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# Abutment loading in deep cave mines: towards understanding susceptibility to strainbursts

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## Abstract

*Deep cave mining is an inevitable requirement to meet the growing global demand for valuable minerals such as copper and gold. The experiences from historical and current deep mining suggest that the rock masses encountered at depth are more likely to be stronger, more brittle, and less jointed. While this may be a favourable condition for some mining and civil projects, under the high abutment loading associated with cave mining, the rock surrounding the mine drifts is susceptible to strainbursting, a sudden and high-energy failure mode. Loading conditions in cave mines can evolve rapidly over the course of mining, which can cause shifts in the susceptibility and triggers for strainbursting. Historical perspective on the strainbursting hazard in deep mining is presented in this paper, as well as a recent case study of the DMLZ mine where data-driven assessments have been applied to better understand the strainbursting hazard under the abutment loading condition. The strainbursting phenomenon can be difficult to manage in a complex cave mining environment. Therefore, tools and strategies for analysis of the occurrence of strainbursting that can be used to better constrain and manage the problem are discussed.*

**Keywords:** *cave mining, deep mining, rockbursting, strainbursting, data analysis*

## 1 Introduction

Rockbursting has been a recognised problem in deep mining since the early 1900s (Whyatt et al. 2002). As a simple definition, a rockburst is an occurrence of dynamic rock failure that causes damage to underground excavations. Rockbursts are associated with the release of seismic energy, which can be measured, and the source located using spatially dispersed arrays of uniaxial and triaxial geophones installed in a mine. Both damages to the rock mass and the installed ground support can be classified as rockburst damage.

A strainburst is a type of rockburst where the damaging mechanism is that of rapid brittle stress fracturing of the rock around the periphery of an excavation. Stored strain energy in the rock surrounding the excavation is released during the fracturing process and forces are generated which are strong enough to accelerate fragments of rock to high velocities (e.g. up to 5 m/s suggested by Kaiser & Malovichko 2022). Strainbursts can be triggered by quasi-static loading, transient loading, and seismically induced loading from remote seismic events. In the case of the latter, seismic events may be located near to the observed excavation damage but also remotely from the damage location where the triggering of seismic energy was initiated.

Rockbursts are increasingly occurring in cave mines, and they are potentially becoming more disruptive as these mines push deeper into higher-stress environments. The goal of this paper is two-fold. First, we would like to highlight the importance and relevance of the experiences from the first deep cave mines. Second, we would like to provide some context of the assessments that can be used to better constrain and control the strainbursting problem in a cave mining setting with examples presented from a case study mine. In particular, the focus of this paper is on the intense straining of the rock surrounding the excavations that occurs ahead of the undercut and cave due to the abutment loads.

## 1.1 Cave mining and increasing strainbursting with depth

Demand for valuable minerals associated with large and low-grade porphyry ore deposits (e.g. copper, nickel, zinc, and gold) is expected to continue to grow, and the number of new ore deposits being discovered is diminishing (Watari et al. 2021). Mine operators are therefore evaluating and developing deeper deposits where experience has shown that the strainburst hazard can be a controlling factor in the development and operation of the mine, sometimes becoming the main driver for operational decision-making. In particular, exposure of the massive, brittle rock commonly encountered at these depths to the cave abutment loads has the potential to cause widespread rockburst damage to mine drifts and infrastructure (e.g. drawpoints, ore passes, etc.), disrupting both development and operational activities.

Cave mining at shallow depths (e.g. < 500 m) has been historically recognised as a mining environment with limited storage of strain energy in the near field rock masses compared with room and pillar mining or stoping operations (Brady & Brown, 2005). For shallow block cave mining, where the orebodies are naturally caveable due to jointing, the vertical propagation of the cave limits the abutment loading condition and therefore reduces susceptibility to strainbursting.

However, at greater mining depths, the orebodies are often less naturally caveable, which necessitates greater undercut widths to initiate caving. The horizontal orientation of the footprint and long tabular shape of the undercut slot and cave causes the rock masses above the cave to become cantilevered (Figure 1). The rock pillars in the footprint therefore act as one of the abutments for the cantilevered rock (hence the term abutment loading).

The abutment loading condition in deep or high-stress cave mines can cause considerable storage of strain energy in the pillars ahead of the cave and undercut slot. Due to the sequencing of cave mines, thousands of metres of drift may be exposed to the abutment loads with sometimes widespread strainbursting occurring in clusters (termed rockburst clusters by Roy et al. 2022). These rockburst clusters need to be distinguished from the often localised strainbursting problems experienced with more shallow cave mines and with other mining methods/tunnelling.

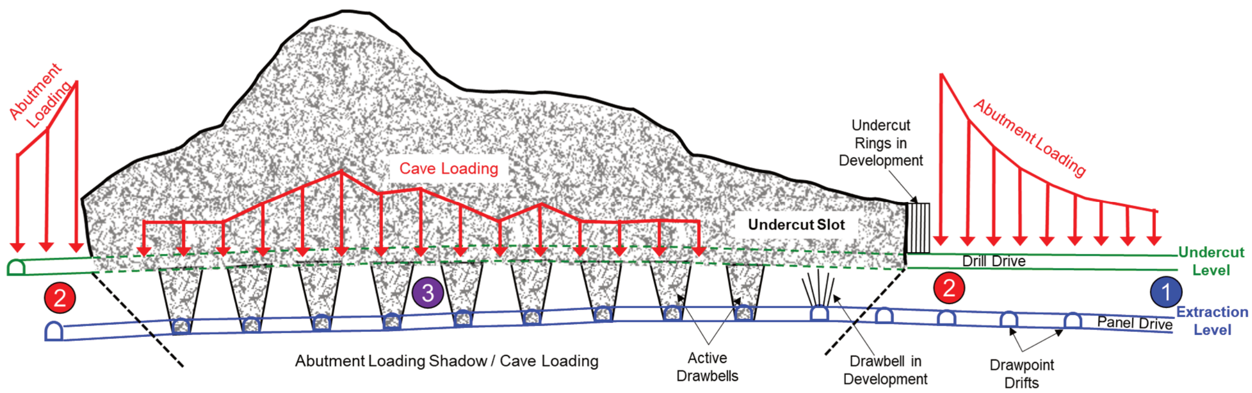



**Figure 1 Schematic cross-section through a deep cave mine identifying both the abutment and cave loading conditions**

Further, at least three triggering mechanisms for strainbursts can occur in cave mines (quasi-static, transient, and seismic loading conditions). It is likely that during development and early operation of a cave mine, the in situ stresses and incremental loads from the advance of the undercut and cave are the most important triggering mechanisms (quasi-static and sometimes transient loading). Once mucking has started and cave growth is occurring, the stress disturbance of the mine increases, which can create conditions for seismic loading due to activation of faults causing remote seismicity. Therefore the triggering mechanisms for strainbursts can be expected to evolve as the cave mine becomes more mature. Development of a new and deeper mine level can also represent a step change in strainbursting conditions with increased potential for activation of existing faults or shear ruptures occurring. For example, remote seismic events observed in the crown pillar between the Teniente Sub-6 and Teniente 4 South levels at the El Teniente complex of mines in Chile were associated with considerable rockburst damage (e.g. Kaiser et al. 1996).

## 1.2 Examples of strainbursts in cave mines

Strainbursts have been observed at numerous caving operations including the El Teniente complex of mines (Teniente 4 South, Teniente Sub-6, Reservas Norte), Northparkes, Perseverance, Cadia, Telfer, and the Grasberg complex of mines (DOZ and DMLZ). The resulting damage from the strainbursts often appear similar with fragments of rock and broken support elements unravelling or being ejected into the drift, often occurring over many linear metres of the drift (Figure 2). The strainbursts can generate forces that are strong enough to rupture and shear fully grouted steel bars, fray and rupture cable bolts, pull off rock bolt plates, crack and crush shotcrete and mesh liners, and crush steel and concrete lintel sets.

Commonly, the rockburst damage from strainbursting is most severe in the ribs of the drifts due to the mostly vertical abutment loading concentrating brittle stress fracturing in the ribs, but it is not uncommon for roof falls and floor heave to occur. In some cases, the authors have observed evidence of ground motion driven (or assisted) failure (e.g. shakedown) that is associated with the flurry of seismicity during the rockburst cluster.


**Figure 2 Strainburst damage at (a) Teniente Sub-6 panel at El Teniente (Kaiser et al. 1996); (b) Perseverance Mine (Hopkins et al. 2018); (c) Northparkes Mine (NSW Department of Industry, 2017); (d) DMLZ mine (photo courtesy of PTFI)**

## 1.3 Useful literature and best practices

In the 1980s and 1990s, there was a significant push in Canada, South Africa, and the United States to improve understanding of the underlying mechanisms and triggers of rockbursts, which had caused many fatalities in mines (e.g. Hedley, 1992; Ortlepp & Stacey, 1994; Kaiser et al. 1996; Ortlepp, 1997). While these publications are almost three decades old, the knowledge and experiences recorded are still valuable to current mining operations. There have since been numerous technical articles and books published discussing various aspects of rockbursting including state-of-the-art numerical modelling, empirical criteria, application of machine learning, dynamic ground support, and seismic monitoring. Zhou et al. (2018) recently reviewed rockburst-related literature, providing a summary of the state-of-the-art assessment types. Notably, over 60 different empirical criteria listed in the literature from 1972 to 2017 were presented that have been used to forecast rockburst conditions.

### *1.3.1 Best practices*

With respect to cave mining, Butcher (1999) outlined five specific design rules for block cave mines to avoid rock mass damage within the draw horizon at depths greater than 500 m, which can be summarised as follows:

1. Advance undercutting is the preferred sequence to control extraction ratios and exposure.
2. Control the undercut front geometry to avoid large lead-lag distances.
3. Control the undercut rate and avoid mining too fast.
4. Separate the extraction and undercut levels vertically as much as practical.
5. Undercut from the weakest to strongest ground to propagate the cave as quickly as possible.

While the rules proposed by Butcher (1999) are still relevant, they are unlikely to fully address the strainbursting hazard for mining depths greater than 1,000 m where the rock masses are more critically stressed. At least one notable exception to rule 5 was discussed by Laubscher (2000) based on experience at the San Manuel mine, where undercutting from weak to strong rock was not favourable for cave growth and fragmentation. Further, as is often the case in mining, it is not always possible to conform strictly to these rules due to other constraints and unforeseen conditions.

### *1.3.2 Preconditioning*

Preconditioning by hydraulic fracturing or confined blasting is becoming a critical component of deep cave mining due to the stronger, more massive rock being encountered at depth. Most preconditioning is targeted at the cave back to improve cave back propagation and fragmentation (He et al. 2016), but an additional benefit is a potential reduction in unfavourable loading conditions in the abutments (e.g. reduction in remote seismic events and less stable arch problems causing high abutment loads).

### *1.3.3 Ground support*

Ground support is the last line of defence in strainburst prone ground. Kaiser & Moss (2021) outline a ground support approach that is based on deformation capacity rather than energy capacity, which has been proposed to deal with rock masses that yield by stress fracturing and strainbursting. Monitoring displacement of the surface of the support can provide an indication of the remaining capacity of the support system which allows preventative support maintenance (PSM) to be scheduled. Finally, a gabion system, created via retention of stress fractured rock, may improve the resilience of the support system under dynamic loading conditions.

## 2 Case study: the DOZ and DMLZ experience

The Deep Ore Zone (DOZ) and Deep Mill Level Zone (DMLZ) mines were developed to extract porphyry and skarn style mineralisation (copper and gold). The East Ertsberg Skarn System (EESS) hosts the orebody which has been progressively mined deeper by PT Freeport Indonesia (PTFI) since the 1980s using cave mining methods (Casten et al. 2020). As such, the experiences from the DOZ and DMLZ are an excellent example of how geotechnical conditions can change with increasing mining depth, particularly with respect to strainbursting conditions.

The mature DOZ block cave mine will soon be decommissioned when the DMLZ cave, with a footprint approximately 500 m deeper, approaches and breaks into it. The dominant controlling geotechnical problem in the DOZ was the occurrence of inrushes of wet muck (Casten et al. 2020) but strainbursts were also observed. Strainbursting in the DOZ was an irregular and localised problem, which mostly occurred when the cave was well established. Often, the strainbursts were associated with poor lead-lag geometries or localised stress concentration due to drift intersections. The strainbursts were almost always triggered by load redistribution from adjacent undercut ring or development blasting.

In the DMLZ, Roy et al. (2022) describe a situation of sometimes widespread strainburst damage occurring in temporal clusters (termed rockburst clusters) during the ramp-up to production. Compared to the strainbursts which occurred in the DOZ, the damages from the strainbursts in the DMLZ were considerably more extensive and severe with sometimes thousands of metres of drift being damaged at a time. There was also a notable evolution in the severity and triggers for the rockburst clusters, with the most severe rockburst clusters potentially being triggered by mucking or delayed load redistribution rather than the immediate load redistribution from blasting. Mucking was reported by Hedley (1992) as one of the triggers for rockbursts in stoping operations in Eastern Canada.

The rockburst clusters in the DMLZ were associated with a flurry of heightened seismic activity within the abutments of the cave. Once mine personnel could safely re-enter the mine, damage to the mine drifts was observed and recorded to track the spatial location and the qualitative severity of the damages. Later back-analysis and comparison of the mapped rockburst damage and the located seismic events showed that the damage was spatially and temporally correlated to the seismic events, and the interpreted source mechanisms were dominantly non-shear (Roy et al. 2022). Remote seismic events were not associated with the rockburst clusters and therefore mining induced strainbursting was confirmed as the dominant rockburst damage mechanism, even though the extents of damage was sometimes more consistent with that observed due to large remote fault slip type rockbursts.

Disruption to the development and production schedule in the DMLZ from the rockburst clusters was considerable due to the rehabilitation requirements, and many operational changes were adopted (Casten et al. 2020; Simanjuntak et al. 2020). Most of the changes adopted in the DMLZ were on theme with the design rules suggested by Butcher (1999). One notable operational change was the introduction of hydraulic fracturing to condition the cave back which is described by Nugraha et al. (2020). The hydraulic fracturing was essential in improving caveability of the orebody.

# 3 Assessment of susceptibility to the strainburst hazard

There is no single assessment that can adequately address the strainbursting hazard in a complex mining environment such as a block cave mine. Due to uncertainty in geological models, stress forecasts, and the complex underlying phenomena, accurate prediction of strainbursting is not a realistic goal, and there is a need to forecast potentially hazardous conditions both spatially and temporally. Further, most mining projects rely on experience-based decision-making, and there is a continual need to collect, maintain, and interpret data related to the rock mass response to mining. Ideally, assessments of the strainburst hazard for a cave mine will cover a range of types, which can be updated as mining progresses (Table 1).

In the remainder of this paper, select assessments identified in Table 1 will be discussed at a high level with examples of data from the DMLZ. Where relevant, comparisons are made to other cave mining operations and mining methods where a similar rock mass response has been noted.

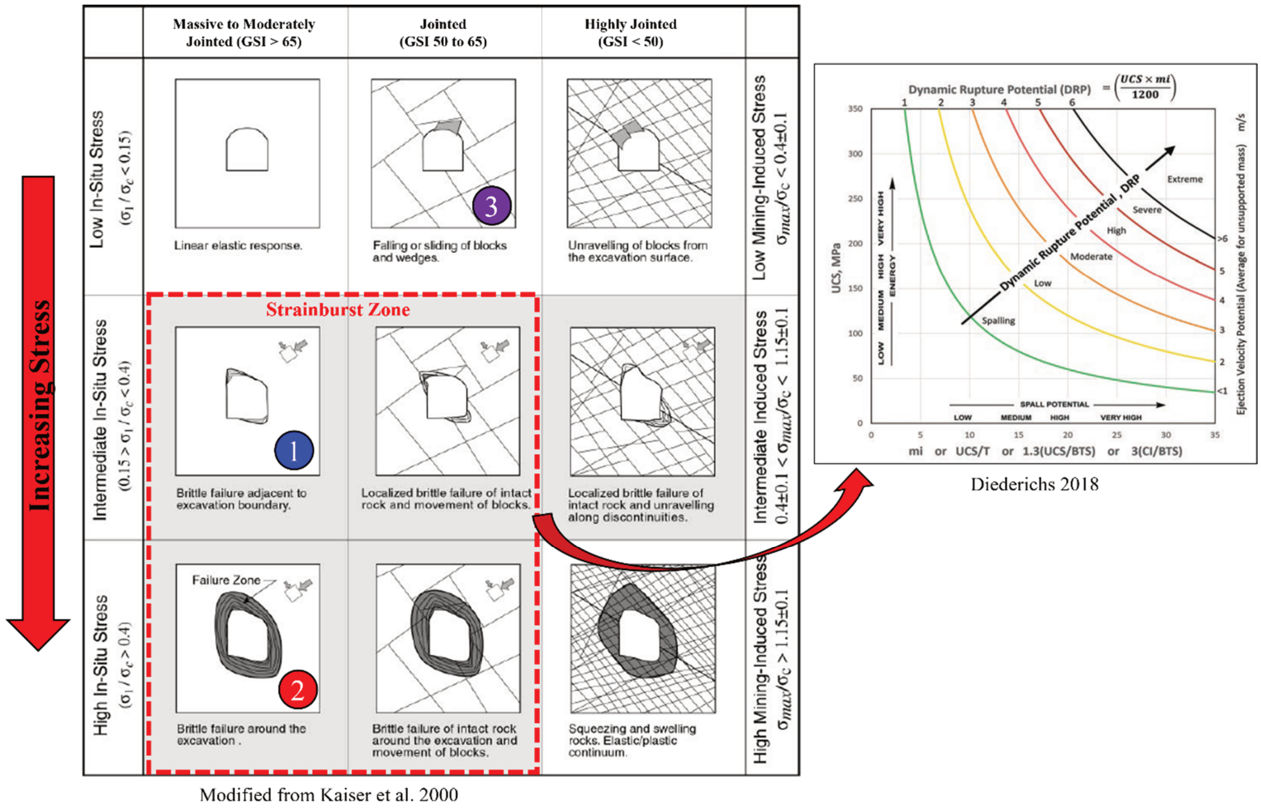
**Table 1 Assessment types and examples for strainburst hazard susceptibility**

| Assessment types | Example assessments |
|---|---|
| Rock mass characterisation | Geotechnical domaining<br>Structural modelling |
| Empirical assessments | Rock mass behaviour matrix (Kaiser et al. 2000)<br>Dynamic Rupture Potential (Diederichs 2018)<br>Other empirical rockburst criteria (Zhou et al. 2018) |
| Numerical assessments | Mine scale stress models to evaluate the abutment loading conditions (i.e. stress forecast)<br>Excavation scale models to evaluate depth of stress fracturing, deformation, and ground support performance |
| Exposure assessments | Quantifying the amount of excavation exposure to the abutment loading condition |
| Rockburst databasing, visualisation, and analyses | Rockburst damage database<br>Rockburst cluster database<br>Identification of seismic source mechanisms<br>Comparison of seismic event locations with mapped rockburst damage<br>Duration of seismic flurry<br>Identification of rockburst damage and trigger mechanisms<br>Evolution in triggering mechanisms<br>Statistical analyses to identify important explanatory variables |

## 3.1 Rock mass characterisation

It is now widely accepted that there is a trend towards more massive rock masses being encountered at depth in porphyry deposits and the existing rock mass classification tools are not adept for assessing these (Bewick 2021). For example, the strong primary ore at the El Teniente complex of mines in Chile was associated with the first rockbursting problems in the Teniente 4 South panel (Flores 1993), and the massive and strong Diorite in the DOZ and DMLZ was associated with increased strainbursting and seismicity with depth. The Diorite in the DMLZ has an estimated GSI > 80 with RQD ~100 being prevalent.

As general guidance, rock masses with GSI ≥ 65 can be expected to experience brittle stress fracturing, rather than shearing along existing discontinuities and therefore be susceptible to strainbursting (left side of Figure 3). Bewick (2021) provides additional guidance on rock mass characterisation for caving operations.




(a) (b)

**Figure 3 (a) Rock mass behaviour matrix showing a zone of potential strainbursting behaviour (modified from Kaiser et al. 2000, strainburst zone after Kaiser & Moss 2021); (b) Dynamic rupture potential chart to assess whether the rock will rupture dynamically. Refer to Figure 1 to see corresponding numbered circles showing where different rock mass behaviour can be expected in a deep cave mine**

An added complexity for cave mining in porphyry deposits is the influence of veining heterogeneity. The role of veining in cave back propagation and fragmentation has gained considerable attention over the last decade (e.g. Brzovic & Villaescusa 2007). Veining also plays a role in the excavation scale behaviour (e.g. Day 2019; Bewick 2021), and while it is currently not well defined within the context of existing rock mass classification tools, early work suggests that higher veining intensity, possibly regardless of vein strength relative to the host rock, can lead to concentration of brittle fracture processes.

Core logging and simple interpolation of vein counts across the footprint in the DMLZ revealed that veining intensity ranges from approximately four veins/m to greater than 20 veins/m. Roy et al. (2022) showed a correlation between increased strainbursting activity with increasing vein counts in the DMLZ footprint. Similarly, Day (2019) showed that increased quartz veining intensity resulted in greater overbreak around development drifts at the deepest mine level at El Teniente. Thus, if the rock mass response is still largely dominated by brittle stress fracturing (e.g. instead of shearing along weak veins), veined rock masses may be prone to strainbursting at lower induced loads in comparison to the same but less veined host rock.

Larger-scale geological structures such as faults, shear zones, and dykes can also store strain energy that can be released by mining activities, and these structures need to be modelled and compared against the mine geometry. In stoping operations, a well-known rule of thumb is to avoid mining towards potentially problematic structures. However, in a cave setting, there is less flexibility and control of the mining direction as the undercut is advanced and therefore areas around these structures need to be identified as potentially hazardous, perhaps even with targeted installation of enhanced ground support.

## 3.2 Stress forecast

The most basic and necessary numerical modelling exercise that is required for a block cave mine is a mine scale assessment of the mining induced stresses. Of particular interest is the straining of the pillars ahead of the undercut slot and cave. It is within this zone of high abutment loads that the majority of strainburst damage has been observed in the DMLZ (Roy et al. 2022) and in other cave mines (e.g. Flores 1993; Kaiser et al. 1996). Thus, a sound understanding of how the in situ stresses will be rotated and magnified as the cave abutment loads are realised is fundamental for any assessments of strainbursting.

Depending on the stage of the project, the stress analyses may be first completed in 2D (e.g. Flores 1993; Roy & Bewick 2020). Arguably, this is a useful exercise to compliment a subsequent 3D model, as 2D analyses can be orders of magnitude faster to build and run. At the feasibility level and as development of the mine is beginning, typically a 3D continuum model with relatively coarse zones is constructed to better capture the complexity of the mine geometry, geology, and sequencing. For the DMLZ, a FLAC3D model was created, which explicitly captures the advance of the development mining, the advance of the undercut, and cave shapes which were forecasted by other means (Figure 4). Note that the FLAC3D model was initially created for back-analysis but the fundamental nature of the model is the same as an initial forecast model, albeit with different model calibration strategies.

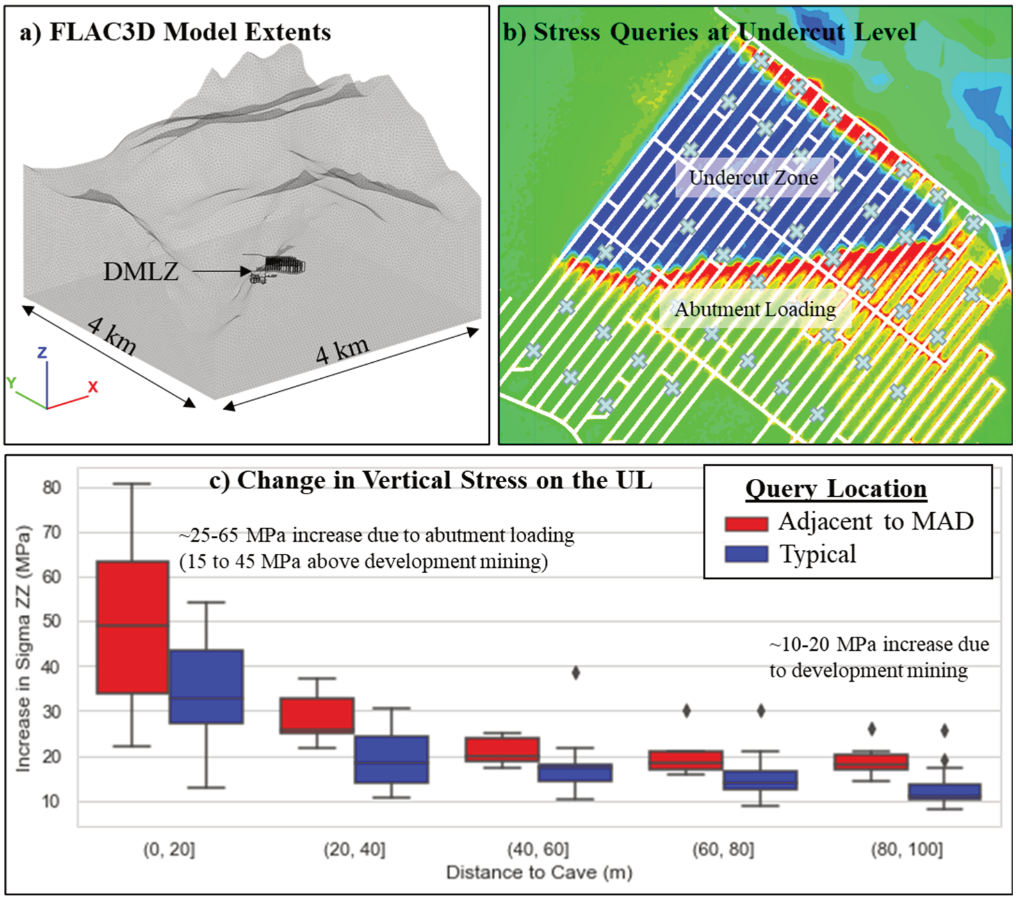



**Figure 4 (a) Isometric view of the DMLZ FLAC3D model extents; (b) Plan view showing contours of the maximum principal stress on the undercut level and the locations of stress query volumes; (c) Compiled stress query data by distance to the cave and relative location with respect to the cross-cutting Main Access Drives (MADs)**

Interrogation of the results of the stress forecast model is required to contextualise the evolving loading condition within the abutments of the cave. To do so in the DMLZ, volumetric queries were created that were centered within the rock pillars on both the Extraction Level (EL) and Undercut Level (UL). By tracking the stresses at each stage of the model over many query locations, as well as the relative location of the query volumes with respect to the advancing cave, a useful forecast of the abutment loading condition was developed (e.g. Figure 4c). Note that the stresses that develop in the confined cores of the pillars are being queried and the local stresses at the boundaries of the pillars will be much higher, hence the need for excavation scale sub-models.

In the case of the DMLZ, the major principal stress (pre-mining) within the orebody is sub-horizontal and trending approximately north-northwest (Groccia et al. 2020). As the undercut was advanced in the DMLZ, the FLAC3D model shows the development of the abutment loading condition causing the major principal stress to rotate and become mostly vertical. As a result, the vertical component of stress was observed to experience the greatest change in magnitude (Figure 4c).

In the DMLZ, the unfavourable impact of the cross-cutting Main Access Drives (MADs) on the undercut level is clear when the queried model data is grouped and presented by distance to the cave (Figure 4c). The mine-scale model has therefore given a first indication of areas that may be more susceptible to brittle stress fracturing and strainbursting as well as provided a forecast of the stress condition for other assessments. Even a preliminary numerical model can reveal the competing interests between operational flexibility and stress management in a cave mine (e.g. the 2D model presented by Roy & Bewick (2020).

A well-known rule for deep mining is to keep the extraction ratio low when the stresses are anticipated to be high. Whyatt et al. (2002) discuss this practice in relation to the Coeur D'Alene mining district and the same concept applies to deep caving. A balance needs to be struck between operational flexibility and increasing the susceptibility to stress driven hazards such as strainbursting. In the DMLZ, the advance undercutting method was later modified to reduce the extraction ratio and eliminate many unfavourable drift intersections in later panels.

## 3.3 Empirical assessments

A preliminary assessment of the possibility of strainbursting behaviour can be undertaken using the approaches outlined by Kaiser et al. (2000) and Diederichs (2018) as shown in Figure 3. Essentially, the important aspects to identify are:

1. Whether the rock mass will yield via brittle stress fracturing or by shearing/rotation along existing discontinuities. A GSI ≥ 65 or 70 is a commonly reported limit to delineate these different rock mass responses (e.g. Bewick 2021).

2. Whether the in situ and mining induced stresses will be high enough to cause the rock surrounding the excavations to fracture. Kaiser et al. (2000) provide guidance for ratios of in situ and mining induced stresses that can cause zones of stress fracturing to develop around a drift (left side of Figure 3).

3. Whether the rock will tend to fail abruptly or more gradually. Diederichs (2018) presents the Dynamic Rupture Potential (DRP) chart based on case studies from mainly civil tunnelling projects to show that stronger rocks and more brittle rocks tend to fail more dynamically (i.e. they store more strain energy pre-peak and shed load rapidly post-peak) and therefore have higher DRP (right side of Figure 3). However, strong rocks also require higher induced stresses to initiate stress fracturing and may therefore be more resilient to the abutment loads.

Experiences in the DMLZ suggest that strainbursting behaviour might be observed first in rock masses with low to moderate DRP (i.e. the weaker end of the spectrum of brittle rock masses with GSI ≥ 65). As the abutment loads increase with the size of the cave, rock masses with higher DRP may also become prone to strainbursting. Thus, an early indicator for future problematic rock masses is when strainbursts or even spalling are noted close to the undercut front where the abutment loads are highest. Abutment loads will tend to increase as the undercut is widened and therefore similar behaviour can be expected to expand laterally from the edge of the undercut within similar geotechnical domains.

## 3.4 Exposure assessments

An often overlooked aspect for the strainburst hazard in cave mines is a simple assessment of the evolving exposure of development drifts to the abutment loading condition. As the undercut front is widened, greater extents of drift will be exposed to the abutment loads, which increases the susceptibility to strainbursting. Figure 5 shows an example of tabulation of linear metres of exposed drift on the undercut and extraction levels of the DMLZ. Even if we consider a constant zone of stress influence ahead of the undercut slot (e.g. 40 m), the increasing metres of drift exposed grows with the cave simply due to a larger perimeter. If we consider a more realistic scenario where the zone of stress influence also increases with the width of the undercut, the exposure can increase dramatically (the red dashed lines in Figure 5 are shown for demonstration purposes).

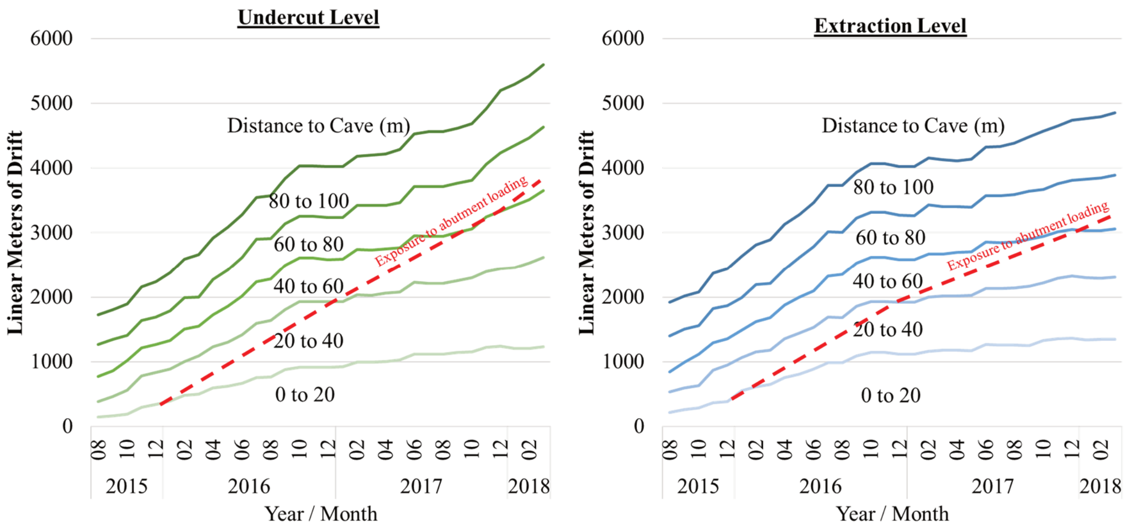



**Figure 5 Tabulation of linear metres of drift exposed to the abutment loading condition in the DMLZ (modified from Roy et al. 2022) showing increasing exposure over time. The red dashed lines represent the combined effect of the increasing perimeter of the cave and the growing stress influence**

## 3.5 Database assessments

While the first panel in a cave mine may be designed and constructed without any prior experience, the future panels in the cave can benefit from these first experiences of the rock mass response to mining. It is therefore imperative that rockbursts be recorded and tracked in a database. Anecdotal information is valuable, but it can be biased and sometimes conflicting, therefore statistical analyses can be undertaken on the collected data, which can provide insight and rigor into the identification of important explanatory variables (e.g. the multivariate logistic regression discussed by Roy et al. 2022). The horizontal nature of the footprint of a cave mine lends itself nicely to statistical modelling using a grid system.

During development of the footprint, observations of spalling and strainbursting are clear indicators that conditions can be expected to worsen under the abutment loads. Further, experiences in the DMLZ suggest that strainbursts often occur multiple times in the same general locations of the footprint under the increasing abutment loads. This is intuitive because the strainbursts are an indication of highly stressed rock. Thus, unless the pillars have completely shed load or have become stress shadowed, future increases in abutment loads may illicit a similar rock mass response.

### *3.5.1 Rockburst databases*

Roy et al. (2022) showed the importance of delineating two databases for cave mines. The Rockburst Damage Database (RDD) is used to track the occurrence of rockburst damage by linear metre of damaged drift (georeferenced data). Important characteristics of the damage can be tracked in the RDD including the qualitative Rockburst Damage Index, the area of the drift profile that was most heavily damaged, and descriptions to identify the condition of the ground support. The Rockburst Cluster Database (RCD) is used to compile relevant information associated with the temporal cluster of rockburst damage (e.g. triggering mechanisms, the duration of the seismic flurry, the number of seismic events, the total linear metres of damaged drift). Compilation of both databases enables useful visualisation and analyses of the data (examples shown in Figure 6). The Rockburst Cluster Index (RCI) created for the DMLZ is also shown in Table 2 which provides a semi-quantitative scale for the severity of the rockburst clusters (refer to Roy et al. 2022 for details of the RDI and RCI calculations).

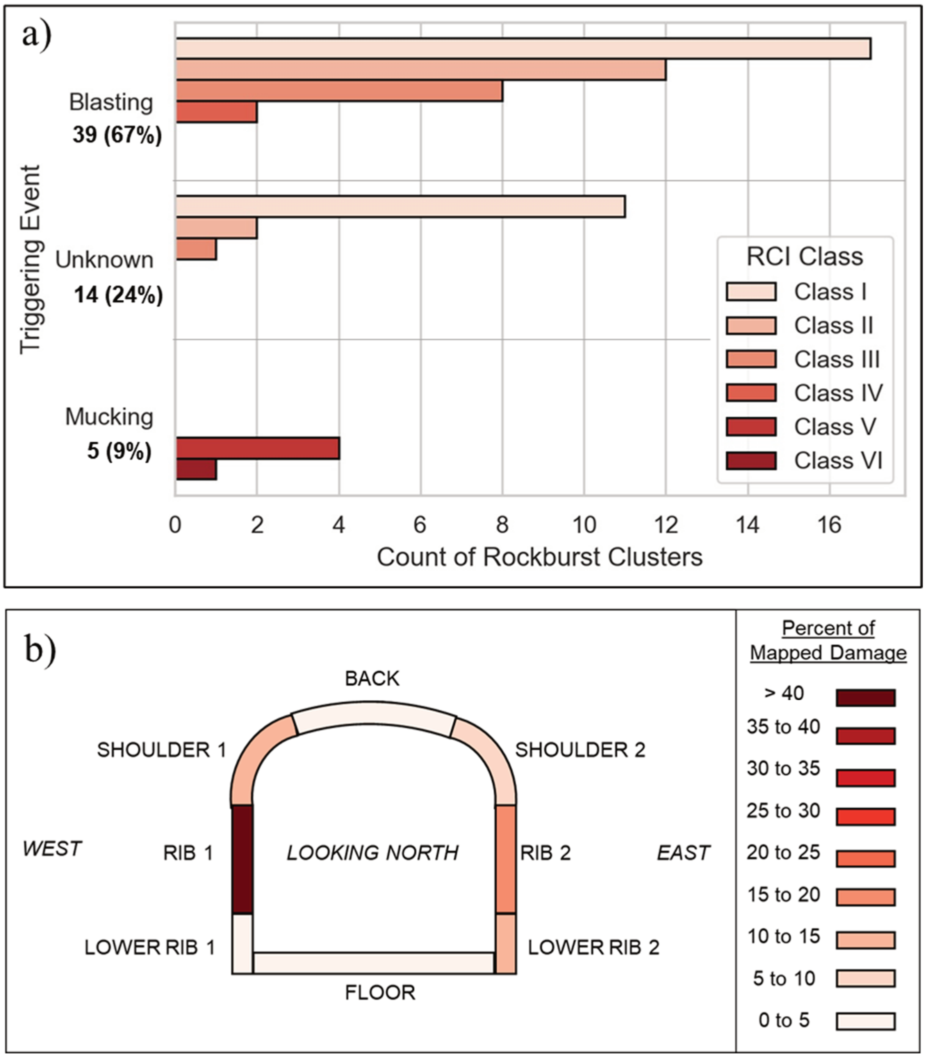



**Figure 6 (a) Identified triggering events from the Rockburst Cluster Database in the DMLZ by RCI (Table 2); (b) Distribution of areal locations where rockburst damage was mapped in the DMLZ Rockburst Damage Database (from Roy et al. 2022)**

**Table 2 Rockburst Cluster Index (RCI) developed for the DMLZ (Roy et al. 2022)**

| RCI class/range | Typical outcomes from the rockburst cluster |
|---|---|
| Class I (<100) | Minor and local disruptions to mining activities. Local rehabilitation may be required (e.g. specific sections of the Drill Drives or Panel Drives) |
| Class II (100–200)<br>Class III (200–500)<br>Class IV (500–1,000) | Moderate disruption to mining activities. Local loss of access and some targeted rehabilitation efforts required. Mining may not be significantly Disrupted but local deviations in production may result (e.g. temporary loss of access to a Drill Drive resulting in uneven undercutting). |
| Class V (1,000–5,000) | Many hundreds of metres of rockburst damage. Temporary suspension of mining activities. Loss of access to local areas of the footprint (e.g. multiple Drill Drives or Panel Drives). Major rehabilitation efforts required and several months of production disruptions |
| Class VI (>5,000) | Thousands of metres of rockburst damage. Temporary suspension of mining activities. Loss of equipment access to large portions of the footprint. Major rehabilitation efforts required and many months of production disruptions |

### *3.5.2 Seismic databases*

Seismic monitoring has become routine at operating cave mines and the processed data can be tremendously valuable to understand rockbursting phenomena. For example, it is common to see a relationship between the locations of the seismic events and mapped rockburst locations or damage (Figure 7). The observation of coincident seismicity and rockburst damage suggests that the rockburst damage mechanism is dominantly strainbursting. Of course, local shakedown and ground motion assisted failure are likely contributors to the observed damages.

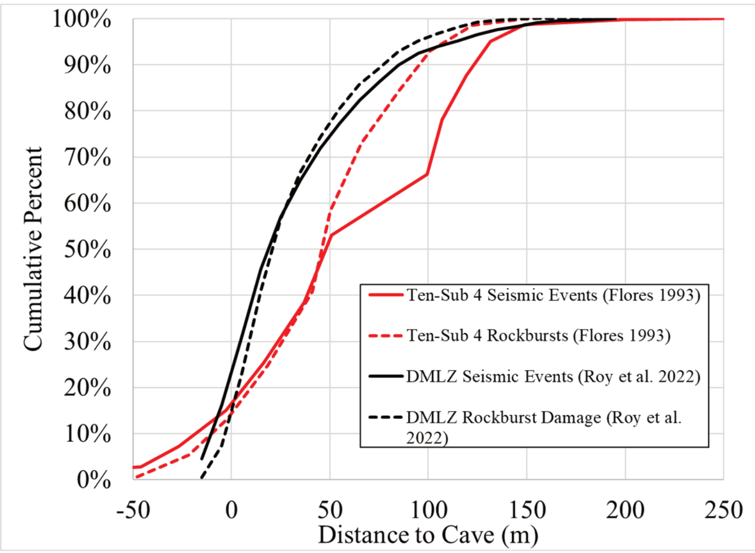



**Figure 7 Comparison of the cumulative percent of seismic events in the DMLZ mine and Ten-Sub 4 mine against the rockburst damage locations in the respective mines showing similar distributions**

In both the Ten-Sub 4 mine at El Teniente and the DMLZ mine at Grasberg, there is a clear relationship between the lateral extents of seismicity within the footprint and the locations of the rockburst damage. During undercutting and cave advance in both mines, the rockburst damage and seismicity was limited to within approximately 150 m from the cave front. The development mining at both mines was advanced well past 150 m in front of the cave, therefore, the extents of the seismicity and damage may be an indication of the extents of the abutment loading condition at the time of the data collection. In the case of the DMLZ, almost 80 percent of the damage occurred within 50 m from the cave front.

Seismologists also routinely identify source mechanisms of the recorded seismic events, which can provide useful indications of the type of rockburst that is being experienced. Strainbursts typically have an implosive or non-shear source mechanism (Ortlepp & Stacey 1994) whereas the source mechanisms from remote seismic events (e.g. shear rupture or fault slip) are typically shear dominated. The magnitude of the seismic events can also be considerably higher for fault slip and shear ruptures, sometimes having the effect of masking the smaller seismic events occurring locally at the damage locations (Ortlepp 1997).

The distinction between co-located and remote seismic events is critical and can often be a challenge when comparing mapped rockburst damage locations against the seismic database. The location accuracy of the seismic system based on controlled tests needs to be considered as well as the possibility of temporary degradation of location accuracy during the flurry of seismic activity. During the rockburst clusters experienced in the DMLZ, it was not possible to relate individual seismic events to the damage locations for this reason (Roy et al. 2022). It was also shown that the magnitude of the largest seismic event associated with the rockburst cluster was not related to the extents and severity of rockburst damage experienced (due to the strainbursting mechanism) but rather the number of seismic events recorded during the seismic flurry showed a reasonable correlation.

# 4 Conclusion

Increasing cave mining depths are leading to conditions that increase susceptibility to strainbursting, including higher stresses and more massive rock masses. While it may be obvious to expect considerable rock mass damage due to the abutment loading condition, experience in the DMLZ suggests that the damage associated with strainbursting can be widespread and cause considerable mining delays. Therefore, assessments that can be used to evaluate the strainburst hazard in a cave mining environment have been highlighted in this paper, with example assessments from the DMLZ and comparison to other mines.

It is not a reasonable expectation that any single assessment will provide a suitable forecast of the potential for strainbursting, therefore it is valuable to perform numerous complementary assessments as well as record and interpret relevant data during mining. The assessments discussed in this paper include rock mass characterisation, numerical stress forecasts, empirical assessments, exposure assessments, and database assessments (rockburst and seismic data). Each of these assessments can be updated for new mining areas and as new data becomes available. Improved understanding and forecasting of the strainburst problem allow decision makers to operate deep cave mines more safely and efficiently.

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