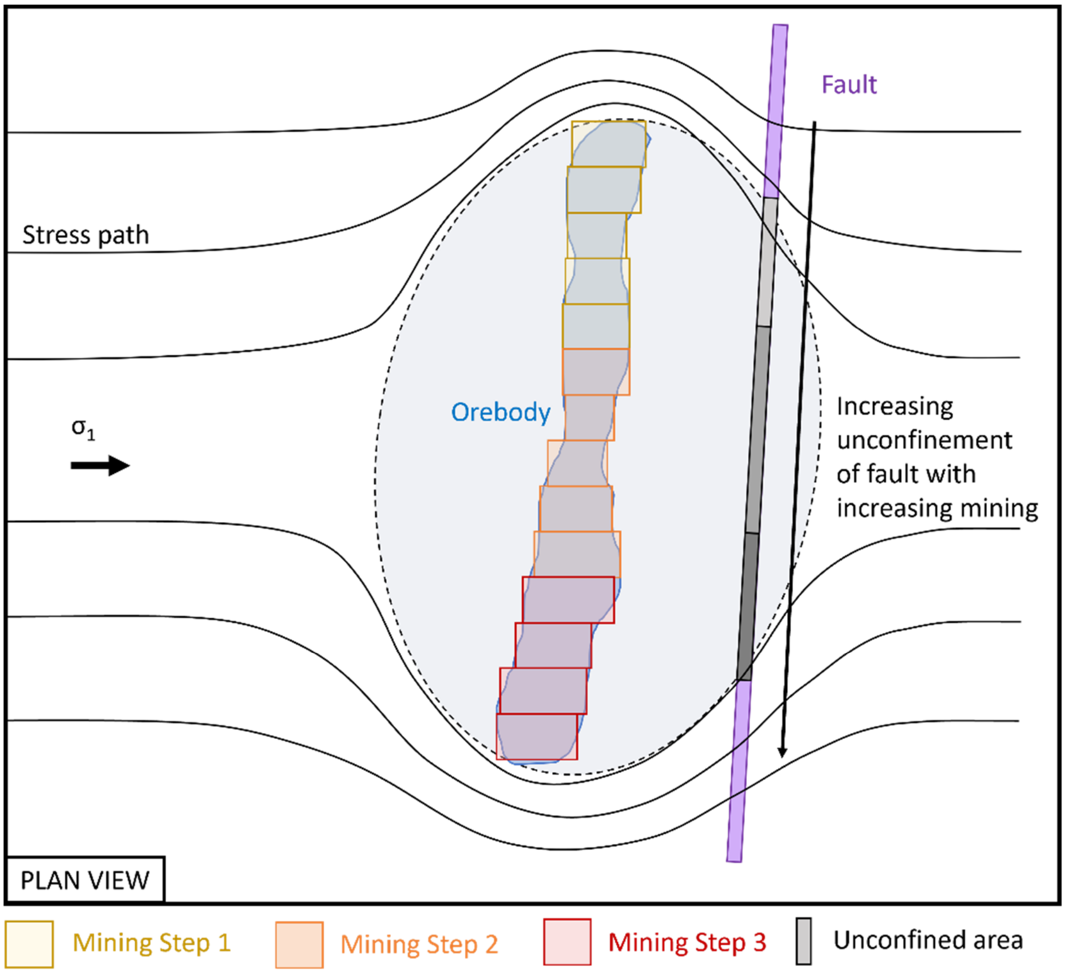

Figure 11 Schematic of increasing unconfinement of fault with increasing mining.

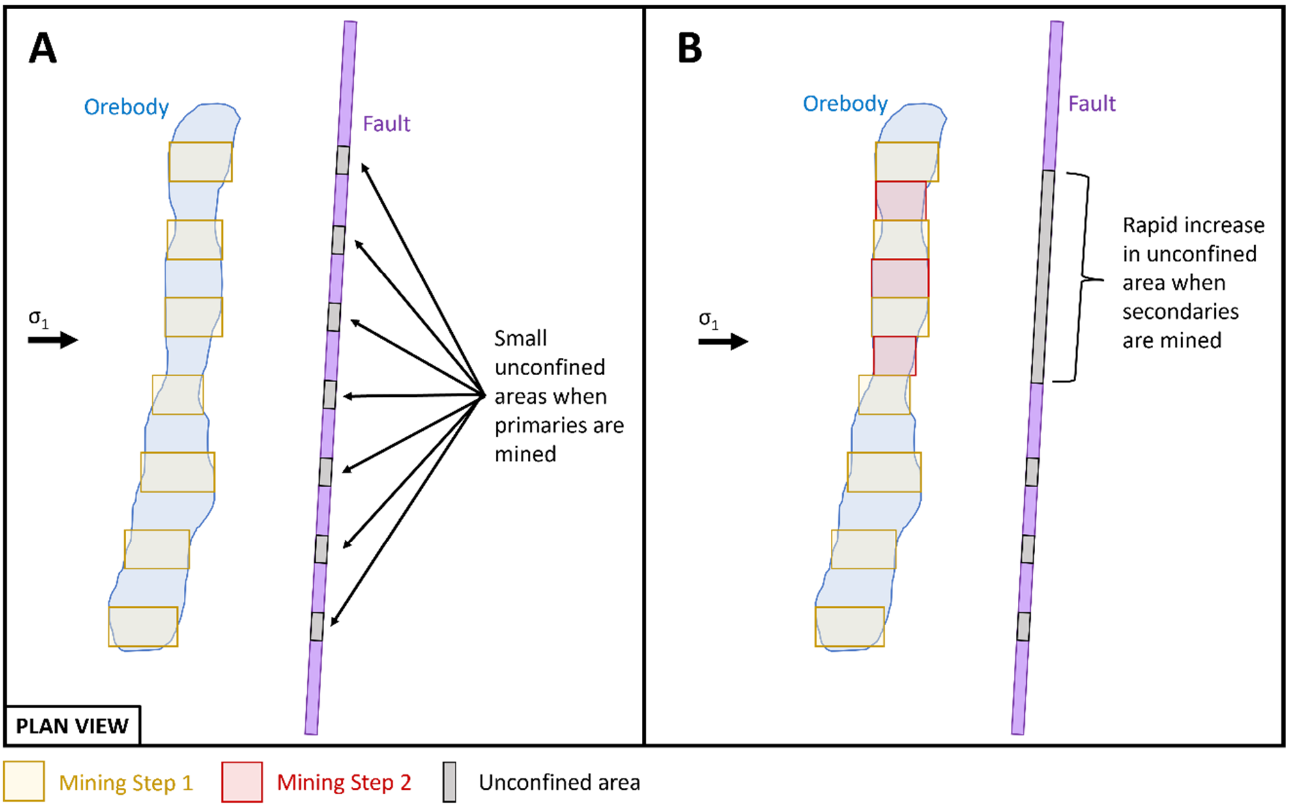

Figure 12 Schematic showing unconfinement of fault when mining only primaries (A) and after mining secondaries (B).

The recovery of major sill or rib pillars separating two large mining areas is an extreme case of rapid expansion of the potential fault slip area , where the unconfined area of a fault could double over the very short period of time of the pillar recovery. A significant jump in the upper limit event magnitude (M_{UL} – as defined by Wesseloo 2018) compared to what had been experienced during the mining of each individual area becomes possible because of the sudden increase in the total potential slip area.

This is illustrated in Figure 13, where two independent mining areas (A and B) are joined, causing a large and rapid increase in the unconfined area along the fault.

Therefore, as a general rule, progressive unconfinement of faults with pillarless mining or by systematically taking secondary stopes shortly after the primaries (i.e. from the centre towards the abutments or from one abutment of the orebody to the other) allows for a progressive increase in seismic hazard (rather than sudden jumps) and is therefore less likely to produce extreme seismic events when compared with merging two independent mining areas. For thick orebodies, significant stress redistribution occurs when mining abutment stopes, which extend the strike length of the extracted area (such as the situations previously described in **Error! Reference source not found.** and **Error! Reference source not found.**). Mining footwall panels in these orebodies can also concentrate the shear stress on faults sub-parallel to the orebody adding to the potential for slip on these faults (Figure 14).

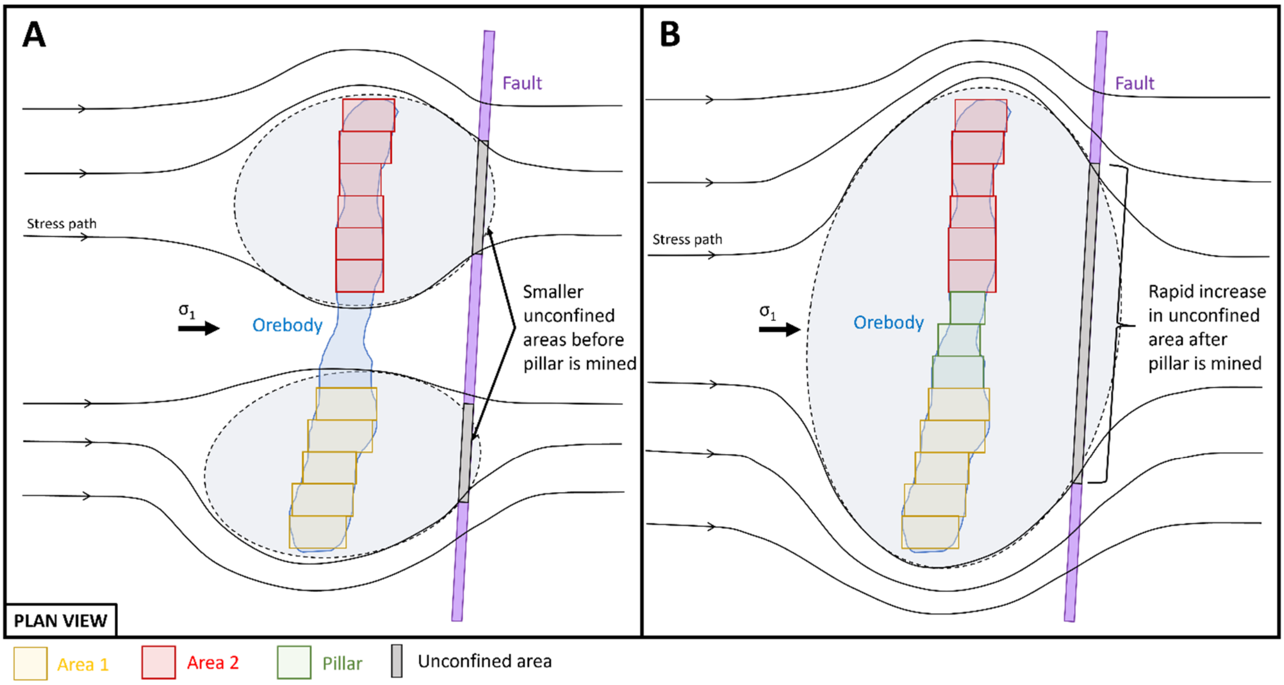

Figure 13 Schematic of unconfinement along fault before (A) and after (B) pillar between two areas is mined.

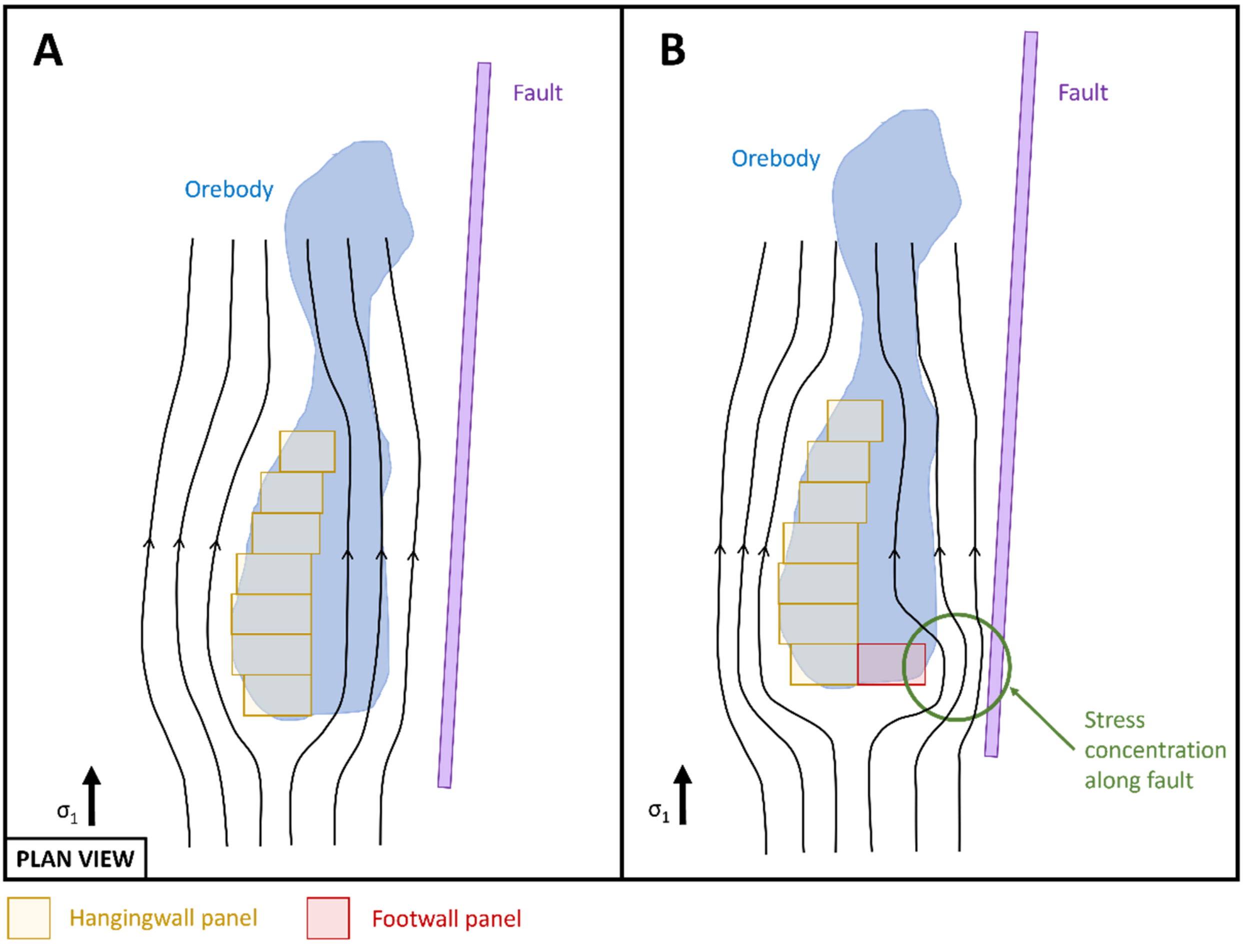

Figure 14 Schematic of stress concentrations along fault before (A) and after (B) footwall panel is mined.

3.1 Managing large seismic events in caving mines

Cave mining is a geomechanically controlled mining method relying on rock mass failure mechanisms for extraction and fragmentation of the orebody. One characteristic of caving methods is the very rapid rate at which the rock mass is fragmented creating rapid stress redistribution over very large areas, impeding energy release from being dissipated gradually. This can result in strain energy being stored locally (sometimes on faults) and released as large seismic events. The seismic risk from potential fault slip in deep block and panel caving mines can be high during undercutting as well as during breakthrough.

Experience has shown that advancing the undercut front parallel to faults can increase shear stress and deconfinement on seismically active faults and produce large seismic events in areas where personnel exposure is significant (Figure 15). The orientation of the undercutting front is often a compromise between keeping the main drives parallel to sigma 1 to minimise stress induced fracturing/squeezing and not retreating parallel to potentially seismically active faults. At the time of making the decision on the orientation of the undercut front retreat, there is often significant uncertainty as to the stress orientation as well as the structural model (particularly the identification of seismically active faults). This emphasises the importance of fast-tracking activities related to the development of orebody knowledge during feasibility studies and continuing to refine the structural model during development of the mine infrastructure.

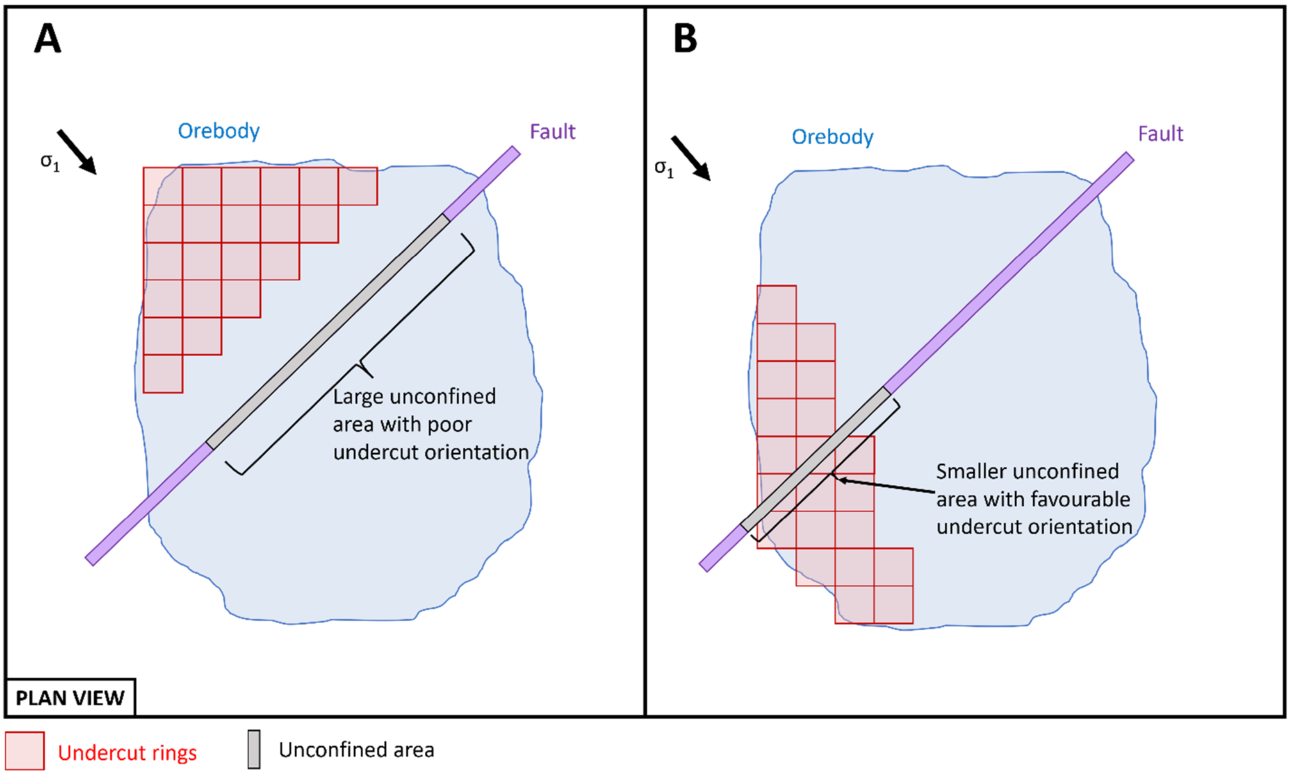

Figure 15 Schematic showing the effect of poor (A) and favourable (B) undercut orientation on unconfinement of fault.

Cave breakthrough to surface or through an existing mined area is another critical period of elevated seismic risk. Preceding a cave breakthrough, the lower cave propagation is effectively shrinking a crown (or sill pillar). As the pillar yields, there is a major transfer of stress from the crown/sill to the underlying area of the cave causing a major stress redistribution towards the extraction level. More specifically, this induces vertical shear stress and unconfining of any sub-vertical structures present parallel to the cave. Cases of caves breaking through an existing mined out area is akin to sill and rib pillar recovery in open stope mines where two large mining areas become connected, producing very large unconfined area prone to slip on sub-vertical faults, as illustrated in Figure 16.

The breakthrough period will also see a rapid increase in horizontal shear stress below the cave, sometimes activating seismically active faults in or near the extraction level. It is therefore common that the cave breakthrough period corresponds to when the seismic hazard is at its maximum. After the breakthrough is completed and the stress re-adjustment and high seismic response period took place, the seismic hazard decreases to a lower residual level. This is the stage where production has a reduced impact of seismicity and can be optimized.

In sublevel caving, the main drivers of large fault-slip events are the unconfinement of faults sub-parallel to the orebody, transecting or near the infrastructure (drives, cross cuts, orepasses, etc.), generally in the footwall. Again, identifying the seismically active faults early to locally increase support capacity and avoiding leaving pillars are key mitigating actions to lower the probability of large damaging events.

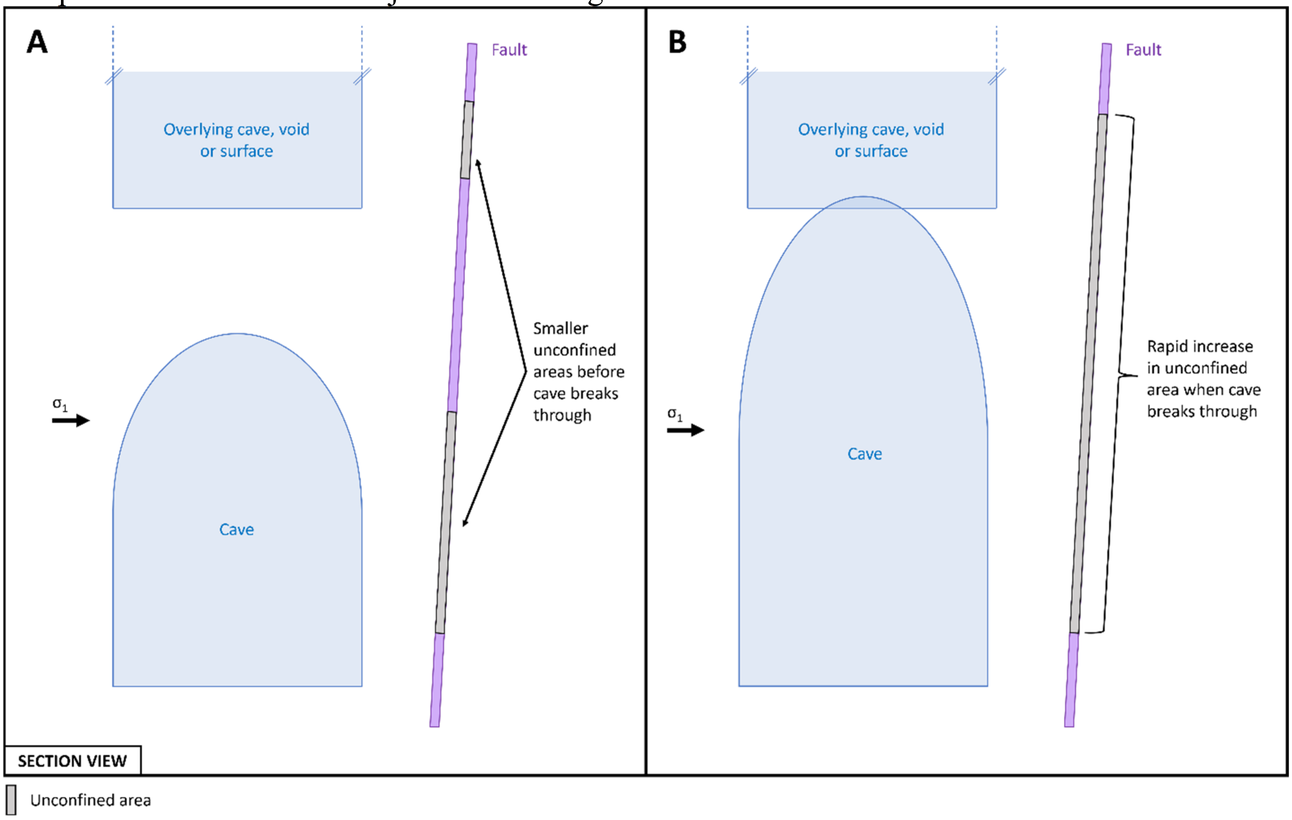

Figure 16 Schematic of increasing unconfinement of fault before (A) and after (B) cave breakthrough.

4 DISCUSSION AND CONCLUSION

This paper provides observations and opinion from a survey of 23 mines regarding their use of structural models as an input to manage large seismic events. The arguments brought forward in the paper are supported by decades of involvement with seismically active mines around the world.

The status of structural models in mature mines are often inadequate to understand the source and the mechanisms of large seismic events. Not all faults have the capacity to generate large seismic events and the early identification of the ones that are prone to such behaviour is required to enable the development and timely implementation of both strategic (extraction sequence) and tactical (ground support and exclusion) rockburst mitigation action.

There are two essential components required to achieve this:

- A microseismic monitoring system capable of locating events with sufficient accuracy to be able to differentiate activity along different structures
- A functional structural model adapted to seismic response monitoring

The identification of structures prone to seismic response should start as early as possible. When faults produce large magnitude events, the structural model should be at a refined stage in this area of the mine and the seismic system coverage and accuracy should be fit for purpose. By this point in time, the mine should be undertaking forensic studies as described in the previous section, to facilitate early mitigation measures. Too often, when mines begin to experience large seismic events and seismic damage becomes more frequent, mines have to play catch up, sometimes with the expansion of the seismic system and often with the refinement of the structural model.

The Authors have observed that forensic studies are rarely undertaken at mine sites. This can be due to the inadequacy of structural models as previously discussed. Furthermore, many mines have insufficient resources and expertise to conduct comprehensive seismic back analysis studies. They dedicate most of their resources to planning and executing production. The tendency in the industry is to rely on very complex mine wide numerical modelling studies, generally forfeited to consulting firms, hoping to gain some understanding and forecasting of seismic hazard. The danger in this approach is that modelling cannot compensate for a lack of knowledge of the structural model of the mine, which are the common sources of the large seismic events. Without including the sources of seismicity in the model, the results can provide convincing, but often misleading forecasting output – as the driving mechanisms are not captured.

Back analyses are best undertaken by site personnel who have an intimate knowledge of the mine and its seismic response. These studies are key to identify seismic sources and understand mechanisms, i.e. the cause (extraction sequence and stress change on seismically active faults) and effect (large seismic events). A very useful outcome from these studies is the development of a seismic hazard ranking system applied to all up-coming stopes in the sequence, with relevant mitigating actions. Back analyses of large events ($M_w > 2$) provide an opportunity to refine this ranking system.

ACKNOWLEDGEMENT

The authors would like to thank the staff at the mines who responded to the survey – without them this paper would not have been possible.

REFERENCES

Graham, J., Waheed, U. & Mikula, P. A. (2023). Empirical charting for dynamic ground support at Flying Fox and Spotted Quoll mines. in J Wesseloo (ed.), Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining, Australian Centre for Geomechanics, Perth, pp. 115-128, https://doi.org/10.36487/ACG_repo/2325_07.

Gibowicz, J. & Kijko, A. (1994). An introduction to Mining Seismology, Academic Press, San Diego.

Mikula, P. A. (2012). Progress with empirical performance charting for confident selection of ground support in seismic conditions. in Y Potvin (ed.), Deep Mining 2012: Proceedings of the Sixth International Seminar on Deep and High Stress Mining, Australian Centre for Geomechanics, Perth, pp. 71–89, https://doi.org/10.36487/ACG_rep/1201_05_.

Mikula, P. & Gebremedhin, B. (2017). Empirical selection of ground support for dynamic conditions using charting of support performance at Hamlet mine. in J Wesseloo (ed.), Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining, Australian Centre for Geomechanics, Perth, pp. 625–636, https://doi.org/10.36487/ACG_rep/1704_42.

Ortlepp, W. D. (1992) Invited Lecture: The design of support for the containment of rockburst damage in tunnels – An engineering approach. Proceedings of Rock Support and Underground Construction, (Editors: P. K. Kaiser and D. R. McCreath), Rotterdam: A.A. Balkema, pp. 593-609.

Potvin, Y., Wesseloo, J., Morkel, G., Tierney, S., Woodward, K. & Cuello, D. (2019). Seismic Risk Management practices in metalliferous mines', in W Joughin (ed.), Deep Mining 2019: Proceedings of the Ninth International Conference on Deep and High Stress Mining, The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 123-132, https://doi.org/10.36487/ACG_rep/1952_10_Potvin

Wesseloo, J. (2018). The spatial assessment of the current seismic hazard state for hard rock underground mines. *Rock Mechanics and Rock Engineering*, 51(6), pp.1839-1862.

Woodward, K. & Wesseloo, J. (2015). Observed spatial and temporal behaviour of seismic rock mass response to blasting. *Journal of the Southern African Institute of Mining and Metallurgy*, 115(11), pp.1044-1056.