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Discussion and Discovery

Discussions on rockburst and dynamic ground support in deep mines

Charlie C. Li[a,*], Peter Mikula[b], Brad Simser[c], Bruce Hebblewhite[d], William Joughin[e], Xiaowei Feng[f], Nuwen Xu[g]

[a] Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[b] Mikula Geotechnics Pty. Ltd., Kalgoorlie, Australia
[c] Glencore Company, Sudbury, Canada
[d] The University of New South Wales (UNSW), Sydney, Australia
[e] SRK Consulting, Johannesburg, South Africa
[f] China University of Mining and Technology, Xuzhou, China
[g] Sichuan University, Chengdu, China

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ABSTRACT

The paper is a summary of discussions on four topics in rockburst and dynamic ground support. Topic 1 is the mechanisms of rockburst. Rockburst events are classified into two categories in accordance with the triggering mechanisms, i.e. strain burst and fault-slip burst. Strain burst occurs on rock surfaces when the tangential stress exceeds the rock strength in hard and brittle rocks. Fault-slip burst is triggered by fault-slip induced seismicity. Topic 2 is prediction and forecasting of rockburst events. Prediction for a rockburst event must tell the location, timing and magnitude of the event. Forecasting could simply foresee the probability of some of the three parameters. It is extremely challenging to predict rockbursts and large seismic events with current knowledge and technologies, but forecasting is possible, for example the possible locations of strain burst in an underground opening. At present, the approach using seismic monitoring and numerical modelling is a promising forecasting method. Topic 3 is preconditioning methods. The current preconditioning methods are blasting, relief-hole drilling and hydrofracturing. Defusing fault-slip seismicity is difficult and challenging but has been achieved. In very deep locations (>3000 m), the fracturing could extend from the excavation face to a deep location ahead of the face and therefore preconditioning is usually not required. Topic 4 is dynamic ground support against rockburst. Dynamic ground support requires that the support system be strong enough to sustain the momentum of the ejecting rock on one hand and tough enough on the other hand to absorb the strain and seismic energies released from the rock mass. The current dynamic support systems in underground mining are composed of yielding tendons and flexible surface retaining elements like mesh/screen and straps. Yielding props and engineered timber props are also used for dynamic support.

1. Introduction

Rockburst and dynamic ground support are the two hot topics in rock mechanics and rock engineering. Underground mining has reached such depths where rockburst is unavoidable and becomes more serious with increasing depth. Rockburst often occurs in deep mines and tunnels but also in shallower locations, such as buckling at lower stress levels. It is important to have a good understanding of the mechanisms of rockburst in order to combat the hazard with appropriate engineering measures. Mining practitioners have gained a good amount of valuable experience and knowledge on rockburst and dynamic ground support through the onsite observations, laboratory tests, theoretical and numerical studies. People have consensus on some issues, but not on others. Experts were gathered in a forum held during the 3rd International Conference on Rock Dynamics and Applications – RocDyn-3 (Li et al., 2018a) to discuss relevant issues on the topics. This paper is a summary of the

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[*] Corresponding author.
E-mail address: charlie.c.li@ntnu.no (C.C. Li).

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experience, thinking and comments of the panel members and audience attending the forum. The speakers are from different corners of the world and their experience and knowledge are gained in different types of mines (metal, mineral or coal) under different rock conditions, and based on different input data (either instrument measurements or observations). Some thoughts and comments may appear contradictory, but they reflect the complexity of the issues and imply that much more research is needed to clarify the observed phenomena.

In this paper, the terminology of 'seismic event' is used to express a seismic activity in the rock mass that is perceivable without the help of instruments. A seismic event refers to a macro- or mega-, but not micro-seismic activity.

2. Mechanisms and types of rockburst

Rockburst is a terminology that describes a specific form of rock failure. Based on observations in gold mines in South Africa and on the seismic investigations by Cook (1963), Salamon (1983) correlated rockburst to mine seismicity and defined it as a sub-set of seismic events that cause damage to mine workings. He stated that all rockbursts are seismic events but not all seismic events become rockbursts. Field monitoring showed that seismic events of energy less than 100 kJ did not cause rockburst (i.e. rock damage), while events higher than 1.5 GJ absolutely caused rockbursts. The attention of Salamon (1983) was on rock damage caused by seismic waves.

Based on field observations, Ortlepp and Stacey (1994) defined rockburst as rock damage in a tunnel, resulting from seismic events. In other words, rockburst occurs after seismic events, that is, the rockburst and the seismicity are not necessarily one and the same event. A strain burst is characterised by the occurrence of the burst and the generation of seismicity at the same time. In contrast, rock ejection caused by seismic waves from a remote seismic event is called seismic or fault-slip burst. Rock failure has the following forms in South African deep mines: strain bursting, buckling, face crushing, virgin shear in the rock mass and reactivated shear on existing faults and/or shear on existing discontinuities. The first three failure types could be triggered by seismic events, but they also could be caused by the static stress concentration. The last two are the sources generating seismic events.

Kaiser et al. (1996) stated that a rockburst occurs around an excavation in a sudden or violent manner and is associated with a seismic event. A rockburst is a dynamic damage event (sudden or violent) in this definition. They further classified rockbursts into the self-initiated type and the remotely triggered type. The former refers to rockburst that occurs when the stresses exceed the rock strength and failure proceeds in an unstable or violent manner. The latter is triggered by remote, relatively large-magnitude seismic events.

A common understanding is that rockburst is a dynamic rock failure event which involves transformations from the static strain energy to fracturing and kinetic energies during bursting. The triggering mechanism of a rockburst event could be stress concentration or fault-slip seismicity. Rock ejection, the intensity of which is mainly dependent on the static stress concentration, is called *strain burst*, and the ejection triggered by seismicity is called *fault-slip* or *seismic burst.*

2.1. Strain burst

A strain burst occurs on exposed rock surfaces in forms of intact rock crushing (Fig. 1a, b), buckling of slabs (Fig. 1c) and ejection of rock blocks (Fig. 1d). The last two forms may be also simply owing to the failure of asperities on pre-existing discontinuities but not involve intact rock failure. An important characteristic of strain burst is that there is no damaging vibration prior to rock failure. Damaging vibration is generated during and after bursting. The bursting process of a strain burst event is illustrated in Fig. 2. Fig. 3 shows a rock surface that was undergoing strain bursting on the roof of a metal mine drift in a massive quartzite at a depth of approximately 1000 m. Frequent and intensive bursting commenced on the roof surface immediately after the advance blasting with rock spalling down slice by slice. The bursting became less frequent with time, but continued even after shotcreting and rockbolting. It is seen in the figure that some of the bolts were exposed for approximately 0.3–0.5 m after the rockbursting.

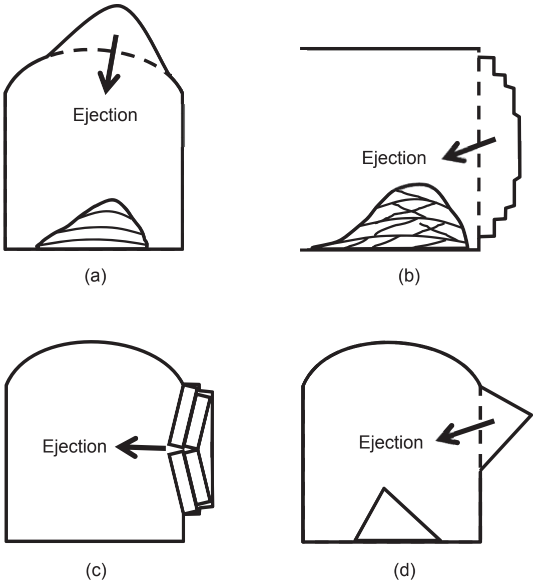

Fig. 1. Different forms of strain burst: (a) Bursting of intact rock, (b) Face bursting, (c) Buckling, and (d) Ejection of rock block.

In some cases, the elevated tangential stress in the rock after excavation is not high enough to fail the rock but very close to the rock strength. A small-scale mine seismic event could superimpose an extra stress component to the static stress and thus trigger a rockburst. The intensity of such a rockburst is still dependent on the static strain energy in the rock mass. Therefore, it belongs to the category of strain burst even though it is triggered by a seismic event. The seismic event in this case only plays a role of triggering but contributes little energy to rock ejection.

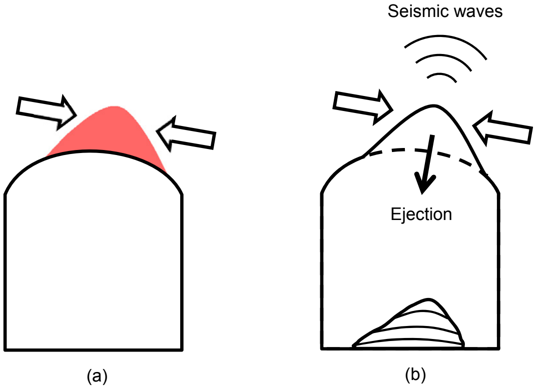

Fig. 2. (a) Fostering and (b) bursting of a strain burst event in intact rock.

Fig. 3. The rock surface after a strain burst in a massive quartzite in a deep metal mine.

The superficial rock usually is finely fragmented into thin and knife-sharp slices in a strain burst event. The intensity (or violence) of the event is determined by the static strain energies stored in the ejected rock and in the surrounding rock mass. The magnitude of strain burst events is relatively small compared with fault-slip burst events. It is in the range of −0.2–1.5 in the Richter scale according to Ortlepp and Stacey (1994).

2.2. Fault-slip burst

Stress changes caused by underground excavation can lead to slippage of some pre-existing faults or even shear failure of intact rocks in the near field of an underground opening. The latter form of failure is also called faulting. Both fault slippage and faulting generate seismic waves that propagate from the hypocentre outward in the rock mass. A violent rockburst event may be triggered when powerful seismic waves arrive at the underground workings, as the case shown in Fig. 4. This is the so-called *fault-slip* or *seismic burst*. The kinetic energy to eject rock in a fault-slip burst event comes from the seismic waves in pre-fractured and destressed rock masses, but it is contributed by both the seismic waves and the elevated static stresses in highly stressed intact or slightly damaged rock masses. Fault-slip burst usually is more powerful than strain burst and thus often causes severe damage. The magnitude of fault-slip burst events is in the range of 1–5 in the Richter scale according to Ortlepp and Stacey (1994). Fig. 5 shows the damage of a fault-slip burst event to a mine drift, triggered by a seismic event of $M_n = 3.8$.

It is commonly acknowledged that the hypocentres of the seismicity that triggers fault-slip burst events are located at various distances from the underground opening. The locations of the hypocentres are often determined automatically by the seismic monitoring systems and sometimes those locations could be hundreds or even thousands of metres distant from the major damage in the burst event. However, it is often found by manually reprocessing the waveforms that the real distance was much shorter than that suggested by the auto-processed data. Sometimes the hypocentre was in fact within the damage area.

Fig. 5. A fault-slip rockburst triggered by a seismic event of $M_n = 3.8$ in a metal mine (Courtesy of David Counter).

3. Forecasting and prediction of rockburst

It is always desirable in engineering practise that rockburst could be predicted in advance. A common sense among many deep mining practitioners is that a *prediction* of a seismic event means a statement for the *location*, *timing* and *magnitude* as well as *mechanism* for the event in a satisfactory accuracy. The location and magnitude of an event can be predicted very accurately, but timing cannot be predicted at present. *Forecasting* refers to the probability for an event or a parameter. A forecasting could be 50% chance of three large events in one year in a large volume of ground, while a prediction needs to adequately specify where, when and how an event occurs. The transition between a forecasting and a prediction may be regarded as a continuum rather than a step change. It is better to use the term of forecasting in stating the probability for the occurrence of rockburst and seismic events.

Many hold that rockburst can be forecasted if knowledge of the rock mass behaviour is sufficient and adequate methods are adopted. Strain burst is limited in a specified space and volume and it is relatively easier to forecast strain burst than fault-slip burst. *The most promising method* for forecasting of strain burst may be

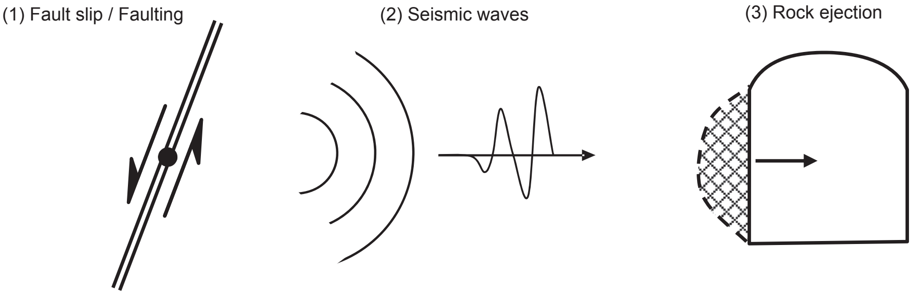

Fig. 4. A sketch illustrating the fault-slip seismicity and the triggered rockburst.

seismic monitoring which depicts the response of the rock mass to change in stress state during excavation. The timing and intensity of rockburst are still difficult to determine by the seismic monitoring method at present even though some successful cases have been reported. Numerical modelling can be adequate to identify the burst-prone locations. Geology needs to be taken into account in forecasting since erratic geology can lead to anisotropies in rock fracturing and thus change the stress distributions in the rock mass in question.

3.1. *Experience in Australian metal mines*

It is currently not possible to predict actual rockburst and seismic events since the understanding and data are simply not sufficient about such a complex phenomenon taking place in an environment containing so many interactive and changing variables such as pre-mining and mining-induced stresses, depth, and geology (lithology and structural discontinuities). Neither current seismic monitoring nor numerical modelling is able to produce reliable predictions in terms of location, timing and magnitude. However, it is possible, with increasing confidence and using a range of technologies, databases and experience, to forecast the proneness of a particular mining environment for such events to occur. For instance, it is feasible to forecast strain burst, if knowledge and analysis (including numerical modelling) of likely rock mass behaviour and historical seismicity are sufficient to identify places vulnerable to strain burst during particular periods of mining. However, seismic event data as currently collected and analysed in many mines provide only limited guidance for forecasting. Sometimes with enough knowledge about a vulnerable area, forecasting is attempted. This is evident in the ability of some practitioners who ‘know their ground’ to define a specific time exclusion window in anticipation of a large event to follow a certain blast, and occasionally get it right.

It is believed that the rock mass ‘shows its fingerprints early’, meaning that spatially, vulnerability to seismic reaction is detectable via seismic monitoring during early stages of mining. Locations of seismic clusters during early mine development are not accidental. The rock mass is ‘speaking’ possibly owing to fracturing and/or slippage on discontinuities.

Fault-slip forecasting is likely less reliable than strain burst forecasting, because slip initiation is dependent on gradual or sequential failure of restraining rock bridges or asperities. Fault-slip and strain burst events are both driven by stress changes resulting from mining. However, the contribution of the sequential failure process adds variability to the fault-slip end of the spectrum.

It is surprisingly difficult to forecast a rare (or large) seismic event in the rock mass, regardless of knowledge of the geology and the stress state. Such a forecasting is similar to weather forecasting in dry climates where rainy days are few and far between. Forecasting rainy days in such regions has a large error rate (Matthews, 1997).

Many triggering variables participate in the preparation of a seismic event and in particular in the size of the event. Triggers include aspects of geological structure, rock property variations, blast effects, and stress variations. Geometrical irregularities are excluded – they can be regarded as catalysts introduced by mining that may initiate various triggers.

Sometimes those triggering perturbations cascade into causing exceptional behaviour. In climate studies, this field is called threshold and pattern dynamics. The concept is that sudden processes are governed by the reaching of critical threshold values in a range of influencing factors.

It appears that seismic triggering factors are usually passive, and mainly activate over short time periods (probably hours to seconds) prior to events. Whether the triggers cascade into a large event or not depends on fine and unmeasurable details of the mining environment. This field is called chaos theory (a branch of mathematics focussing on the behaviour of dynamic systems that are highly sensitive to initial conditions). This makes large events inherently unpredictable as it is difficult to identify which passive triggering factors may activate.

Therefore, the focus of forecasting must move onto monitoring of signals associated with the cascading process or preparation process that will result in a large event. Prediction methods need to monitor the short-term effects of the activated triggers, in much the same way as radar is used to monitor open pit wall movements for indications of tertiary creep leading to failure.

Immediate processes during the ‘preparation window’ for a seismic failure are suggested to include: (1) acoustic radiation from micro-failure processes, (2) geophysical radiation (electrical or magnetic field changes), and (3) production of charged ions associated with rock fracture, which then diffuse through the rock mass. The second of these may be most promising, and in fact it was the subject of an experiment at Mt Charlotte mine. Electromagnetic emissions (EME) are thought to result from crack formation due to stress increase or stress relief. In June 1996, an experiment was conducted in deep underground during a mass blast, to search for EME associated with fracturing of rock during seismic events (O’Keefe and Thiel, 1996; Mikula, 2005). The experiment was a first step in assessing whether radiation may be a useful indicator of impending seismicity. Radiation was indeed detected, showing the sensitivity of the technique, and some EME events and seismic events were correlated. EME events indicating extensions of long cracks were observed. However, shortfalls in the then available computer equipment made analysis difficult, as computer response times were too slow to handle the huge volumes of data.

This should encourage research into the geophysical or ionic signals emitted by rocks during the loading process leading to failure. Certainly, something significant is emitted, as animals are able to sense an impending quake. Just as canaries can warn of methane in coal mines, a technological canary should be able to warn of failure processes in seismic environments.

3.2. *Experience in the Sudbury Basin, Canada*

Strain burst forecasting is hampered by erratic geology. The breccia deposits are not homogeneous, linear and isotropic. For example, the face shown in the photo in Fig. 6a has granitic material along the top and lower right (uniaxial compressive strength (UCS) of ~250 MPa) and a large brecciated dyke fragment in the core (UCS up to 415 MPa) with quartz/carbonate veining within it. There are some erratically distributed copper veins (UCS of ~120 MPa) in the dyke fragment. Careful examination of the lower right of the photo in Fig. 6b shows that the lower granitic material is abnormally fractured with tightly spaced cracks dipping down to the right at an angle of about 30°. Current technologies such as numerical modelling can accurately forecast zones of elevated stress. However, the local reaction to that stress will vary with the local geological character. In the example, the copper vein would deform, the dyke material would store energy, and the lower right fractured granite would accommodate the stress with subtle joint displacements. Local fracturing owing to erratic geology could retard the stress concentration so that a strain burst forecasted in a homogeneous medium could never occur.

In the Sudbury Basin, many strain bursts are a combination of large seismic events – perhaps a fault slip – that triggers the strain energy concentration around the opening. The approach to manage strain burst risks is to identify areas with elevated strain burst risk, and use dynamic support and exclusion periods (primarily blast re-

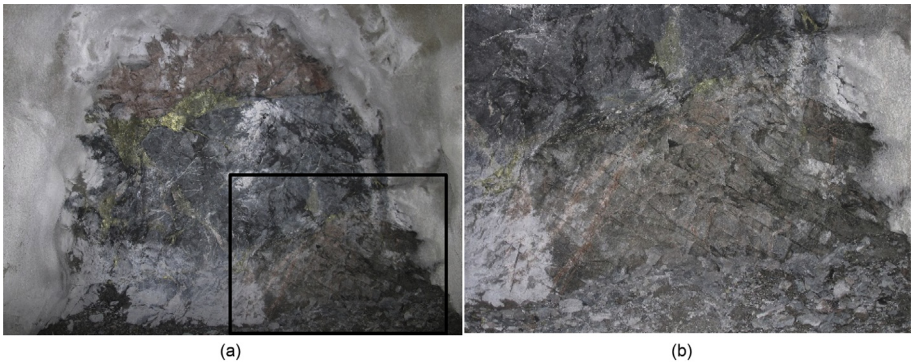

Fig. 6. Different types of rocks exposed on an excavation face: (a) The face, and (b) The close-up of the lower right of the face.

entry protocols) to mitigate the risk. The enhanced support is installed over hundreds of metres of drives, but strain bursts occur only over a few metres.

The nature of the faulting in the mines of the Basin is also geometrically complex, and difficult to accurately delineate. Gouge thickness varies from a few millimetres to several centimetres for the typical faults, and there is often limited offset. They are curvy-linear features with highly variable continuity. Today's numerical modelling tools can simulate fault behaviour reasonably well. However, the ability to generate accurate fault models from the geological information needs improvement, which is probably the fundamental limitation for accurate forecasting. If the fault is not well characterised, forecasting may be very difficult.

It suggests that seismic monitoring is the best tool for forecasting. The monitoring gives feedback on the rock mass responses to mining. Location accuracy of seismic monitoring needs to be improved. When the accuracy is satisfactory, many of the concepts from the early time (Mendecki, 1996; Mendecki and van Aswegen, 2001) work well. The concepts described by Mendecki and others include stress and strain proxies to infer rock mass response to mining. Seismic parameters such as radiated energy, energy index, and apparent stress can be related to stress conditions in the rock mass. Parameters such as seismic moment and cumulative apparent volume can be related to rock mass deformation. Rock fracturing around openings in deep hard rock mines can vary in depth from a few decimetres (at the tunnel scale) to several metres or even tens of metres around the stoping fronts. Location errors of tens of metres do not allow enough resolution to accurately define fracture zones; however, location errors in the order of a few metres can. Applying the concepts of Mendecki (1996) and Mendecki and van Aswegen (2001) with accurate seismic locations can lead to a robust understanding of stress-strain conditions around mined-out areas. For example, reasonable numerical model calibration (depth of fracturing around mined-out areas) becomes possible. Calibrated models can be good forecasting tools. Most mines put in planar footwall arrays with a one-dimensional (1D) velocity model, and the spatial resolution suffers. What are needed is workable three-dimensional (3D) velocity models, tight sensor spacing, and with some decent 3D spread.

Tomography might also be promising, but it is currently mired in resolution problems. Synthetic rock mass models (e.g. discrete fracture network (DFN), and bounded block models) are able to probabilistically forecast rock mass behaviour. Improved diamond drilling is helpful in proactively identifying anomalies and variable rock mass characteristics. For example, acoustic televiewer surveys in the same diamond drill holes that geologist uses to delineate an orebody can identify stress breakouts, and seismic monitoring sensors can be deployed early on in the same holes.

The future deep deposits in some mines in the Sudbury Basin will have the backbone of a seismic array in place prior to sinking the shaft. Experience is that critically loaded fault systems will react early on to mining disturbances. Early detection of anomalous behaviour will aid in the understanding of geotechnical risk.

3.3. *Experience in Australian coal mines*

In coal mines, strain bursts are also referred to as coal bursts. In Australia, a number of such events were reported in recent years, including the one which led to a double fatality at the Austar Mine in 2014. For forecasting of seismic events in coal mines, the first step is to know the nature and location of such faults, relative to the mining geometry. The next is to understand the mining-induced stress impacts on such locations. Then the use of techniques such as drilling ahead to assess ground conditions and stress impacts around the faulted region, together with seismic monitoring to detect any level of activity on the fault as mining approaches, would be the most likely techniques for forecasting (linked to a database of previous experience in such conditions to assess proneness of rockburst).

3.4. *Experience in South African mines*

The experience in South Africa is that stress concentrations can be modelled with reasonable certainty. Strong brittle rocks are more likely to strain burst. Stiffness contrasts and local structure also contribute. Areas more prone to strain bursts can therefore be identified. The timing of the stress changes due to mining can provide an indication of when strain bursts are more likely to occur.

The patterns of microseismicity have been studied for more than two decades. Temporal changes in the seismic parameters such as energy index, activity rate, apparent volume, viscosity and Schmidt number, are routinely analysed for mining areas, which include pre-existing faults, for short seismic hazard assessment in South African mines. While these analyses do provide some insight into the changes in rock behaviour, the methods have not provided reliable, accurate short-term prediction of fault-slip rockbursts. Spottiswoode (2010) analysed the patterns of seismicity in two South African deep mines and argued that there are no distinctive changes in seismic activity rate in the days before large seismic events. He concluded the following "*much as one hopes to predict whether damaging seismicity might occur somewhere in the next shift, this is not possible at present*" and "*medium-term forecasting of seismicity is viable; short term prediction is not*".

Back analysis of spatio-temporal patterns of seismicity and forward modelling can provide a good indication of potential hazardous areas. These methods are used to identify areas, which are more likely to experience rockburst damage and will require extra support. Mining layouts can also be adapted to reduce the frequency of occurrence of damaging seismic events. In South Africa, the concept of excess shear stress (ESS) on geological structures has been used to investigate the influence of mining layouts on geological structures. The energy release rate (ERR) and volumetric closure concepts are used to optimise mining layouts. Malovichko (2017) suggested a promising method for simulating seismicity, which has been used to forecast seismic hazard on an Australian tin mine.

3.5. *Experience in China*

Trials were once made to evaluate the potential of strain burst in coal mines through stress measurements and by means of geological radars. No meaningful conclusions were reached in those trials because of the complexity of the geology and difficulties in the interpretation of the measurement data. It is difficult to differentiate a strain burst from mechanical impact and seismic burst signals. It seems that microseismic monitoring is a promising means to evaluate the proneness of rockburst. There have been many successful cases of rockburst forecasting in China, for examples by Tang and Wang (2010), Feng et al. (2015), Xu et al. (2016) and Ma and Tang (2018).

4. Characteristics of rockburst and seismicity

Strain burst often occurs in hard rock in depth more than 1000 m and is more frequently in undisturbed than disturbed rock. The location of strain bursts can be quite accurately forecasted by numerical modelling if the orientations of the in situ rock stresses are known. For instance, it was once observed that the first slice, or the bottom slice, in a cut-and-fill stope approximately 1000 m below the ground surface was subjected to severe strain burst immediately after excavation blasting (Li et al., 2018b). Thin fragments of rock were ejected on the newly exposed surfaces in the initial slices. The bursting frequency became slower with time and rock fracturing accompanied by bursting sounds gradually was moving deeper into the rock mass a few hours after excavation blasting. Excavation of the subsequent slice in the stope exposed densely spaced fractures around the opening of the previous slice. Because of the pre-fracturing of the rock mass, the intensity of strain burst became less in the subsequent slices. Strain burst occurs in stressed intact rock. Pre-fracturing could reduce the intensity of strain burst or even completely get rid of strain burst.

Fault-slip bursting could occur in mines when the mined-out volume is large enough. Both location and timing of fault-slip bursts are difficult to forecast. Fault-slip burst usually is more powerful than strain burst. The burst piles are composed of mixed materials from very fines fragments to large rock blocks (see Fig. 3).

Some hard rock mines in the Sudbury Basin of Canada experienced fault-slip, pillar, and strain bursts. The massive rock mass units can explode violently into small fragments, with ejection velocities of several metres per second. In contrast, blocky rock mass units can accommodate displacement via joint movement. Burst-prone support is more successful in blocky than massive rock masses. The 'cannon shot' of small fragments requires excellent retainment. Load transfer to tendons is difficult. The block movement in the jointed rock mass solicits yielding tendons more readily.

In the South African deep gold mines, various rockbursts occur: strain bursts, face bursts, pillar bursts, fault-slip bursts, and shear rupture (Ortlepp shears) up to $M_n = 5.5$ (Ortlepp and Stacey, 1994; Ortlepp, 1997). These mechanisms are also observed in other mines around the world.

The *S*/*P* energy ratio refers to the ratio of the S-wave energy to the P-wave energy. It is often used to define a seismic event as a fault-slip or fracturing process. A key observation from many mines is that event source mechanisms are a combination of both processes. It is incorrect to use the *S*/*P* energy ratio to define an event as solely one or other process. What is called a 'fault-slip' event includes the fracture of asperities and rock bridges, while a 'strain burst' event includes some slip on a critical structure, even if very small. The *S*/*P* ratio may be regarded as identifying a position on a continuum between slip and fracture. The higher the *S*/*P* ratio, the more dominant the role of slip, which indicates the presence of more and larger slip surfaces within the rock mass, and correspondingly smaller or fewer rock bridges and asperities opposing slip.

If fault-slip is dominant, and numerous rock bridges and asperities are present and fracture one by one, the failures may eventually cascade together and allow a major slip to occur. This is part of why slip-dominant events can be of quite large magnitude and can occur a long time after blasting. Importantly, since the preparation (involving pre-event fracture of asperities) can take a long time and emit much radiation and/or ions, these emitted signals could more likely be detectable with appropriate instrumentation. In contrast, fracture-dominant events may have a shorter preparation time, and equilibrium may be reached quickly after the event if large stiff surrounding rock-bridge abutments have taken up the stress load.

One of the authors with many years of experience on mine sites in Australia has processed a great number of seismic event waveforms, and knows the mines and the sensor arrays very well. It was found that on countless occasions, auto-processed data suggested that events hundreds or even thousands of metres distant were to blame for major damage. However, after manually reprocessing the waveforms, such distant event locations were found to be quite wrong, or there was a known bias that located event hypocentres up to a few tens of metres away from true positions. The worst damage tended to be close to the source, and almost always close enough to be regarded as near-field damage.

In coal mines, bursting often occurs in the inner gob-side entry, on the entry driving face, and the coal mining face. Most of burst events are triggered by mining excavation together with faulting or other structural geology defects or changes in ground conditions. Locations where massive geological units are close to the coal seam can also act as triggers or remote sources of energy release in the surrounding rock mass.

5. Preconditioning

Preconditioning refers to engineering measures to defuse burst activities caused by stress changes during rock excavation. Preconditioning for strain burst is intended to reduce the chance of unwanted dynamic stress fracturing in a location. It is done by methods like pre-blasting (e.g. Konicek, 2018), pre-drilling and hydrofracturing. Preconditioning to defuse strain burst seismicity is reasonably well understood. Defusing fault-slip seismicity, however, is different and challenging, because it is not usually feasible to reduce stress on a fault or major structure other than by allowing movement on the fault. The focus is therefore on managing the fault movement in a controlled manner, i.e. with minimised shock. This is done at Mt Charlotte mine, where a technique called 'tight slot blasting (TSB)' has been trialled and is now routinely and successfully implemented (Mikula et al., 2005; Kempin et al., 2007).

TSB uses a cushion of broken blasted rock to act as a shock absorber, and impede the ability of a fault-slip movement to sharply accelerate and decelerate. Slip velocities and distances are lower, meaning that energy released is also lower. The strategy has been used at the mine multiple times since 2007 in high stress abutments, and has kept seismic reactions to an acceptably low level.

Technically, a TSB is designed to excavate a long slot directly through a final stressed abutment, using a rapid and intense blast sequence, rapidly fired (within 1.5 s), with a low swell ratio (25%–30%), so that the slot substantially fills with choke-blasted rock. During the blast process, the stressed rock in the slot is transformed immediately into backfill in the slot. Monitoring has shown that rock removal lowers the stress in parts of the nearby rock mass, while the newly placed backfill provides considerable resistance to substantial fault-slip movement that otherwise could deliver a significant seismic event.

Finally, various practitioners report the ability of a baggage zone of broken rock (fractured during previous seismic disturbances but retained in place by ground support) around their drives and drifts to provide very good protection against subsequent seismic disturbances, even from nearby large events. Conceptually, this is a form of preconditioning imposed on the excavation, and is worth investigating to discover why it works and how it could be artificially simulated.

In South Africa, people had some success with stress diversion blasting at the scale of tens of metres. Some geometries are amenable to a relatively tight drill curtain that is choke blasted. As long as sufficient material is displaced to divert stress flow, mining in the shadow of that later can be trouble free. Jumbo style ‘destressing’ is still more of an art than a science. It is usually poorly applied and not well understood. It has been some success in face preconditioning which in theory lowers the local energy storage capacity at the skin of the excavation, and/or pushes a highly stress face ‘over the edge’ at a controlled time (with the blast). Hydraulic fracturing is another way to destress the rock mass, probably by lowering the ability of the rock to store energy.

Preconditioning by blasting has been successfully carried out in the 1980s in some Scandinavian underground mines, but it is seldom used for rock destressing because of a practical issue associated with safety. The explosives in some holes sometimes fail to detonate during blasting. The undetonated explosives must be got rid of before excavation continues. It is dangerous to remove the undetonated explosives.

Relief-hole drilling is another method for reducing strain burst risk. Destressing by drilling relief holes was once used in a cut-and-fill mine stope in a Scandinavian deep metal mine. The drilling was indeed time-consuming and it took a longer time to advance a round. However, the mining operation was less stopped by bursting in the slice and the slice (approximately 100 m long) was mined out approximately one week shorter than the previous slice without relief-hole drilling. In that trial, 3 or 4 tightly spaced holes were drilled sub-vertically in the most stressed position in the roof of the drift. The holes need to be oriented correctly in order to achieve the optimum preconditioning effect.

Preconditioning of the stope face is sometimes carried out in South African deep mines. This is most commonly achieved with 3 m long, face perpendicular drill holes, spaced 3 m apart. Face parallel preconditioning has been attempted, but difficulties with drilling long holes in very highly stressed ground have prevented this from becoming a more routine approach (Toper et al., 2000). The objective is simply to move the high stress concentration further ahead of the face and to provide a cushion of broken rock. It has been used successfully to mitigate face bursting. In the very deep (>3000 m) stopes, the depth of fracturing ahead of the stope face is much greater and therefore preconditioning is usually not required.

6. Current dynamic ground support practises

Dynamic ground support requires that the support system should be strong enough to sustain the momentum of the ejected rock and tough enough to absorb the strain and seismic energies released from the rock mass. The components of the support system have to be compatible in deformability in order to avoid premature failure of the system. The current dynamic support systems in underground mining are composed of yielding energy-absorbent tendons and flexible surface retaining elements like fibre shotcrete, mesh/screen, straps and lacing. Some yielding energy-absorbent tendons are introduced by Li et al. (2014) and Li (2017). In addition, yielding props and engineered timber props are used as dynamic support, such as in South Africa. The philosophy of the current dynamic ground support is that the majority of the kinetic energy is absorbed by the yielding bolts in the support system and the main function of the surface retaining elements is to restrain the rock deformation between bolts and transfer the surface load to the yielding bolts. Essentially, a strong and stiff surface retainment could lead to fine fragmentation of the rock and thus a large amount of energy is dissipated for rock fracturing instead for rock ejection. A satisfactory surface support should be strong and fully cover the rock surface.

6.1. Australian experience

Support installed on or into the rock mass for management of dynamic conditions in mines comprises some permutation of bolts, cables, mesh or screen, straps and fibre shotcrete. However, no existing support type is ideal. Mikula and Brown (2018) mentioned many performance index targets for bolts in seismic conditions, and similar targets exist for all components and systems of components.

A very important observation, personally or communicated by geotechnical practitioners at many Australian mines, is that the edges of seismic damage zones are clearly and sharply defined or terminated, often by such as lithology changes, presence of major structures acting as wave guides, or significant changes in installed ground support.

There are several variables that usually have gradational effects, e.g. rock mass properties, geological structures, stress variations, distance between event source and excavated void, and spatial distribution of P- and S-wave in the seismic radiation field. These generally do not vary sharply, thus it would be reasonable to expect that if they controlled the intensity of damage, that intensity would also gradually change. Yet, even in the absence of much variation, sharp terminations to damage zones keep appearing.

However, two additional variables may lead to a sharper definition of the failure zone. The first one is *momentum transfer*. When the dynamic strain imposed on the rock mass adjacent to the excavation surface reaches fracture point or ejection point, the dislodged block of rock removes momentum and energy from the rock mass. The adjacent rock mass may then move to a more stable condition. The second parameter is *ground support unmatched*. Ground support components may not be matched to the ideal ground control requirements during the damage process. Typically ground support, after a peak point, loses resistance as displacement increases; while in contrast, the ground requires more resistance to achieve control the more it displaces. A tipping point can be reached where failure cannot be stopped by the ground support. This is the ‘tipping point’ principle, such as that used in a bimetallic strip or pop-disc thermostat that inverts at a given temperature (a movement from a first to a second state of equilibrium where the states are dissimilar).

Consider how fibre shotcrete layers are able to provide high initial resistance. The mobilised rock mass encounters resistance after a very small displacement, and at that point the velocity of the movement – and the kinetic energy of the moving rock block – is still low. If bolts are installed to take up the fibre shotcrete loads, and the event is not too intense, damage is avoided. But if in an adjacent zone, the disturbance is able to fracture the fibre shotcrete, the resistance falls, the factor of safety falls, and major damage can develop depending on the particular circumstances. A sharp termination to the failure area is generated.

Bolts as currently used may not be the ideal form of ground support in dynamic conditions. There are other ways, for instance yielding props are used in South Africa and elsewhere. It may be time to consider something new.

6.2. Canadian experience

The combination of yielding tendons and a robust retainment system is required for hard rockbursting. Heavy gauge mesh, relatively tight bolting (approximately 1 m × 1 m), and attention to the details are important. Weak links, such as sharp edged plates guillotining the mesh need to be eliminated or at least buffered. For example, plates over straps both reduce the chance of guillotining and promote better load transfer to the tendon.

For a simplified approach that caters to both dynamic and pseudo static loadings, steel stretch bolts work well. One could argue a softer yielding tendon that displaces more readily at lower loads would have less deformation incompatibility with the retainment (mesh). However, gravity-driven failure and excessive rock mass dilation (which equates to a loss of inherent rock mass strength) need to be catered for. The choice would come down to a simpler solution to execute use of one tendon type versus a mixed bolting pattern of static and dynamic style bolts.

6.3. South African experience

In South African mine tunnels, yielding rockbolts are used with chain link (diamond) mesh and lacing (de-stranded hoist rope). Various types of yielding rockbolts have been used. In mechanised mines, weld mesh and sometimes straps are used in preference to mesh and lacing. In stopes, hydraulic props or engineered timber props are used as dynamic support, usually in conjunction with backfill. More recently, rockbolts are routinely installed in stopes and temporary nets have been introduced to improve surface support.

7. Concluding remarks

A rockburst is a dynamic rock failure event which involves transformations from the static strain energy to fracturing and kinetic energies during bursting. The triggering mechanism of a rockburst could be stress concentration or fault-slip seismicity. Rock ejection caused by static stress concentration is called strain burst, and the ejection triggered by seismicity is called fault-slip burst.

A strain burst occurs in forms of intact rock failure, buckling of slabs, face crushing and ejection of rock blocks. Strain bursting rock usually is fragmented into thin and knife-sharp slices. A fault-slip burst is triggered by seismicity generated by shear faulting and sudden shear movements along discontinuity planes. It is usually more violent than strain burst.

Prediction of a seismic event means a statement for the *location*, *timing* and *magnitude* as well as *mechanism* for the event with a satisfactory accuracy. The location and magnitude of an event can be predicted very accurately, but timing cannot at present be predicted. Forecasting refers to as the probability for an event or a parameter. Most of the monitoring practises are forecasting rather than prediction. Fault-slip forecasting is likely less reliable than strain burst forecasting. Seismic monitoring is the best tool for forecasting at present. Numerical modelling is adequate to identify the burst-prone locations. Geology needs to be taken into account in forecasting since erratic geology can lead to anisotropies in rock fracturing and thus change the stress distributions in the rock mass.

Serious strain bursts often occur in hard rock in depth more than 1000 m and more frequently in undisturbed than disturbed rock. The general location of strain bursts can be quite accurately forecasted by numerical modelling. Pre-fracturing could reduce the intensity of strain burst or even completely get rid of it. Fault-slip bursting could occur in mines when the mined-out volume is large enough. Both location and timing of fault-slip bursts are difficult to forecast. Fault-slip bursts usually release more energy than strain bursts do. The burst piles are composed of mixed materials from very fines fragments to large rock blocks.

The S/P energy ratio may be regarded as a parameter identifying a position on a continuum scale between fault-slip and rock-bridge fracture. The higher the S/P ratio, the more dominant the role of fault-slip, and correspondingly the smaller or fewer the rock bridges and asperities.

Preconditioning is implemented through pre-blasting, predrilling and hydrofracturing. Preconditioning to defuse strain burst seismicity is reasonably well understood. Defusing fault-slip seismicity, however, is different and challenging. Field observations manifest that broken rock, fractured during previous seismic disturbances but retained in place by ground support, is able to provide very good protection against subsequent seismic disturbances. In the very deep (>3000 m) stopes, the depth of fracturing ahead of the stope face is much greater and therefore preconditioning is usually not required. Preconditioning by blasting is less used mainly because of a safety issue associated with the management of undetonated explosives. Relief-hole drilling is neither often used because of its time-consuming.

Dynamic ground support requires that the support system should be strong enough to sustain the momentum of the ejected rock and tough enough to absorb the strain and seismic energies released from the rock mass. The components of the support system have to be compatible in deformability in order to avoid premature failure of the system. The current dynamic support systems in underground mining are composed of yielding energy-absorbent tendons and flexible surface retaining elements like fibre shotcrete, mesh/screen, straps and lacing. The current dynamic support could be improved by increasing the strength and stiffness of the surface support as well as strengthening the bolt-mesh/shotcrete link.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Dr. Charlie C. Li is professor of rock mechanics for civil and mining engineering at the Norwegian University of Science and Technology (NTNU) in Norway. Li received his BSc degree in 1981 and MSc degree in 1984, both in geological engineering, in Central South Institute of Mining and Metallurgy (at present Central South University), and his PhD in mining rock mechanics at Lulea University of Technology (LUT), Sweden, in 1993. After that, he was employed as a research associate and then associate professor at LUT until 2000. He worked then in the Kristineberg mine of Boliden Mineral Ltd., Sweden, as mining engineer for 4 years. He has been the professor of rock mechanics at NTNU since 2004, in charge of the teaching and research program in the subject of rock mechanics as well as the rock mechanics laboratory. He is a member of the Norwegian Academy of Technological Sciences (NTVA). He is the European Vice-President of the International Society for Rock Mechanics and Rock Engineering (ISRM) for the term of office 2015–2019. Prof. Li has more than 30 years' experience in rock mechanics and ground control for mining and civil engineering. His major interests are stability of rock and rock masses, rock support and underground space design. In the last two decades, he has devoted his research to the theory and practise of rock support, particularly under high rock stress conditions. He has profound knowledge in the performance of rockbolts and other types of rock support elements. He invented a dynamic rock support device of high energy absorption capacity, the so-called D-Bolt, in 2006. The bolt has been worldwide used for underground rock support in burst-prone rock masses, for instance in Sweden, Canada and Australia. He published a book entitled "Rockbolting – Principles and Applications" in 2017.