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Insights from studying intrinsic hard rock behaviour for rockburst hazard identification

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Abstract

In conventional laboratory rock tests the classical post-peak behaviours of hard rock are defined by two distinct post-peak behaviours: one is self-triggered or violent (so-called Class II), and the other is stable (so-called Class I). Recent laboratory rock test results using a novel testing machine, along with reviews of field observations, suggest that there seems to be only one type of post-peak deformation behaviour for hard rock if the rock is loaded using axial-strain-controlled loading. The previously identified self-triggered post-peak behaviour captured by conventional rock testing machines is now considered artificial. This work offers clear insights into identifying and addressing violent hard rock failures in deep mining. In such settings, mining-induced stresses can reach the rock mass strength near excavations, leading to seismic hazards like rockbursts that pose significant threats to workplace safety and mining activity. Based on deep mining practices across different regions worldwide, a review followed by a discussion was conducted on rockburst conditions in various mining scenarios, including stoping with or without backfill, room-and-pillar mining, block/panel caving and sublevel caving.

Keywords: *loading system stiffness, Class I post-peak behaviour, Class II post-peak behaviour, rockburst hazard, stoping, caving, room-and-pillar mining*

1 Introduction

With the increase of extraction at depth, e.g. deep hard rock mining at over 1–2 km depths, the excavation-induced stresses applied to the rock mass near the excavation surface can reach the in situ strength of the rock mass, leading to rock failure. For instance, many of the underground mines in the Canadian Shield, a world-class mining area that is rich in both base-metal and precious-metal resources, have migrated to deep levels due to the depletion of resources near the surface during the last two to three decades. Although in situ stresses can vary drastically in space by nature, the regional stresses in the Canadian Shield are well tested and documented. Deep hard rock mining activities can lead to stresses that may well increase, reaching the in situ rock mass strength (Wagner 2019; Morissette et al. 2017; Varden & Woods 2015). Once the rock mass is subjected to a stress state that is approaching its peak strength, mining excavations are required to tolerate rock mass yield and potential seismic loading while not compromising workplace safety. It is therefore necessary to study the failure process of the rock mass and its impact on ground control strategy.

It is convincing to test the rock mass failure process in the field whenever possible to determine if the test results reflect in situ rock mass behaviour. Unfortunately this is difficult and prohibitively costly. Instead, rock mechanics engineers often resort to numerical modelling for rock engineering design. However, results

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obtained from laboratory rock property testing still serve as the premise for drawing conclusive findings from numerical or analytical studies on rock mass behaviour. Based on laboratory testing on intact hard rock samples it is commonly agreed that the post-peak behaviour of rocks can be classified into Class I and Class II failure types (see Figure 1, where LSS is loading system stiffness and k1 is the post-peak stiffness of rock). The Class I type implies that rock failure will not continue without further deformation applied to the rock externally; the Class II type suggests that rock failure will self-initiate as soon as the applied load is beyond the rock strength. However, when the LSS is smaller than the critical LSS condition of a Class I rock, i.e. LSS < k1, it indicates a soft loading condition under which the Class I rock will experience a violent failure process once the rock strength is reached.

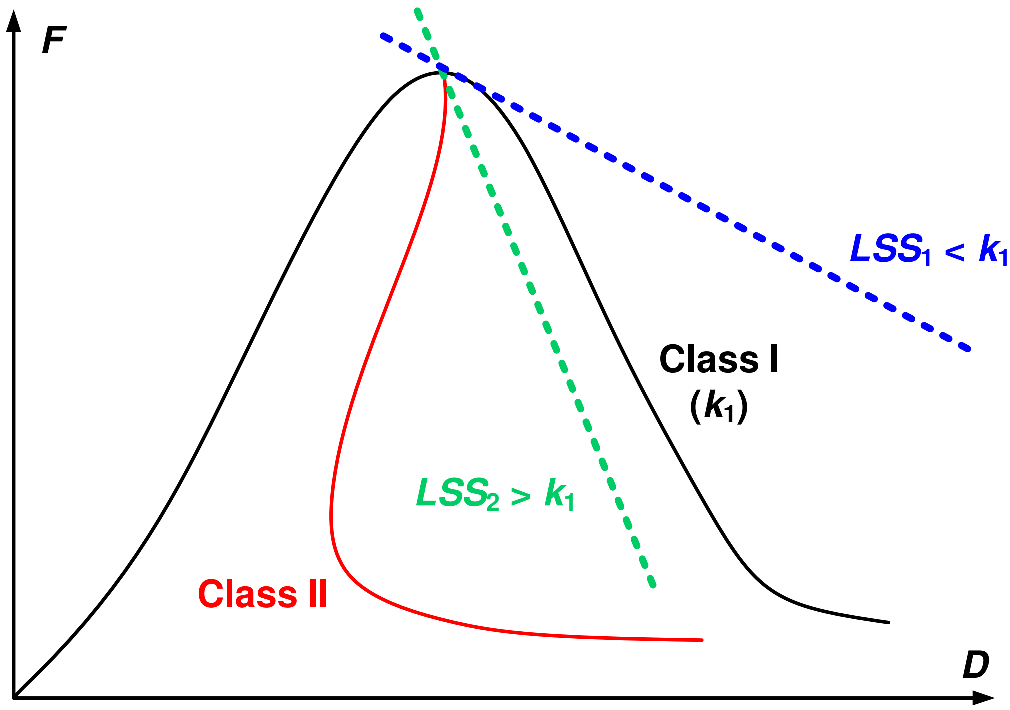


Figure 1 Class I and Class II post-peak behaviours of rocks

Deep hard rock mining can cause the rock mass to yield or even fail in high-stress regimes. However, rock mass failure in the form of rockburst does not occur frequently, considering that excavation activities at different scales happen almost every day in underground mining. Compared with blasting large open stopes, which are limited by visual observations of rock mass failure modes after the blast, regular 4 m-long development rounds with typical cross-section dimensions of about 5 m width and 5 m height are routinely blasted as a development activity in active mines. This provides a good opportunity to visually assess the way and how often hard rock mass fails if the excavation-induced stresses reach the rock mass strengths.

Driven by the field observations from deep mining discussed above, this paper first revisits two fundamental questions in rock mechanics: does the Class II post-peak behaviour observed in laboratory rock tests reflect real intrinsic rock behaviour and, if so, what are the true intrinsic rock behaviour(s) that control the violent rock failure cases in deep mining? The remainder of this paper reviews the dominant factors contributing to violent rock failure, based on field experience in using different mining methods.

2 Post-peak behaviour of hard rock from past laboratory studies

Hard rock manifests its property in terms of high strength and a sudden strength drop once failure occurs. It has been known since the mid-1960s that testing machines require a system stiffness higher than the post-peak stiffness of rock to capture the Class I curve and must be fast enough to react to the Class II post-peak behaviour (Cook & Hojem 1966; Bieniawski 1966). A conventional stiff test machine normally consists of a steel frame that hosts the rock specimen inside, end loading platens contacting the specimen to distribute the load and a hydraulic ram to deform the specimen. In this case the loading component of the system with the lowest stiffness controls the overall LSS (Hudson et al. 1972).

As it is difficult to significantly improve the stiffness of the hydraulic ram which has the lowest stiffness compared with the other loading components, Hudson et al. (1972) attempted to improve the loading sensitivity by developing a servo-controlled test machine which allows any extra energy to be extracted from the test machine during the post-peak deformation stage, rather than releasing it to rock specimens, so that the monitoring of the rock failure process is under control. A comprehensive review of the development of traditional stiff testing systems for rock property tests is not the focus of this study and may be found elsewhere (Xu 2017).

With the aid of traditional stiff testing machines the complete load-deformation relations (axial loading direction) of rock are recorded and categorised into two classes of post-peak behaviours, which are Class I type and Class II types (as illustrated in Figure 1). A Class I failure type shows a strain-softening behaviour, as opposed to a Class II failure type which shows that the rock strength decreases with a decrease of axial deformation in the post-peak deformation stage. According to Wawersik (1968), Class II is an unstable failure type because energy has to be extracted from the external loading system to record the complete post-peak behaviour. In contrast, Class I post-peak behaviour can be recorded when rock fails in a stable fashion with continuous energy input from the external loading system.

A rockburst is a seismic event that causes damage to the ground support system or excavation, or which leads to personal injury. A rockburst occurs when a rock fails in a violent fashion, releasing extra energy in the rock failure process that prevents the rock from following a stable deformation process similar to what is observed in laboratory testing. For any rock subjected to either laboratory or field loading conditions, extra energy has to be provided by the external loading environment to cause violent failure of brittle hard rock. In comparison, as illustrated in laboratory observations, for Class II behaviour no extra energy is required from the external loading environment to cause a violent failure of the rock because the failure process is 'self-initiated'. According to Wawersik (1968), to inhibit violent failure, energy needs to be extracted from the Class II fail type during the post-peak deformation stage, with the help of an external loading environment, by reversing the rock deformation.

Past field experiences well document that rockburst hazards mostly occur within, or in proximity to, excavation activities, with the exception being some delayed rockbursts (Feng et al. 2012) due to a combination of rock creep, stress redistribution, remote triggers and other related factors. For underground rock engineering, excavation-induced stresses concentrate near the excavation fronts, creating an elevated high-stress environment accompanied by increased strain energy and rock deformations. Once the excavation front advances far enough beyond the area of interest, such as a heavily mined-out area in a stress shadow, the local stresses decrease, as does the total stored strain energy. Therefore there is often an elevated stress environment near its boundary rather than a completely stress-relaxed environment that drives rockburst occurrence. In other words, violent rock failure often occurs in the presence of extra energy input (i.e. deformation increase) rather than energy output (i.e. deformation decrease).

Rockbursts occur mostly in hard rocks. When hard rock specimens are subjected to low confinement in laboratory testing, reflecting the stress conditions of rock masses near excavation surfaces, brittle rock failure is typical. This process represents the laboratory-observed behaviour of hard rock. Class II post-peak behaviour observed in the laboratory is caused by lateral-strain-controlled loading, which causes the machine to unload post-peak due to a large increase of dilation (Cai et al. 2021; Hou et al. 2022). Rockbursts in field observations mostly occur under stress-increase conditions along with extra energy input. However, real-life rockbursts do not frequently occur near excavations, even for routine development round blasts in metal mines that are over 1–2 km deep. In deep mining, spalling (or 'onion skin') is commonly observed in the backs of drifts, suggesting that the local boundary stresses are high enough to progressively cause stress damage to the rock mass without suddenly shattering it. Thus it is necessary to study whether the hard rock in the field will fail violently or burst once the excavation-induced stresses reach the rock mass strength.

3 Studies on intrinsic hard rock post-peak behaviour and its implication on a rockburst mechanism

3.1 Laboratory test results using Stiffman

A novel stiff rock testing machine called Stiffman, with composite loading frames and relay loading, was developed to overcome the technical difficulties of conventional rock testing machines, such as insufficient loading system stiffness, inability to use axial-strain-controlled loading in the post-peak deformation stage and limited strain capacity to reach the residual state. Details about the development and innovations of Stiffman can be found elsewhere (Cai et al. 2021; Hou et al. 2022).

Stiffman has been used to test a wide range of brittle hard rocks (with uniaxial compressive strength [UCS] over 200 MPa) from mining and civil projects in Canada and China. The experimental results show that Stiffman can reliably capture complete post-peak stress–strain curves of brittle hard rocks under axial-strain-controlled loading. With axial-strain-controlled loading in uniaxial tests all the rock specimens tested exhibited Class I behaviour, while those under lateral-strain-controlled loading exhibited Class II behaviour. It is thus demonstrated that Class II post-peak stress–strain curves obtained by lateral-strain-controlled loading are caused by the unloading of the actuator in response to the servo-control system in order to maintain a constant lateral strain rate (Cai et al. 2021).

3.2 Impact of loading rate and other loading conditions

It has been well documented that across a wide range of rock types such as coal, sedimentary rocks and hard rocks, the post-peak behaviour of rocks becomes more ductile and rock strength increases with an increase in loading rate. This observation has been confirmed by numerical modelling experiments which exclude the influence of rock sampling differences on testing results. These rock tests, including conventional UCS tests, according to the loading rates applied, can be classified as quasi-static rock tests. On the other hand, two extreme loading conditions in hard rock laboratory tests lead to different observations on rock post-peak behaviours:

- When rock is subjected to a constant load of about 80% of its UCS it is a creep test under the static loading condition. If the rock eventually fails it usually fails suddenly, after a long period. The strength obtained is called the long-term strength of the rock, which is lower than the UCS obtained from quasi-static rock tests.
- When rock is subjected to a dynamic loading condition, such as using the Split Hopkinson Pressure Bar (SHPB) method, it fails violently due to the high-speed impact. The failure load increases with the increase in impact speed (or input energy) from the SHPB.

Moreover, it is well known that rock strength, whether at the laboratory sample scale or the field scale, increases with an increase in rock width (i.e. the surface dimension perpendicular to the loading direction), which essentially increases the confinement within the rock. According to elastic mechanics, increased confinement allows materials to behave elastically to store more strain energy before yielding.

Referring to insights from a comprehensive numerical modelling campaign by Xu (2017) on the impact of different loading conditions, including LSS, and combined with recent test results from Stiffman, the following statement is made by the authors on characterising intrinsic hard rock behaviour (Figure 2):

> *There is no standard intrinsic hard rock deformation behaviour that can be captured by a single stress–strain relation. Instead, different loading conditions representing varying loading statuses of rocks (i.e. static, quasi-static, dynamic), and hence different external input energies, lead to different hard rock deformation behaviours. Dynamic loading conditions, in particular, often cause violent rock failure.*

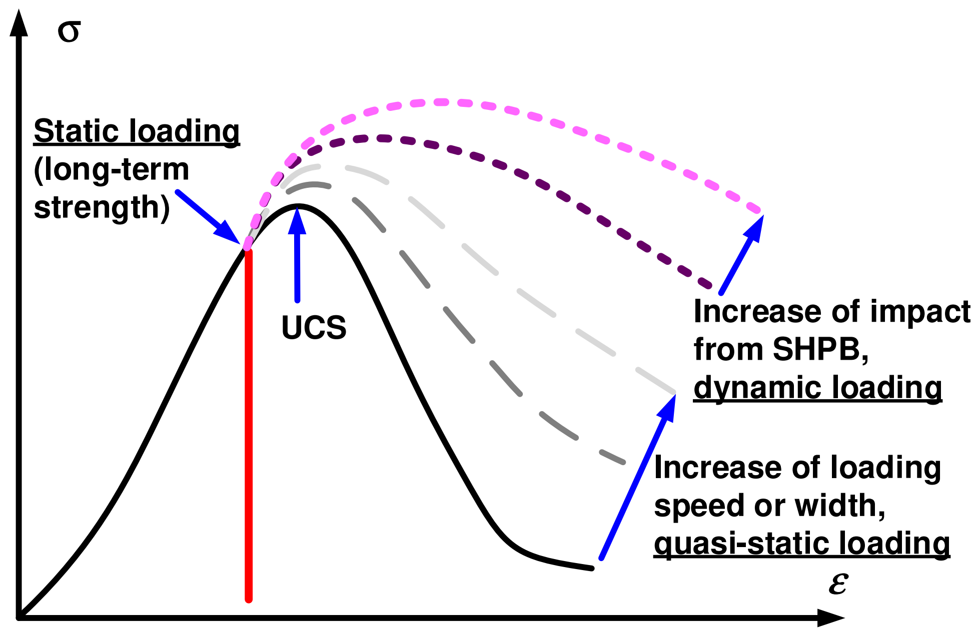


Figure 2 Impact of loading conditions on the post-peak behaviours of rock

3.3 Violent rock failure process

It becomes clear that the violent rock failure process is determined by the energy input from an external source rather than the energy stored inside the failing rock. There is no consensus on the definition of the rockburst mechanism; some incorrectly proposed that rockbursts in hard, massive rock are due to Class II post-peak behaviour. We broadly define any rockbursts occurring underground as a violent rock failure process that happens when the external input energy rate exceeds what the inherent rock mass can quasi-statically sustain. The development and driving mechanisms of a rockburst process (Cai & Kaiser 2018; Kaiser & Malovichko 2022) are explained as follows and illustrated in Figure 3.

Underground mining creates excavations ranging from large-scale caves, stopes, panels and rooms to small-scale chambers, drifts and shafts, etc. In a stress-elevated environment near an excavation boundary, most fractured rock masses occur as bulking or spalling due to high tangential stress and low confinement. These rock masses, whether reinforced with ground support or not, will contribute significantly to the burst volume once a rockburst initiates. The depth of the fractured rock masses is primarily determined by their geomechanical properties, i.e. the virgin stress state prior to excavation, the final excavation boundary shape, and the surrounding mining activities before and after the excavation.

Outside the fractured rock mass volume is typically a relatively solid volume of rock mass. This solid rock mass, where high stress is concentrated, often serves as the primary energy source that initiates rockbursts, including those triggered by a remote seismic source. It is important to recognise that high stress within the same solid rock mass volume can be localised (e.g. in one shoulder or one section of a drift) due to the inherent inhomogeneity of rock mass properties and rock stresses. This localisation can explain why rockbursts are typically localised events, rarely occurring across a large mining area except in cases of catastrophic failure such as in room-and-pillar mining or block caving, where the failing rock mass can be heavily loaded.

Because the fractured volume stores less energy compared with the solid volume, the energy involved in a rockburst process is controlled by the geomechanical properties of the solid rock mass volume and the energy accumulation process due to surrounding mining activities. For design and modelling purposes, the solid rock mass volume, although composed of rock masses with geological features, can be treated as elastic material in numerical modelling.

With the advancement of mining, when the strength of a fractured rock mass volume loaded by its adjacent solid rock mass volume is reached, a dynamic failure condition is permitted, and the rockburst damage can be in the form of ejection, fall of ground (if from the roof) or rock mass bulking (if from the floor or wall corner) (Cai & Kaiser 2018). Depending on the total energy released from the solid rock mass volume, the waveform length of the remote seismic source (if any that is the trigger), the interlock of rock masses, the performance of installed ground support and other factors that may not have been identified to date, a portion up to the full depth of the fractured rock mass volume will burst, constituting the violent failure process. In extreme cases, where the stress and released energy are high enough, a portion of the solid rock mass volume adjacent to the ejecting volume can disintegrate and burst along with the ejecting volume, contributing to the total burst volume.

Once the external energy starts to release and the burst volume is ejected, the energy release rate affects the ejection velocity and the energy release duration affects the total burst volume. Together, the ejection velocity and the total burst volume determine the severity of a rockburst, usually expressed as seismic energy, which relates to the strength of a seismic event and is typically represented by the seismic magnitude. Studies suggest that mining-induced burst durations are in the range of milliseconds, making the energy input rate the major driving factor of a rockburst event (Simser 2019). In contrast, if the energy input rate is not high enough compared with the maximum energy-absorbing capacity of a rock mass during a quasi-static failure process, a dynamic failure condition is not permitted.

Mining activities are the external sources that lead to dynamic failure. This dynamic failure condition can be reached in the short-term by mining activities such as stope blasts and mucking, which can cause immediate stress redistribution and thus rockbursts. In these cases, stress change is a better indicator for assessing rockburst hazards. Alternatively, it may take a long time to reach the dynamic failure condition through mining activities such as mine sequencing and layout, which effectively change LSS. Because the rock stress must reach rock strength for the LSS criteria to be meaningful, and LSS is not a tangible term that can be easily quantified or measured, a practical means for rockburst hazard assessment is monitoring and/or predicting high-stress mining conditions.

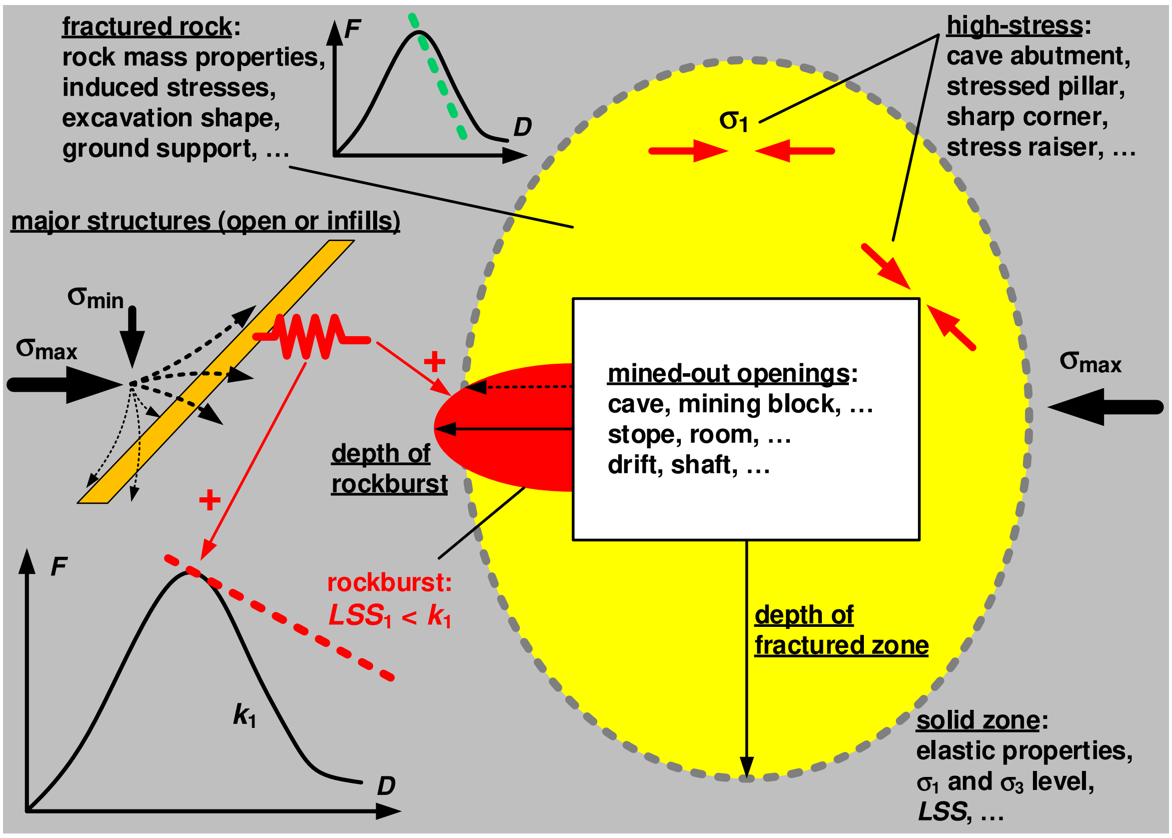


Figure 3 Failure mechanisms of hard rock excavation

4 Insights on ground control measures in deep mining

Rock mechanics as an independent discipline has a history of about just six decades. Despite this, there has been a vague link between rock mechanics and its application in ground control, especially in stress-driven mining environments. It is likely that when bridging rock mechanics theory and underground mining, a communication barrier may arise for audiences lacking either hands-on experience in underground mining or proficiency in rock mechanics. These two disciplines are typically introduced in separate realms, even during their university instruction. Many of the preferred ground control measures to manage rockburst hazards are strategic, so are predominantly at the hands of mine planners and operators who may not possess as much in-depth knowledge of ground control practices as rock mechanics practitioners. For this reason, in the following context, we will draw upon the rock mechanics basics revealed in this study.

In the following discussion we consider a rockburst and large seismic event equally crucial as mining-induced geohazards and, therefore, as interchangeable terms. The rationale is that rockbursts are associated with seismic events while large seismic events, although not always causing rockbursts, can pose a risk to workplace safety, depending on their proximity to mine workings. Additionally, we will focus on reviewing large rockbursts such as pillarbursts that are difficult to mitigate. Strainbursts, also a common type of violent rock failure, are usually associated with low seismic moment magnitudes (≤1) and released energy scales in the order of kJ/m^2. A competent ground support system and/or some administrative measures can contain a strainburst hazard if implemented proactively. In contrast, the released energy from a pillarburst or fault-slip event can be several orders of magnitude higher.

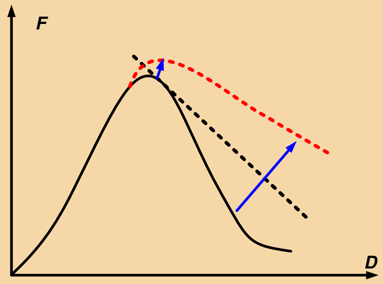
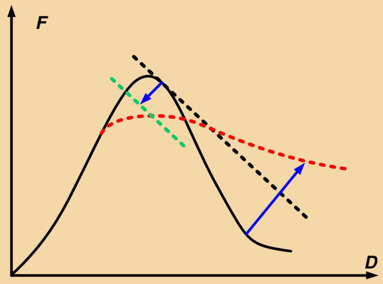
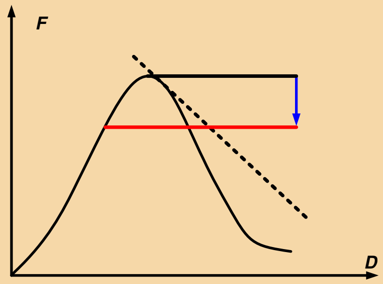
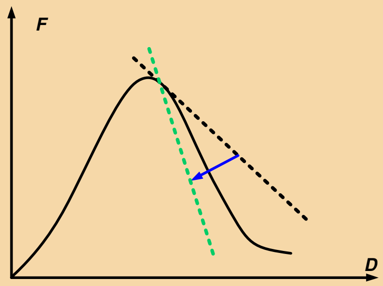
4.1 Rockburst and its prevention in theory

The severity of rockbursts, once initiated when rock stress reaches the rock strength, is controlled only by the energy input from the external loading system. The released energy level can also be assessed by LSS if the rockburst is initiated in a quasi-static manner. From a rock mechanics perspective it is plausible that, if one of the following four quasi-static loading conditions is met, a rockburst can be avoided; otherwise, it will occur:

- Condition 1A – the strength of a fractured rock mass volume that is vulnerable to rockburst is increased beyond the stress level applied by the surrounding rock mass.
- Condition 1B – the fractured rock mass volume is de-stressed in a way that its post-peak deformation behaviour or brittleness appears to be more ductile. Hence only a quasi-static rock failure process can occur.
- Condition 2A – the stress level of the surrounding rock mass being exerted on the fractured rock mass volume is reduced to lower than the strength of the fractured volume so that a rock failure will not occur.
- Condition 2B – the local mine stiffness is increased so that it is stiffer than the post-peak stiffness of the fractured rock mass volume. Hence a violent rock failure process can be avoided.

The above four conditions are further illustrated and explained in Table 1, along with corresponding engineering measures that may possibly be considered to meet these conditions. It shows that to fulfil Conditions 1A and 1B, engineering measures, mostly tactical, can be considered to affect the deformation behaviours of the ground that is burst-prone. To fulfil Conditions 2A and 2B, however, strategic engineering measures must be adopted in an attempt to optimise the external loading conditions adjacent to the burst-prone ground.

Table 1 Four quasi-static loading conditions associated with possible measures to control rockburst hazard: red, black/green and blue lines conceptually represent 'engineered' post-peak behaviour, LSS and 'engineered' LSS, respectively

Conditions		Possible engineering measures
1A		Increase confinement Apply/upgrade ground support Minimise blast damage Backfill
1B		Stress shadowing De-stress blast Preconditioning Mucking rates
2A		Change mining method or mine layout Optimise mining sequence Change mining direction Strategic pillar design, such as yielding pillar, stabilising pillar, regional pillar Local mine design, such as just-in-time development, excavation shape, advancing rates and directions
2B		

4.2 Rockburst experience in mining

The violent rock failure process and its controlling factors seem straightforward. It is not, however, an obvious task to apply this rock mechanics knowledge in underground mining. Underground mining is complex due to its 3D geometry, geologies including lithology and major structures, the combination of different mining methods, and mine layout in time and space, and it is further complicated by cost and time constraints compared with civil rock engineering projects in underground space.

It is not uncommon to have rockburst occurrences at depths of only a few hundred metres and, in fact, the largest ever mining-induced earthquakes are associated with soft rock mining (Whyatt & Varley 2008). Rockbursts have also occurred in underground mining where various mining methods are in use. Therefore it is worth reviewing rockburst source mechanisms associated with different mining environments. In doing so, we hope to help identify common causal factors that govern mining-induced rockbursts. This foundational understanding is valuable prior to accumulating years of site-specific experience at various operating mines.

Although related to each other to some degree, the 3D ore grade geometry is one of the most important factors determining the selected mining method(s). To facilitate the discussion, different mining scenarios are loosely grouped by three major orebody shapes and their possible mining methods in Table 2 (VCR stands for vertical crater retreat); other irregular deposit shapes can be treated as a combination of these three shapes. Worldwide mining experience from operating mines on the typical rockburst source mechanisms associated with these mining methods is briefly listed is the last column. Most of the rockburst source mechanisms listed in the table may become more pronounced if intersected by a fault or major geological structure, especially those that daylight into, or are in proximity to, the mine workings at a gentle angle. Rockburst hazards associated with fault-slip events are not listed in the table.

Table 2 Mining methods and associated typical rockburst source mechanisms

Deposit shapes	Mining methods	Typical rockburst source mechanism
Bulk mass or thick tabular: igneous or disseminated ores, normally strong (can be weakened)	Block/panel/incline caving (weak ore, occasionally strong ore)	Pillarburst on extraction level, especially near caving front with post-undercutting Point loading of pillar due to incomplete undercutting blast Stress concentration due to isolated draw Stress damages in abutments due to large/adverse cavity
	Sublevel caving or retreat caving (weak host rock)	Strainburst at immediate production and footwall drift near the cave bottom
	Sublevel stoping with (strong ore, e.g. open stoping, weak ore, e.g. VCR) or without cemented backfill (longitudinal, e.g. Avoca)	Converging fronts of adjacent mining blocks, e.g. sill pillar Waste/barren pillarburst, e.g. dyke pillarburst Diminishing pillar in general, e.g. pillar stope burst Remnant pillarburst in late-stage mining, e.g. shaft pillarburst
Sub-horizontal or inclined tabular: alluvium, coal, evaporites, sedimentary, metamorphic	Drift-and-fill or longwall mining (weak or soft rock)	Secondary or tertiary pillar (drift) burst at depth
	Room-and-pillar (good rock) Post-pillar (thick tabular of varying thicknesses)	Pillarburst caused by collapse of the overlaying arch over interior pillars where barrier pillars are inadequate Cascading pillar failure, e.g. interior pillars fail in a high extraction-ratio area Seismicity associated with crush/yielding pillar failures Pillarburst due to pillar stiffness reduction (increasing pillar height or pillar robbing/slabbing) Roof burst due to the failure of brittle rock layer
Steeply dipping tabular or vein	Cemented backfill (e.g. cut-and-fill, VCR)	Sill pillarburst, e.g. diminishing sill pillar created from either or both overhand and underhand mining
	Rockfill (e.g. Avoca, Shrinkage, Alimak)	Rib pillarburst Sill pillarburst

4.3 Sources of high-stress mining environments

Reviewing the above rockburst source mechanisms, the following generic characteristics of mining-induced rockburst mechanisms can be summarised: mining activities lead to a stress-elevated condition in which (1), stress (σ_1) increase, with or without confinement (σ_3) decrease (i.e. an increase of deviatoric stress), reaches the local rock mass strength and can cause rockburst; or (2), shear stress increase (i.e. excess shear stress), with or without normal stress decrease (i.e. unclamping effect), reaches the rock bridge strength of a geological contact or a major structure, which can cause fault slip-like events.

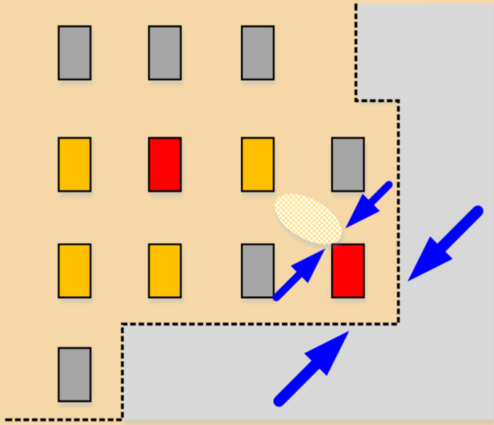
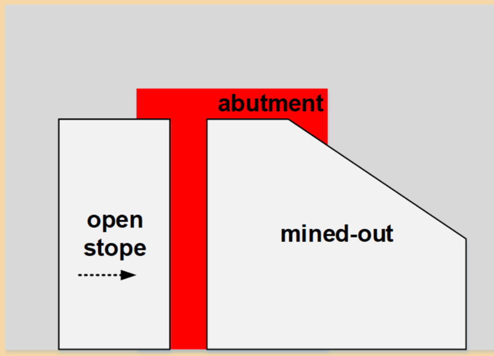
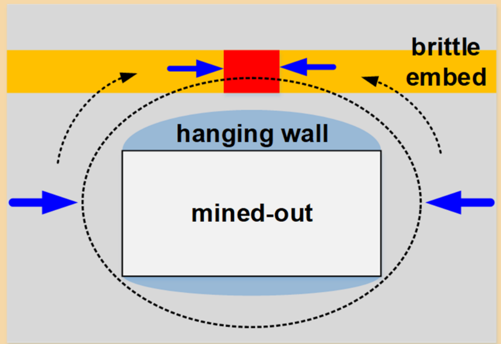
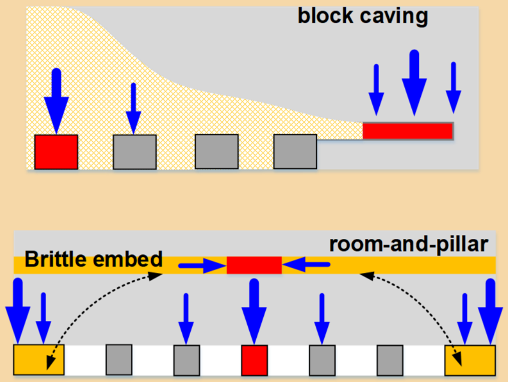
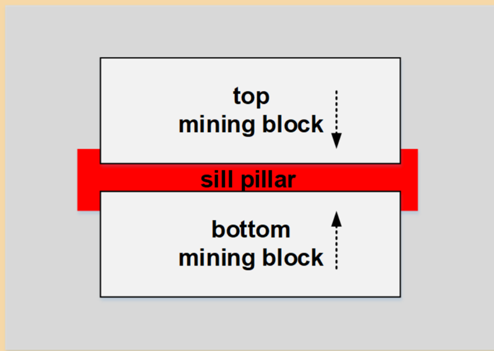
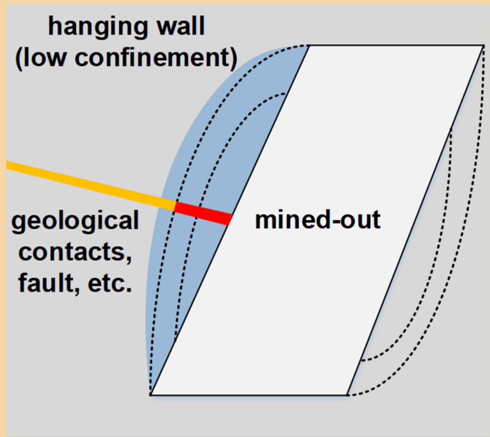
For simplicity in this discussion, the stress-elevated condition is first broadly divided into two categories: highly stressed pillars and highly stressed abutments. We consider any meaningful rock mass volume that is formed by at least two distinct free faces as a pillar (e.g. sill, rib, panel, barrier and shaft pillars). We also consider dykes and any other forms of brittle imbedded lithological units as special pillars because when such a unit is highly stressed its host rocks on both sides are normally at lower stress levels due to stiffness and/or UCS contrast. In addition, any meaningful rock mass volume that is formed by two distinct but connected free faces is considered an abutment (refer to the examples below). Further examining the stress-elevated conditions in different mining scenarios, three major mining-induced high-stress environments are identified (Table 3):

1. Within an active mining area, remaining rock masses can incur highly stressed pillars. Examples are a sill pillar, dyke pillar or any form of diminishing pillar due to converging mining fronts; pillar stope slashing
(e.g. secondary/tertiary stope extraction) or pillar slabbing (e.g. rib pillar); remnants such as panel, barrier and shaft pillars left at the late stage of mining; adverse pillar loading conditions arising from the inclined floor (room-and-pillar);and stress concentration due to isolated draw (block/panel caving), orebody shearing (stoping), etc.
2. Adjacent to an active mining area, host rock can incur highly stressed abutments, especially when the abutment is formed at a sharp angle and is perpendicular to local induced stress (σ_1). Examples include extremities of a mining horizon or mining block in stoping; the advancing front of a room-and-pillar mining panel; an extraction level of a block caving converging with the caving front developed by post-undercutting; and a narrow bottom level following a top-down mining direction (e.g. sublevel caving).

The above two high-stress mining environments are usually the major sources of large seismic events and severe rockburst hazards in which pillarbursts and abutment bursts are the culprits, respectively. Because pillars and abutments typically comprise large volumes of rock masses they can carry and accumulate loads to very high levels of stored strain energy. Often, in the vicinity of mine workings at the late stage of mining, the stresses are transferred to the pillars or abutments if they have not significantly yielded. Note that large, squat pillars, in many circumstances, are difficult to completely fail even in high stresses. Instead they continue to carry loads, thus becoming problematic. When a pillar or abutment yields it can convert a large portion of the stored strain energy into seismic energy due to normally low confinement or uniaxial loading, resulting in a pillarburst or abutment burst. In addition, the hanging wall of a stoping block or the roof of a room-and-pillar mining operation can incur high stresses due to a mixture of the above two high-stress mining environments.

3. The hanging wall or roof can be classified as a special type of abutment with, normally, larger free surface areas than a regular abutment and still be in a low confinement condition. The mining-induced stresses of the adjacent mining area tend to arch over or wrap around and through the hanging wall or roof, and a high-stress environment can occur where it is intersected by adverse geological conditions, e.g. a dyke, fault or any brittle embedded layers.

Table 3 **High-stress mining environments: red areas conceptually represent high-stress mining environments, arrows conceptually indicate stress or mining directions**

Mining scenario	Room-and-pillar mining, block/panel caving	Stoping mining blocks at regional scale	Stoping mining blocks at regional scale
Plan view			
Section view			

In summary, rockburst primarily occurs in the above three major mining-induced high-stress environments. Fault-slip events are not exclusive to any of these environments; rather, they are an independent seismic source of large rockbursts. While the seismic efficiency (i.e. the ratio of kinetic energy to energy released) of a fault-slip event is generally lower than that of a pillar or abutment burst, the total radiated seismic energy from a fault-slip event can be larger than that from a pillarburst due to the scale of the rupture area it can involve (refer to the classical equation of scalar seismic moment $M = \mu \times A \times D$, where μ is the shear modulus of the rocks, A is the rupture area and D is the average displacement offset). Strainburst can occur during lateral development (e.g. drifting) and vertical development (e.g. raiseboring) in high-stress environments, or it can be triggered by a remote large seismic event associated with any of the three types of high-stress environments or a fault-slip event.

It is hoped that the three high-stress mining environments identified provide a fundamental understanding and serve as a starting point for identifying rockburst hazards. To cause a high-stress burst-prone mining environment (i.e. approaching critical LSS) and further create a stress-elevated condition leading to rockburst, two major categories of mining activities from a time span perspective can be classified:

1. In an intermediate-to-long time span it is typically strategic mining activities such as mining method, mine layout and mining sequence that can lead to a stress-elevated condition.
2. In a short-to-intermediate time span it is typically tactical mining activities such as forming a pillar, stope blasting and mucking strategies that can lead to a stress-elevated condition.

Accordingly, managing rockburst hazards from an engineering perspective involves the justification and optimisation of these strategic and tactical mining activities. By adhering to the fundamental principles outlined in Table 1, which specify the conditions to cause or avoid rockburst, it is possible to alleviate the high-stress mining environment and thus manage the rockburst hazard.

5 Conclusion

The intrinsic post-peak deformation behaviours of hard rock are reviewed, with insights from recent laboratory hard rock test results and field observations. It was proposed that there is no standard intrinsic hard rock post-peak behaviour that can be captured by a single stress–strain relation. The peak strength and post-peak deformation behaviour of rocks vary under static, quasi-static and dynamic loading conditions. The Class II rock failure mode characterised by self-initiating violent rock failure when peak strength is reached is an artificial behaviour observed in laboratory rock tests using lateral-strain-controlled loading where the LSS is not high enough.

The critical LSS of the rock, or the input energy rate relative to the post-peak deformation behaviour of rocks that can quasi-statically sustain, determines the rock failure modes and how violent the rockburst hazard could be in the field. With this fundamental rock mechanics knowledge in mind, the first step in assessing (in terms of space and possibly time, on a rough scale) rockburst hazards in different underground mining scenarios is to identify mining-induced, high-stress environments under specific mining activities. These can be broadly classified as highly stressed pillars (including dyke pillars), high-stress abutments (especially those formed with sharp angles near the advancing mining fronts) and hanging walls or roofs intersected by adverse geological features (e.g. faults daylighting into excavation or stressed brittle layers) adjacent to mined-out areas.

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