Caving 2022 - Y Potvin (ed.)

doi:10.36487/ACG_repo/2205_79

A review of rockbursts associated with block caving

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Abstract

Block caving is one of the most cost-competitive underground mining methods available today owing to its low cost and mining efficiency in the application of low-grade and high-volume mineral extraction such as copper and gold. Given that resources are increasingly being discovered at greater depths throughout the world, the combination of stress concentration resulting from the depth of cover, complicated geotechnical conditions such as geological structures, and disturbance caused by mining activities makes rockburst a challenging geotechnical problem. When a rockburst occurs, the release of a sudden amount of radiated seismic energy may cause rock fragments to eject from the excavation vicinity and may have a significant impact on the safety and productivity of mining. The purpose of this paper is to provide a review of the state-of-the-art in the area of rockbursts associated with block caving covering various contributing factors and rockburst mechanisms based on existing cases. With an increasing understanding of contributing factors, failure modes and mechanisms behind rockbursts associated with block caving, prediction and prevention of mining-induced rockburst can be improved in the future.

Keywords: *rockbursts, block caving mines, hard rock*

1 Introduction

For numerous decades, rockbursts and their associated damages, including bulking, rock ejection and rockfall, have been a great concern because of their detrimental impact on mine productivity and worker safety. Rockbursts were documented from the turn of the century. In Kalgoorlie, rockbursts, which caused fatalities and injuries, occurred in 1917 (Potvin et al. 2000). Significant rockbursts are still common worldwide (Kaiser & Cai 2018). For instance, in a recent report ACIL Allen (ACIL Allen Consulting 2019), reported a rockburst-related rockfall caused one fatality and one injury in 2000 in the Big Bell gold mine, Western Australia.

Although block caving is one of the popular underground mining methods nowadays owing to its low cost and high productivity, it is often associated with significant hazards such as airblasts, rockbursts and subsidence. Its application environment has shifted progressively, principally due to two factors, resulting in the change in stress and stored energy levels of that environment. The first factor is the increasing mining depth. During the last century, the undercut depth of block and panel caves increased from roughly 100 m on average in early applications to almost 1,700 m (Eberhardt et al. 2007). Several cave mines in Australia are active at present or planned at depths of more than 1,400 m, including Cadia East and Telfer (Flores-Gonzalez 2019). In this case, the complex geological conditions and increasing in situ stress induced by increasing mining depth, together with the stress redistribution caused by mining activities such as undercutting, resulted in an unfavourable stress condition (Mazaira & Konicek 2015; Sainoki & Mitri 2014; Zhang et al. 2017). The second factor is that more emphasis has been placed on block caving in competent and massive rock masses, where sudden failure is prone to occur, resulting in large amounts of released energy (Chitombo 2010; Flores-Gonzalez 2019; Kaiser 1996).

Since rockbursts are the sudden release of stored strain energy under highly-stressed conditions, it is reasonable to assume that rockbursts are more likely to occur in the current block caving environments than in early applications of the mining method before. Therefore, the further study of rockburst mechanisms is vital to progress towards controlling its occurrence and intensity, where practicable. In this paper, two of the significant factors, in situ stress level and undercutting sequence, which might induce the occurrence of rockbursts in block cave mines, are analysed based on the information of large seismic events or rockburst cases from four block cave mines in Chile, Indonesia, South Africa and Australia.

2 Fundamental concepts of rockbursts

Rockbursts are characterised by damages in the vicinity of tunnels that are directly or indirectly related to a seismic event (Ortlepp & Stacey 1994). The occurrence time and location of a rockburst and its associated seismic event are not necessarily identical. The source and damage mechanism may be considered separately (Ortlepp & Stacey 1994); the seismic event may be seen as the source of rockburst, while rockburst is the combination of source and damage mechanism. Thus, rockbursts can be broadly categorised into self-initiated rockbursts and remotely triggered rockbursts (Kaiser 1996). While the location of source and damage are the same in self-initiated rockbursts, they are distinct in remotely triggered rockbursts. Numerous different rockburst categorisations have been proposed in the past few decades (He et al. 2012; Ortlepp & Stacey 1994), depending on the relevant author's criteria.

The concept of primary and secondary seismic events was introduced for support design as shown in Figure 1 by Kaiser & Cai (2018). In general, a rockburst that occurs without a remote seismic event only has a primary seismic event co-located with the damaged area as seen in Figure 1a. Otherwise, the remote primary seismic event induces a secondary seismic event at the same location as the damage.

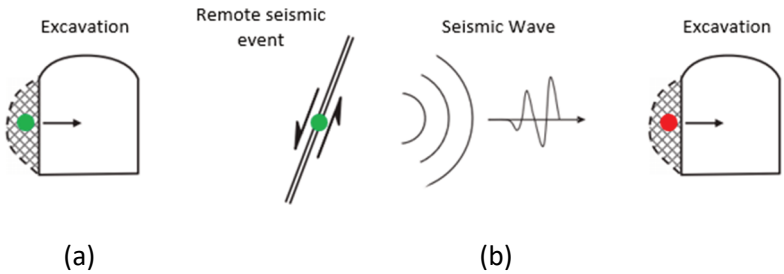


Figure 1 Schematic diagram of the primary and secondary seismic event with the primary seismic event in green dot and the secondary seismic event in red dot. (a) Without remote seismic event; (b) With remote seismic event (Li et al. 2019)

Kaiser & Cai (2018) proposed a novel rockburst classification based on this concept, dividing rockbursts into strainbursts (self-initiated, mining-induced, seismically triggered, dynamically loaded), pillar bursts, and fault-slip bursts. This categorisation allows a brief identification of the energy sources and their contribution to the intensity of each rockburst type.

2.1 Strainbursts

Strainbursts, the most prevalent kind of rockbursts, are the sudden release of energy in the vicinity of excavations as a consequence of violent rock mass failure (He et al. 2014; Kaiser & Cai 2018; Larsson 2004).

Strainbursts occur when stress approaches and surpasses the strength of the rock mass close to the excavation. This situation may occur under a variety of circumstances. For example, rock mass is gradually weakened, allowing strainbursts to occur in a soft loading system after local stress reaches the rock mass strength. The other possible case is that stress redistribution caused by mining operations elevates the stress level in a particular physical location to a point where it exceeds the local strength of the rock mass. Additionally, if a remote seismic event is considered, the abrupt rise in stress caused by the radiated seismic wave may either trigger or partly induce a strainburst, depending on the excess amount of stress provided.

It is critical to understand the energy partition among different sources involved in strainbursts, given that part of the released energy is manifested by rock ejection, which may result in fatalities. Based on the concept of primary and secondary seismic events, it is easier to consider the partition of energy (Kaiser & Cai 2018). If the strainburst contains just the primary seismic event, then only the stored strain energy should be considered. Otherwise, it is necessary to examine if the seismic energy, which is radiated by the remote primary seismic event, should be considered. The intensity of strainburst will not be influenced by this radiated energy if the remote seismic event only serves as a trigger.

2.2 Pillar bursts

Similar to a strainburst, a pillar burst can be self-initiated or triggered, with the rupture or collapse occurring inside the pillar. Once one of the pillars collapses, the stress that was previously stored within it is transferred to other pillars, resulting in an increase in loading. This might result in the worst-case situation known as a 'pillar run', which led to the death of 437 people in South Africa (Martin & Maybee 2000).

In pillar bursts, the width-to-height ratio (W/H) is one of the critical parameters that governs its occurrence and intensity. Figure 2 shows the conceptual stress–strain curve of a pillar under loading, together with two loading system stiffness conditions.

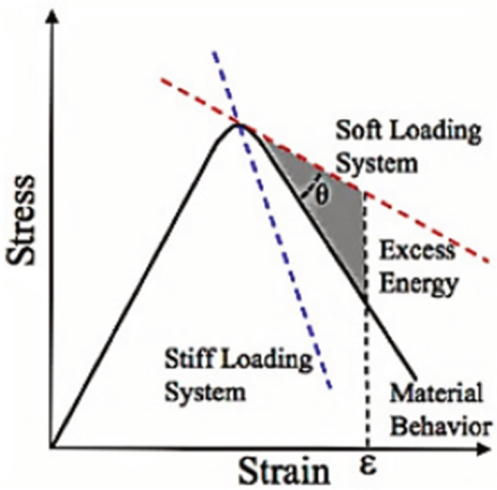


Figure 2 Stress–strain curve of the pillar under two loading conditions (Varder et al. 2017, in Gu 2013)

Referring to the above figure, the strength and stiffness of the pillar affect the amount of stored strain energy in the pillar before failure, while the relationship between the post-peak behaviour of the pillar and the stiffness of the loading system determines if an excess release of energy will happen. With the consideration of the W/H ratio, many researchers found that the strength of the pillar increases with an increasing W/H (Kaiser et al. 2011). Under those circumstances, the stored strain energy grows, which is dangerous should the pillar fail due to the increased amount of energy that might be released. If the post-peak behaviour of the pillar is stiffer than the loading system (Figure 2, red dashed line), the energy transferred to the pillar by the loading system cannot be fully dissipated (area in grey), resulting in the violent failure of the pillar. In shallow hard rock mines, a ratio of W/H ≤ 5 is likely to cause pillar bursts at failure (Ozbay et al. 1995). Therefore, the geometry of the pillar should be considered carefully.

2.3 Fault-slip bursts

Fault-slip rockbursts are directly related to a sudden movement along a pre-existing remote fault or a newly created shear rupture. When the fault slips (i.e. the primary remote seismic event), the generated seismic energy radiates and propagates to the vicinity of the excavation, initiating the secondary seismic event and associated damage there. According to this scenario, the intensity of the fault-slip burst could be governed by both radiated seismic energy from a remote primary seismic event and by the stored strain energy near

the excavation, usually making it greater in the intensity of damage than strainbursts and pillar bursts. The magnitude of fault-slip bursts varies from 2.5 to 5.0 (Richter magnitude) scale (Kaiser & Cai 2018).

However, not all the radiated seismic energy of a fault-slip reaches the boundary of the excavation due to the energy attenuation by geometrically spreading due to the increasing propagation radius, the energy absorption by the rock mass, and the energy scattering by the existence of geological structures (Wang et al. 2020).

Apart from energy attenuation, the wave type and pattern of radiation should also be considered. Two kinds of seismic waves occur during a fault-slip burst: P-waves and S-waves. The movement of rock particles varies in response to the impact of different wave types, which might affect the behaviour of the rock mass. In the view of the three-dimensional space, when a fault slips according to the direction of red arrows, Figure 3 represents the theoretical radiation patterns of P-wave and S-wave. In this figure, the black arrows indicate the direction of particle movement and the green arrows indicate the wave propagation directions, i.e. particles in P-wave travel along the propagation direction, whereas particles in S-wave oscillate perpendicular to the propagation path (Larsson 2004; He et al. 2020).

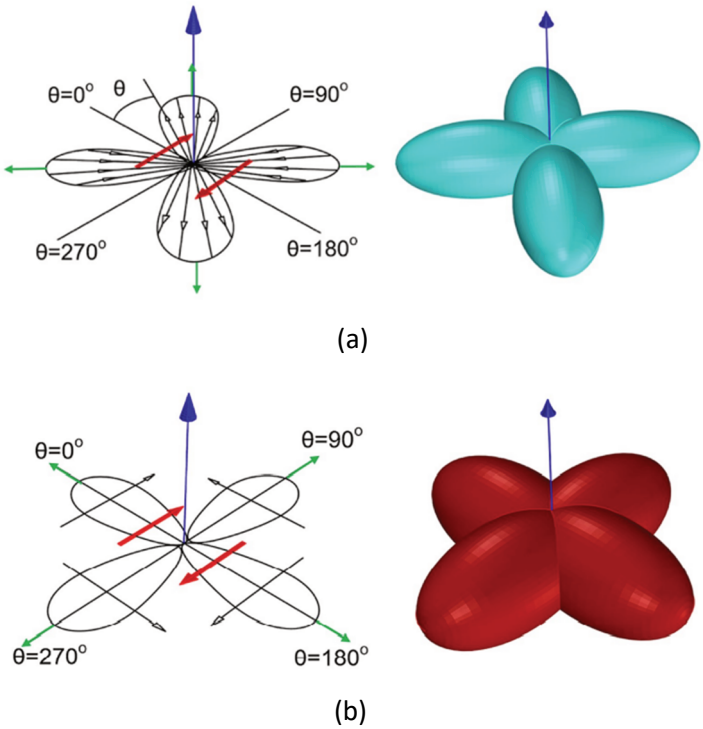


Figure 3 Radiation patterns of (a) P-wave; (b) S-wave in three-dimensional space (He et al. 2020)

3 Large seismic events and rockbursts in block cave mines

3.1 Seismic events during block caving process

A seismic event is the response of rock mass to inelastic deformation resulting in seismic wave radiation (Potvin et al. 2000; Mendecki et al. 1999). Due to the construction procedure and caving mechanism, it is common for the rock mass in block cave mines to continuously fracture throughout the cave operation from the undercut level to the surface or into the above open pit or cave. Therefore, seismic events are intrinsically linked to block caving in its entire procedure and the locations of seismic events vary significantly.

One of the reasons that seismic events happen close to undercut levels or extraction levels is because of the undercut blasting activities. In the Reservas Norte sector, El Teniente, the strong spatial and temporal correlations between major seismic events and undercutting was identified by analysing the locations between seismic events and undercut advance and comparing the cumulative blasted area and the

cumulative number of seismic events, respectively (Potvin et al. 2010). Once the caving process is initiated, some of the seismic events cluster ahead of the cave back, and the locations of the seismic events will go upward owing to the cave propagation. Taking the benefits of the modern seismic monitoring system, this condition can be observed as shown in Figure 4. The region with such recorded seismic events is called the seismogenic zone according to the caving profile defined by Duplancic (Cumming-Potvin & Wesseloo 2014, in Duplancic 2001).

Even the caving process has a spatial and temporal relationship to the seismic events, other factors such as geological structures and lithologies also play significant roles in seismic events distribution. From 2004 to 2008, around 90% of the major seismic events occurred in the vicinity of four major faults in RENO (Potvin et al. 2010). In Palabora, seismicity on one side is deeper than on the other side, which is partially attributed to the undercut advance towards fault (Glazer & Hepworth 2005). Regarding the various lithological regions, the seismic monitoring results show that different responses of seismicity would be revealed on different rock types (Hudyma et al. 2018a).

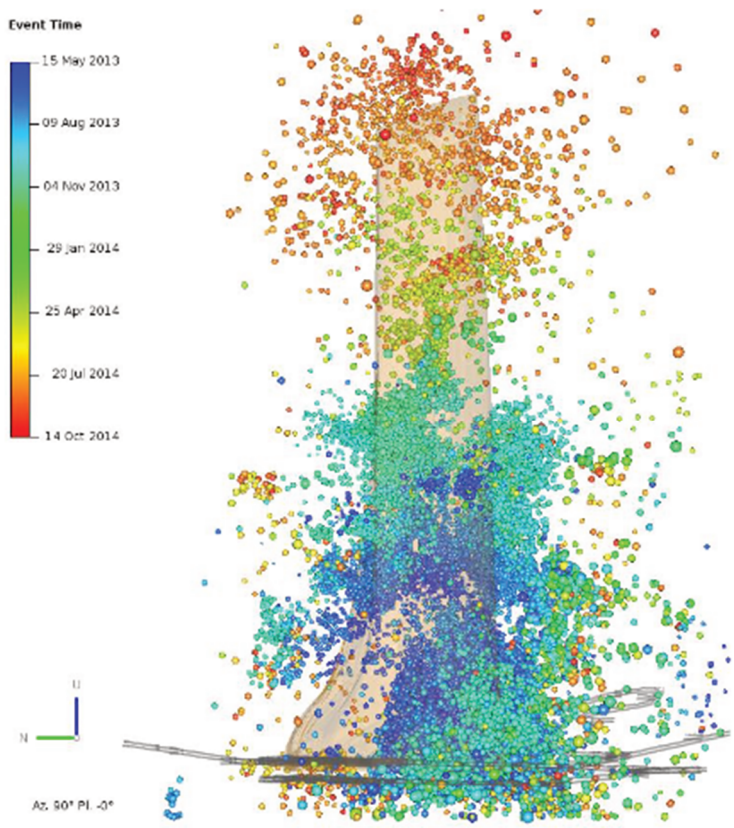


Figure 4 Seismic events propagate vertically with time (Lynch et al. 2018)

Even though most block caving is inherently associated with seismic events, not all seismic events cause damage to accessways or are related to rockbursts. In order to investigate factors that may contribute to the occurrence of rockbursts, several cases are studied here, including those that occurred in El Teniente (Chile), Freeport (Indonesia), Palabora (South Africa) and Northparkes (Australia). It should be highlighted that some significant seismic events considered in this case study may not have induced the damage on site. This is because a major seismic event might trigger a rockburst under some circumstances, e.g. without a sufficient supporting system.

3.2 Summary of large seismic events and rockbursts in block cave mines

Tables 1 to 4 summarise large seismic events and rockbursts in some block caving mines, together with information on the mine's geotechnical and geological environments. It should be noted that not all the reported rockbursts are included due to resource constraints.

Table 1 Summary of large seismic events/rockbursts in El Teniente, Chile

Mine	Sector	In situ stress (MPa)			Main lithologies			Main structural features	Depth	Mining method	Seismic event		Damage location	Data source
		σ_1	σ_2	σ_3	Name	CS (MPa)	ME (GPa)				Number/ type	Magnitude		
El Teniente, Chile	Ten 4	47–60	38–50	21–34	Secondary Andesite	–	–	Barden formation; Lamprophyric dyke	2,347* m.a.s.l	Conventional panel caving	Intense over-breaks***	–	Drifts; heavily supported drawpoint; intersection of haulage drifts and drawpoint drifts	Cuello et al. 2010; Dunlop & Belmonte 2005; Kvapil et al. 1989; Malovichko et al. 2018; Orrego et al. 2011; Pardo 2012; Rojas et al. 2000; Rojas et al. 2001; Rojas et al. 2004
					Primary Andesite	130**	55**				5 rockbursts	–	Pillars between the drifts	
					Primary Diorite	150**	58**							
	Ten Sub 6	–	–	–	Primary Andesite	130	55	Barden formation	2,101* m.a.s.l	Conventional panel caving	Rockburst	3.6 (Richter)	Temporarily established transport gallery	
					Primary Diorite	150	58				Rockburst	3.2 (Richter)	Sub 6 sector	
					Primary Dacite	170	50				Rockburst	4 (Richter)	Production level	
					Marginal Breccia	110	33				Main event	3.7 (Richter)	Main access to the production level	
	Reservas Norte	40–50	34–42	24–32	Andesite	120	60	Master faults; major faults; quartz dyke	–	Pre-undercut variant of panel caving	3 rockbursts	–	Galleries	
					Diorite Porphyry	140	45				Rockburst	3 (Moment)	Affecting galleries all levels of RENO (mainly on production level)	
					Dacite Porphyry	110	30				Rockburst	–	Haulage level	
					Anhydrite Breccia	102	41							

Mine	Sector	In situ stress (MPa)			Main lithologies			Main structural features	Depth	Mining method	Seismic event		Damage location	Data source
		σ_1	σ_2	σ_3	Name	CS (MPa)	ME (GPa)				Number/ type	Magnitude		
	Pillar Norte	31–84*	9–67*	2–34*	Andesite	UCS for all these units vary between 120 and 145 MPa	–	Large-scale faults and a stockwork of small-scale veins	–	Advance panel caving	Rockburst	1.9 (Moment)	Affecting several levels including undercut, production and ventilation levels	
					Diorite Porphyry						Rockburst	2.4 (Moment)	24% undercut level; 66% extraction level; 5% transportation; 4% ventilation	
					Breccias									

*The values are calculated from figures. **Properties for Sub 6 are used here. ***Intense overbreak may or may not be caused by rockbursts or large seismic events.

Table 2 Summary of large seismic events/rockbursts in Freeport, Indonesia

Mine	Sector	In situ stress (MPa)			Main lithologies			Main structural features	Depth	Mining method	Seismic event		Damage location	Data source
		σ_1	σ_2	σ_3	Name	CS (MPa)	ME (GPa)				Number/ type	Magnitude		
Freeport, Indonesia	Deep Mill Level Zone	–	–	–	Diorite	157	52	Several splays of the northwest trending faults	1,500–2,000 m below the surface	Advance panel cave	2 rockbursts	–	Galleries	Angin et al. 2019; de Beer et al. 2017; Fiscor 2010; Primadiansyah et al. 2020
					Limestone	141	64							
					Skarns	120	75							

Table 3 Summary of large seismic events/rockbursts in Palabora, South Africa

Mine	Sector	In situ Stress (MPa)			Main lithologies			Main structural features	Depth	Mining method	Seismic event		Damage location	Data source
		σ_1	σ_2	σ_3	Name	CS (MPa)	ME (GPa)				Number/ type	Magnitude		
Palabora, South Africa	Cave	46	38	36	Carbonatites	75–172	30–58	Dolerite dykes; large fault zones	1,200 m below the surface	Block caving	Seismic events of damage potential	–	–	Brummer et al. 2006; Glazer & Hepworth 2005; Moss et al. 2006; Ngidi & Pretorius 2010; Woo et al. 2012
					Foskorite	26–150	40							
					Pyroxenite	39–136	15–38							
					Glimmerite	37	6							
					Fenite	133–340	10							
					Granite	200–300	31							

Table 4 Summary of large seismic events/rockbursts in Northparkes, Australia

Mine	Sector	In situ stress (MPa)			Main lithologies			Main structural features	Depth	Mining method	Seismic event		Damage location	Data source
		σ_1	σ_2	σ_3	Name	CS (MPa)	ME (GPa)				Number/ type	Magnitude		
Northparkes, Australia	E26 Lift 2	53.2	33.1	22.2	Volcanics	99–116	64–64.2	No significant faulting was noted	900 m below the surface	Block caving	Large seismic event	Around 3 (Richter)	–	Hudyma et al. 2008a; Hudyma et al. 2008b; Ivars et al. 2011
					Diorite	81	59							
					QMP	115–124	62–63							
					BQM	143–144	61							

CS: Compressive strength; ME: Modulus of elasticity; QMP: Quartz monzonite porphyry; BQM: biotite quartz monzonite.

3.3 Significant factors of rockbursts

According to Tables 1 to 4, the following possible significant factors (i.e. in situ stress level and undercutting sequence) that may contribute to the occurrence of rockbursts will be discussed. The effect of in situ stress level will be analysed by comparing the ratio of maximum far-field in situ stress to unconfined compressive strength, and the effect of the undercutting sequence will be assessed by comparing the damage locations using different sequences.

3.3.1 In situ stress level

Because a high-stress environment is one of the necessary conditions for rockburst occurrence (Cai 2016), the in situ stress level in the aforementioned cases is assessed by an empirical method by comparing the values of the ratio of maximum far-field in situ stress to unconfined compressive strength (Kaiser et al. 2000). The results are shown in Figure 5 in which two points are calculated to represent the maximum and minimum ratios for a given mine sector as the in situ stress and compressive strength values vary. It should be noted that DMLZ is not included in Figure 5 due to the lack of data.

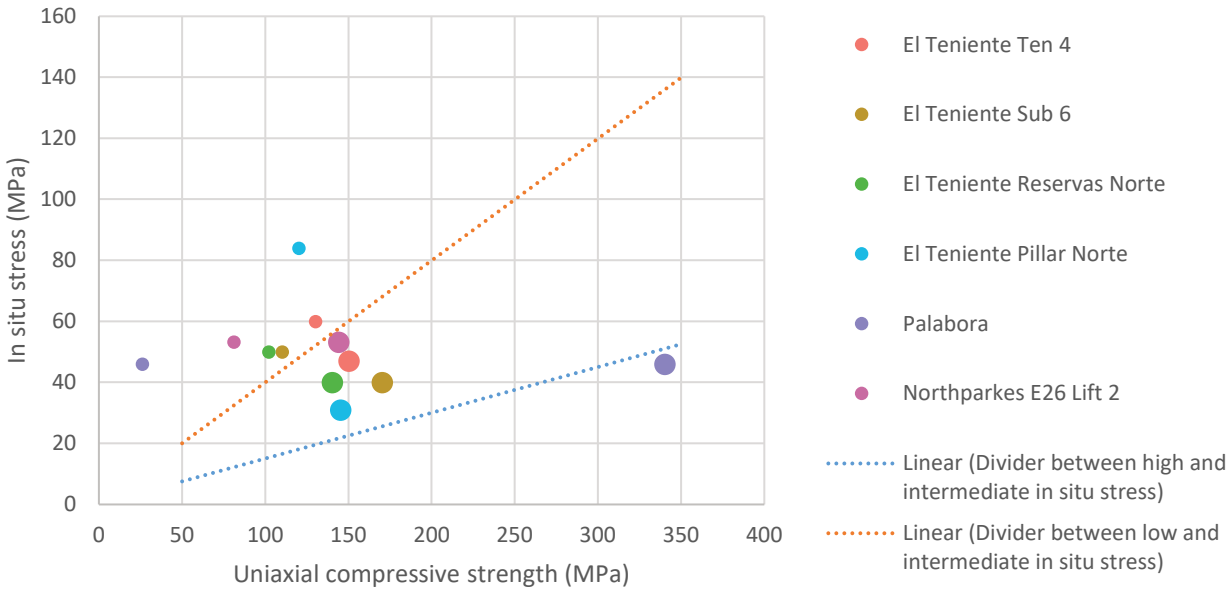


Figure 5 Diagram of the in situ stress to uniaxial compressive strength (large circles represent maximum ratios, while small circles represent minimum ratios)

It should be highlighted here that a few of the compressive strength values in the preceding four summary tables (i.e. Tables 1 to 4) may not correspond to the value obtained when the material is unconfined. However, for this brief analysis, they are considered uniaxial compressive strength (UCS).

According to this empirical method, the blue line (Figure 4) divides the low in situ stress level from the intermediate in situ stress level by a ratio of 0.15, while the orange line divides the high in situ stress level from the intermediate in situ stress level by a ratio of 0.4 (Kaiser et al. 2000).

It is evident that almost all the mines in this study are subject to an intermediate to a high level of in situ stress, in which rockburst is prone to occur (Yang et al. 2017). This high in situ stress is determined by both overburden and tectonic environment. For instance, the in situ stress level is usually high in El Teniente as a result of tectonic processes, and this mine is exposed to high tectonic forces (Kvapil et al. 1989, in Ojeda et al. 1980). However, since usually many sectors will be caved in the same mine site, this high in situ stress can also be affected by induced stresses caused by the relative location to other sectors (mined shapes). It is clear from Table 1 that the Pillar Norte sector has the highest maximum principal stress among others in El Teniente; this is a consequence of its location between two caves as a pillar (Orrego et al. 2011).

3.3.2 *Undercutting sequence*

As seen in Tables 1 to 4, damages caused by large seismic events or rockbursts may occur at a variety of sites across a mine. Incidents with reported damage locations in El Teniente are analysed as shown in Figure 6 after being categorised into undercut level, production level, transportation level, and ventilation level.

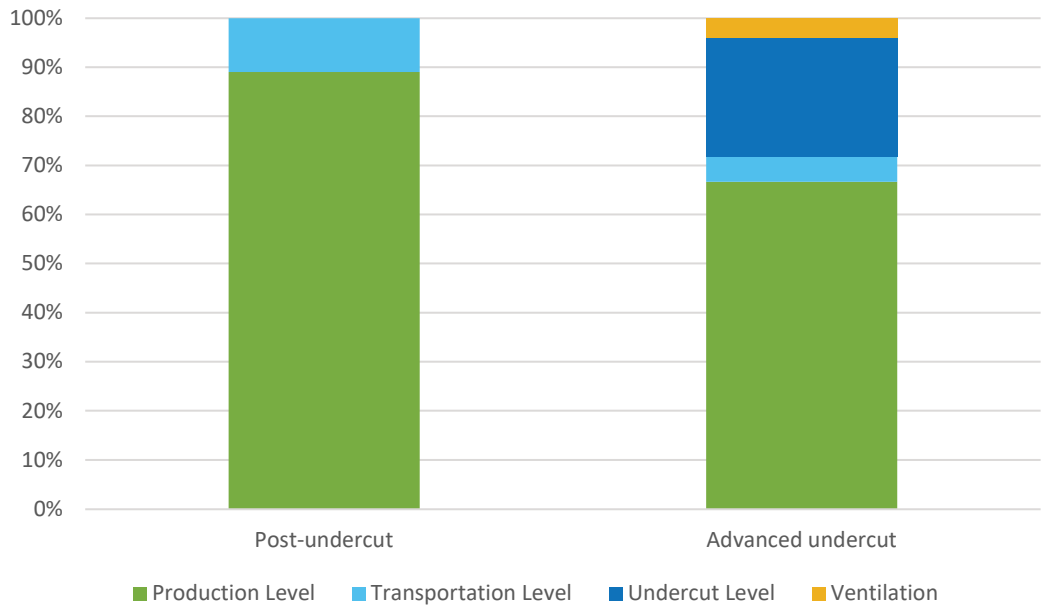
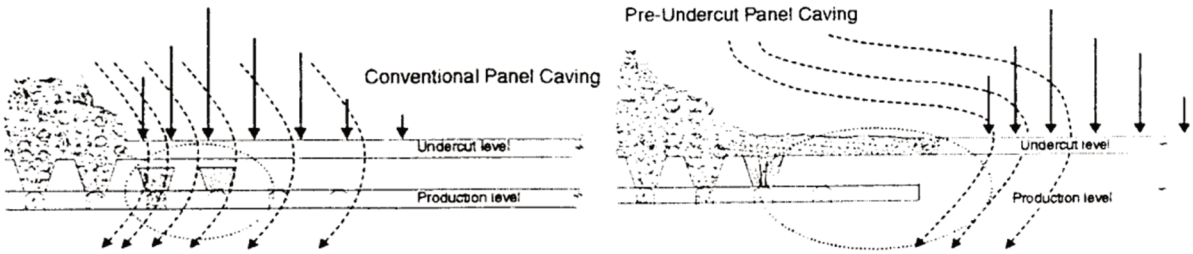


Figure 6 Diagram of the percentage of different damage locations in different mining sequences

There is less damage at the production level in the case of advanced undercutting compared to post-undercutting. However, more damages happened at the undercut level using advanced undercut than post-undercut. Even with the limited number of cases available, this tendency is broadly consistent with what happened in El Teniente (Araneda & Sougarret 2007).

In conventional panel caving, a significant amount of abutment stresses and principal stress paths will be imposed on the production level, as black arrows and dotted lines in Figure 7a, resulting in significant production level damage, similar to those encountered in El Teniente in the 80s and at the beginning of the 90s (Araneda & Sougarret 2007). Pre-undercut panel caving improves the situation to some extent by extending the relative distance between the undercut level front and the production level front and by reversing the sequence of drawbell opening and undercutting. As indicated in Figure 7b, the principal stress paths rarely go through the excavated production level, and the abutment stress in pre-undercut panel caving is focused above the undercut level. As a result, damage at the undercut level might occur more often in pre-undercut panel caving than in post-undercut panel caving. However, due to the limited data here, this is not reflected in the analysis.



(a) (b)

Figure 7 Panel caving with (a) Post-undercut, (b) Pre-undercut (Rojas et al. 2001)

The advanced undercutting approach would outperform the previous two since it combines the benefits of both by reducing the gap between the fronts of two levels and undercutting prior to the drawbell opening to generate a destressed region. The schematic advance undercutting sequence is shown in Figure 8.

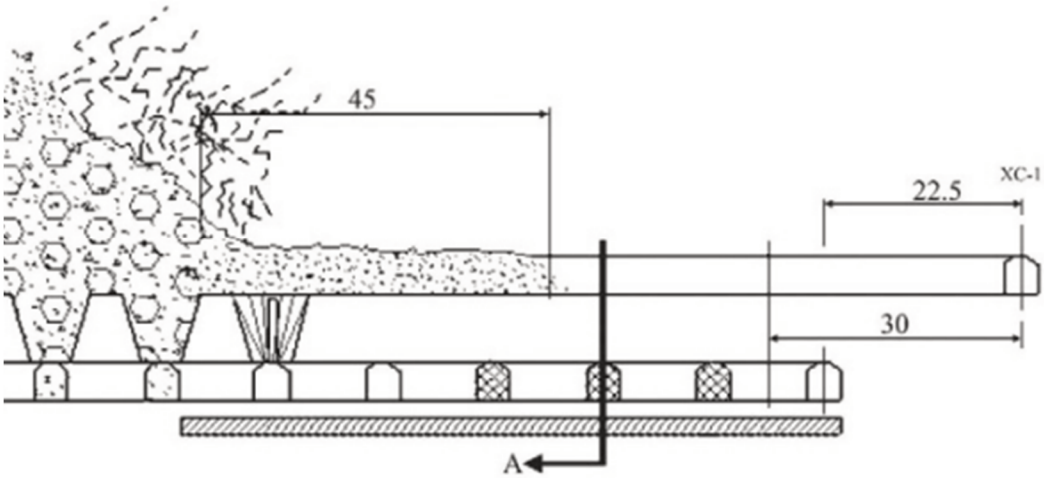


Figure 8 Advance undercutting mining sequence (Brady & Brown 2006)

It is well known that, in comparison to either the post-undercutting or pre-undercutting sequence, the amount of extraction-related damage would be lower with the post-undercutting sequence and the production rate would be higher with the pre-undercutting sequence (Brady & Brown 2006). This is somewhat consistent with the analysis presented here.

4 Rockburst controlling techniques

Numerous rockburst control strategies are used in block caving mines to minimise the occurrence and intensity of rockbursts, including mine layout design, preconditioning, and dynamic ground support (Flores-Gonzalez 2019). According to the categorisation of preventative strategies (Zhang et al. 2017), the latter two techniques fall into the category of active prevention, while mine layout design falls into the category of passive prevention.

Prior to the excavation process, a mine plan is designed, including the selection of undercutting sequences, in order to avoid unfavourable underground conditions. For instance, undercutting sequences, discussed in Section 3.3.2, affect the stress distribution around the production and undercutting levels resulting in an unfavourable local stress environment. However, this mine layout might need to be further changed according to the feedback after inspections in order to mitigate the rockburst hazards (Durrheim et al. 1998).

In terms of active protection strategies, each of the aforementioned approaches provides a unique purpose in preventing rockbursts. Preconditioning may optimise the rock mass properties and stress conditions for cave performance (Flores-Gonzalez 2019; Rimmelin et al. 2020). Either hydrofracturing or confined blasting can accomplish preconditioning; however, there are notable distinctions between the two. Hydrofracturing introduces new large-scale fractures by fluid injection, while confined blasting expands existing discontinuities using explosives (Catalan et al. 2017). The combination of these two procedures is referred to as intensive preconditioning (Figure 9).

The second active protection technique is dynamic ground support, which includes yielding rockbolts. Due to their high ductility and energy absorption capabilities, yielding rockbolts are employed to absorb released energy to prevent rock ejection. Because the energy absorption process varies amongst yielding rockbolts, they may be divided into four categories: ploughing, friction, structural extrusion, and bar stretching. For instance, energy absorption during ploughing occurs as a result of ploughing an element, such as a cone at the end of a cone bolt, through the grout (Wei et al. 2022).

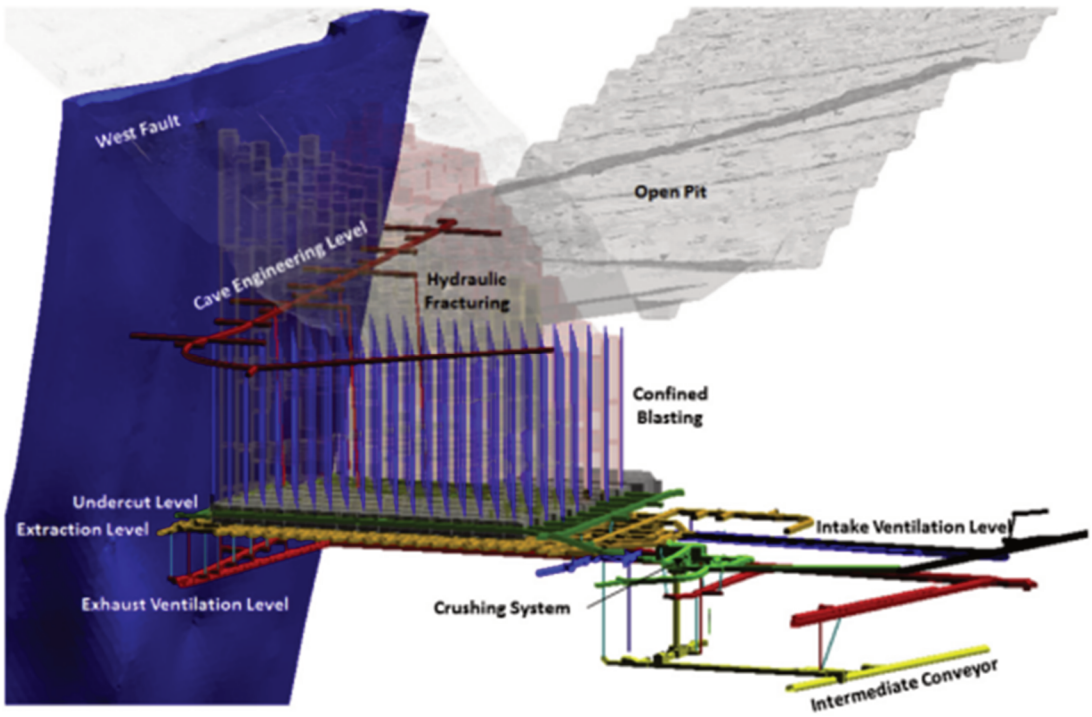


Figure 9 Location of hydrofracturing and confined blasting in intensive preconditioning (Flores & Catalan 2019)

5 Discussion and conclusion

Rockburst is one of the most dangerous hazards in mining due to its high-intensity damage that may cause project delays and personnel deaths. Due to the changing block cave environment as a result of increasing mining depth, rockbursts are more prone to happen as a consequence of the increasing overburden. Thus, it is critical to comprehend the effect of contributing factors in rockburst to mitigate its impacts. Two key elements, in situ stress level and undercutting sequence, that may induce rockburst are discussed in this paper through the collection and analysis of rockburst and large seismic event cases from Chile, South Africa, Indonesia, and Australia.

Unsurprisingly, in situ stress is a substantial contributor to the occurrence of rockbursts associated with block caving. The increasing in situ stress generated by overburden, tectonic movements, and mine geometry, among other factors, may increase the vulnerability to rockburst in mines. The other factor covered in this work is the undercutting sequence, which affects the stress distribution around the undercut and production levels. Advanced undercut panel caving demonstrates effective management of rockbursts near the drifts in El Teniente.

Three approaches are often employed to control rockbursts. Mine layout design before establishment can avoid unfavourable orientation, preconditioning is used to prepare the rock mass for caving and cave establishment; and yielding rockbolts are used to absorb or disperse the released energy in order to limit rockburst damage as the last line of defence.

Even though in situ stress and undercut scheduling seems to be reasonable, some limitations should be mentioned. The first is the limited sample size. A bigger database will be advantageous for identifying additional components to improve understanding of the rockburst process connected with block caving. Secondly, data inaccuracy is a possible issue. The data in this research was synthesised from a selection of published articles throughout the years. The aggregated data, such as in situ stress and rock characteristics, varies greatly. It would be beneficial to augment the sample data by establishing and sharing a worldwide database on rockbursts with academic institutions and industry.

References

ACIL Allen Consulting 2019, *The Economic Impact of the Minerals Research Institute of Western Australia*, ACIL Allen.

Angin, PP, Wattimena, RK, Sahara, DP & Purba, AM 2019, 'Microseismic analysis to identify stress redistribution and minimise rockburst in DMLZ cave abutment, PT Freeport Indonesia', *5th ISRM Young Scholars' Symposium on Rock Mechanics and International Symposium on Rock Engineering for Innovative Future*, OnePetro, Japan, pp. 851–856.

Araneda, O & Sougarret, A 2007 'Lessons learned in cave mining: El Teniente 1997–2007', *Proceedings of the First International Symposium on Block and Sub-level Caving*, The Southern African Institute of Mining and Metallurgy.

Brady, BH & Brown, ET 2006, *Rock Mechanics: For Underground Mining*, Kluwer Academic Publishers, London.

Brummer, RK, Li, H, Moss, A & Casten, T 2006, 'The transition from open pit to underground mining: an unusual slope failure mechanism at Palabora', *Proceedings International Symposium on Stability of Rock Slopes*, Cape Town, The Southern African Institute of Mining and Metallurgy, pp. 411–420.

Cai, M 2016, 'Prediction and prevention of rockburst in metal mines–A case study of Sanshandao gold mine', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 8, no. 2, pp. 204–211.

Catalan, A, Onederra, I & Chitombo, G 2017, 'Evaluation of intensive preconditioning in block and panel caving–Part I, quantifying the effect on intact rock', *Mining Technology*, vol. 126, no. 4, pp. 209–220.

Chitombo, G 2010, 'Cave mining: 16 years after Laubscher's 1994 paper'Cave mining–state of the art', *Mining Technology*, vol. 119, no. 3, pp. 132–141.

Cuello, DA, Landeros, PP & Cavieres, PH 2010, 'The use of a three-dimensional elastic model to identify rock mass damaged areas in the undercut level at Reservas Norte sector', in M Van Sint Jan & Y Potvin (eds), *Deep Mining 2010: Proceedings of the Fifth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 437–450.

de Beer, W, Jalbout, A, Riyanto, E, Ginting, A, Sullivan, M & Collins, DS 2017, 'The design, optimisation, and use of the seismic system at the deep and high-stress block cave Deep Mill Level Zone mine', in M Hudyma & Y Potvin (eds), *UMT 2017: Proceedings of the First International Conference on Underground Mining Technology*, Australian Centre for Geomechanics, Perth, pp. 233–245.

Dunlop, R & Belmonte, A 2005, 'The April 22nd, 2003 Rockburst in the Sub 6 Sector, El Teniente Mine—A Case History', in Y Potvin & M Hudyma (eds), *RaSiM6: Proceedings of the Sixth International Symposium on Rockburst and Seismicity in Mines*, Australian Centre for Geomechanics, Perth, pp. 291–297.

Duplancic, P 2001, *Characterisation of Caving Mechanisms Through Analysis of Stress and Seismicity*, PhD Thesis, The University of Western Australia, Perth.

Durrheim, R, Roberts, MKC, Haile, AT, Hagan, TO, Jager, AJ, Handley, MF, Spottiswoode, SM & Ortlepp, W 1998, 'Factors influencing the severity of rockburst damage in South African gold mines', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 98, no. 2, pp. 53–57.

Eberhardt, E, Stead, D, Elmo, D, Dunbar, S, Scoble, M, Moss, A, Sturzenegger, M, Vyazmensky, A, Tollenaar, R & Eissa, H 2007, 'Transition from surface to underground mining: Integrated mapping, monitoring and modeling data to better understand complex rock mass interaction', *13th ISRM International Congress of Rock Mechanics*, Perth.

Fiscor, S 2010, 'Major open-pit copper mines move underground', *Engineering and Mining Journal*, vol. 211, no. 5, p. 46.

Flores-Gonzalez, G 2019, 'Major hazards associated with cave mining: are they manageable?', in J Wesseloo (ed.), *MGR 2019: Proceedings of the First International Conference on Mining Geomechanical Risk*, Australian Centre for Geomechanics, Perth, pp. 31–46.

Flores, G & Catalan, A 2019, 'A transition from a large open pit into a novel "macroblock variant" block caving geometry at Chuquicamata mine, Codelco Chile', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 3, pp. 549–561.

Glazer, SN & Hepworth, N 2005, 'Seismicity Induced by Cave Mining, Palabora Experience', in Y Potvin & M Hudyma (eds), *RaSiM6: Proceedings of the Sixth International Symposium on Rockburst and Seismicity in Mines*, Australian Centre for Geomechanics, Perth, pp. 281–289.

Gu, R 2013, *Distinct Element Model Analyses of Unstable Failures in Underground Coal Mines*, PhD thesis, Colorado School of Mines.

He, M, Gong, W, Wang, J, Qi, P, Tao, Z, Du, S & Peng, Y 2014, 'Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance', *International Journal of Rock Mechanics and Mining Sciences*, vol. 67, pp. 29–42.

He, M, Xia, H, Jia, X, Gong, W, Zhao, F & Liang, K 2012, 'Studies on classification, criteria and control of rockbursts', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 4, no. 2, pp. 97–114.

He, S, Chen, T, Vennes, I, He, X, Song, D, Chen, J & Mitri, H 2020, 'Dynamic Modelling of Seismic Wave Propagation due to a Remote Seismic Source: A Case Study', *Rock Mechanics and Rock Engineering*, vol. 53, DOI:10.1007/s00603-020-02217-w.

Hudyma, M, Potvin, Y & Allison, D 2008a, 'Seismic monitoring of the Northparkes Lift 2 block cave-Part 2 production caving', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 108, no. 7, pp. 421–430.

Hudyma, M, Potvin, Y & Allison, D 2008b, 'Seismic monitoring of the Northparkes Lift 2 block cave-Part I undercutting', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 108, no. 7, pp. 405-419.

Ivars, DM, Pierce, ME, Darcel, C, Reyes-Montes, J, Potyondy, DO, Young, RP & Cundall, PA 2011, 'The synthetic rock mass approach for jointed rock mass modelling', *International Journal of Rock Mechanics and Mining Sciences*, vol. 48, no. 2, pp. 219–244.

Kaiser, P & Cai, M 2018, *Rockburst Support Reference Book – Volume I: Rockburst Phenomenon and Support Characteristics*, MIRARCO – Mining Innovation, Laurentian University, Sudbury, Ontario, Canada, http://www.imseismology.org/imsdownloadsapp/webresources/filedownload/Cai-Kaiser(2018)-Rockburst-Support-Vol1.pdf.

Kaiser, P, Diederichs, M, Martin, C, Sharp, J & Steiner, W 2000, 'Underground works in hard rock tunnelling and mining', ISRM *International Symposium*, OnePetro.

Kaiser, PK 1996, *Canadian Rockburst Support Handbook*, Geomechanics Research Centre.

Kaiser, PK, Kim, B, Bewick, RP & Valley, B 2011, 'Rock mass strength at depth and implications for pillar design', *Mining Technology*, vol. 120, no. 3, pp. 170–179.

Larsson, K 2004, *Seismicity in Mines: A Review*, technical report, Luleå University of Technology, Luleå.

Li, CC, Mikula, P, Simser, B, Hebblewhite, B, Joughin, W, Feng, XW & Xu, NW 2019, 'Discussions on rockburst and dynamic ground support in deep mines', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 5, pp. 1110–1118, DOI:10.1016/j.jrmge.2019.06.001.

Lynch, R, Meyer, S, Lotter, E & Lett, J 2018, 'Tracking cave shape development with microseismic data', in Y Potvin & J Jakubec (eds), *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 555–564.

Malovichko, D, Cuello, D & Rojas, E 2018, 'Analysis of damaging seismic event on 24 December 2011 in the Pilar Norte sector of El Teniente mine', in Y Potvin & J Jakubec (eds), *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 637–650.

Martin, C & Maybee, W 2000, 'The strength of hard-rock pillars', *International Journal of Rock Mechanics and Mining Sciences,* vol. 37, no. 8, pp. 1239–1246.

Mazaira, A & Konicek, P 2015, 'Intense rockburst impacts in deep underground construction and their prevention', *Canadian Geotechnical Journal*, vol. 52, no. 10, pp. 1426–1439.

Mendecki, A, Van Aswegen, G & Mountfort, P 1999, 'A guide to routine seismic monitoring in mines', *A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines*, p. 35.

Moss, A, Diachenko, S & Townsend, P 2006, 'Interaction between the block cave and the pit slopes at Palabora mine', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 10, pp. 479–484.

Ngidi, S & Pretorius, D 2010, 'Impact of poor fragmentation on cave management', in Y Potvin (ed), *Caving 2010: Proceedings of the Second International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 593–601.

Ojeda, J, Hernandez, E, Ossand6n, G, Enrione, A & Mestre, A 1980, *El porfido cuprifero El Teniente*, internal report, Superintendencia de Geologia, El Teniente, Codelco.

Orrego, C, Cuello, D & Rojas, E 2011, 'Determination of induced stress condition inside Pilar Norte sector', *Mining Technology*, vol. 120, no. 1, pp. 45–52.

Ortlepp, WD & Stacey, TR 1994, 'Rockburst Mechanisms in Tunnels and Shafts', *Tunnelling and Underground Space Technology*, vol. 9, no. 1, pp. 59–65.

Ozbay, M, Ryder, JA & Jager, A 1995, 'The design of pillar systems as practised in shallow hard-rock tabular mines in South Africa', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 95, no. 1, pp. 7–18.

Pardo, C 2012, *Back Analysis of Intensive Rock Mass Damage at the El Teniente Mine*, PhD thesis, Curtin University.

Potvin, Y, Hudyma, M & Jewell, RJ 2000, 'Rockburst and seismic activity in underground Australian mines - An introduction to a new research project', *ISRM International Symposium*.

Potvin, Y, Jarufe, J & Wesseloo, J 2010, 'Interpretation of seismic data and numerical modelling of fault reactivation at El Teniente, Reservas Norte sector', *Mining Technology*, vol. 119, no. 3, pp. 175–181.

Primadiansyah, A, Simanjuntak, K, Leatemia, C & Pratomo, F 2020, 'Ground support selection and development sequences for mass excavation crusher 504 in a deep, hard rock environment', *ISRM International Symposium-EUROCK 2022*, OnePetro.

Rimmelin, R, Chitombo, G & Rojas, E 2020, 'Hydraulic fracturing in cave mining: Opportunities for improvement', *MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining*, University of Chile, pp. 275–288.

Rojas, E, Cavieres, P, Dunlop, R & Gaete, S 2000, 'Control of induced seismicity at El Teniente mine, Codelco Chile', *Proceedings Massmin 2000*, pp. 777–781.

Rojas, E, Dunlop, R, Bonani, A, Santander, E, Celis, S & Belmonte, A 2004, 'Seismic and support behaviour, a case study: the April 22nd, 2003 Rockburst, Reservas Norte sector, El Teniente Mine, Codelco Chile', *Ground Support in Mining and Underground Construction: Proceedings of the Fifth International Symposium on Ground Support*, Perth, Australia, Taylor & Francis, p. 163.

Rojas, E, Molina, R & Cavieres, P 2001, 'Preundercut caving in El Teniente Mine, Chile', *Underground Mining Methods: Engineering Fundamentals and International Case Studies*, pp. 417–423.

Sainoki, A & Mitri, HS 2014, 'Dynamic behaviour of mining-induced fault slip', *International Journal of Rock Mechanics and Mining Sciences*, vol. 66, pp. 19–29.

Wang, C, Cao, A, Zhang, C & Canbulat, I 2020, 'A new method to assess coal burst risks using dynamic and static loading analysis', *Rock Mechanics and Rock Engineering*, vol. 53, no. 3, pp. 1113–1128.

Wei, C, Zhang, C, Canbulat, I, Song, Z & Dai, L 2022, 'A review of investigations on ground support requirements in coal burst-prone mines', *International Journal of Coal Science & Technology*, vol. 9, no. 1, p. 13.

Woo, K-S, Eberhardt, E, Rabus, B, Stead, D & Vyazmensky, A 2012, 'Integration of field characterisation, mine production and InSAR monitoring data to constrain and calibrate 3-D numerical modelling of block caving-induced subsidence', *International Journal of Rock Mechanics and Mining Sciences*, vol. 53, pp. 166–178.

Yang, J, Chen, W, Zhao, W, Tan, X, Tian, H, Yang, D & Ma, C 2017, 'Geohazards of tunnel excavation in interbedded layers under high in situ stress', *Engineering Geology*, vol. 230, pp. 11–22.

Zhang, C, Canbulat, I, Hebblewhite, B & Ward, CR 2017, 'Assessing coal burst phenomena in mining and insights into directions for future research', *International Journal of Coal Geology*, vol. 179, pp. 28–44.