

2-2016

## **Coalburst Causes and Mechanisms**

Justine Calleja  
*University of Wollongong*

Jan Nemcik  
*University of Wollongong*

Follow this and additional works at: <https://ro.uow.edu.au/coal>

---

### **Recommended Citation**

Justine Calleja and Jan Nemcik, Coalburst Causes and Mechanisms, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2016 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019  
<https://ro.uow.edu.au/coal/618>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: [research-pubs@uow.edu.au](mailto:research-pubs@uow.edu.au)

---

# COALBURST CAUSES AND MECHANISMS

Justine Calleja<sup>1</sup> and Jan Nemcik<sup>2</sup>

**ABSTRACT:** Coalburst (also known as coal bump) is a well known phenomenon in underground coal mines internationally, however, it was not recognised as a risk for Australian coal mines until the recent double fatality at Austar Coal Mine in the Hunter Valley in 2014. This paper reviews the international knowledge base from research and practice to provide Australian mining professionals with an understanding of the basics of coalburst causes and mechanisms in order to allow mine operators to address the risk of coalburst in mining safety management plans. This is the first of two companion papers with the second paper, "Coalburst control methods" (Calleja and Porter 2016).

## INTRODUCTION

There has only been one published case of coalburst in Australia – the Austar fatalities reported in 2014 (NSW Mine Safety Investigation Unit 2015). The investigation report recommended that, when encountering pressure burst (coalburst) conditions, mine operators should consider developing a management plan which takes into account a complete worldwide literature search of publications relating to pressure bursts. An extensive international literature search and review has been completed, and this paper summarises the key publications and international experience on coalburst which have been reviewed. This paper can be used as a reference source in combination with any other similarly high quality source to meet the investigation recommendations. It should be noted that any publications (including this one) should be assessed critically based on the quality of real world evidence provided to support findings, and with advice from suitably qualified and experienced professionals prior to engineering application.

## SIGNIFICANCE AND OCCURRENCE OF COALBURST

Whilst the Austar fatalities are the only published case of coalburst in Australia, there has been a long recognition of the occurrence of outburst (bursting of coal due to high gas pressure) in Australia (Hargraves 1980). As a result of the recent identification of coalburst as a separate phenomena from outburst, many researchers and operators in the coal industry are now questioning whether many of the outbursts observed previously may have actually been caused by stress rather than gas pressure or were caused by a gas - stress combination mechanism and were incorrectly labelled as outbursts. Irrespective of whether this turns out to be true, it is certainly true that coalbursts have been occurring in Australia for many years at Austar Mine (NSW Mine Safety Investigation Unit 2015) and similarly there are likely to be many unpublished cases of coalbursts in other Australian mines. However, evidence of these cases is yet to be published and the extent of the risk of coalburst in Australia is still to be defined. This work will form an important component of future research efforts to define and manage the risk of seismicity in underground coal mines in Australia.

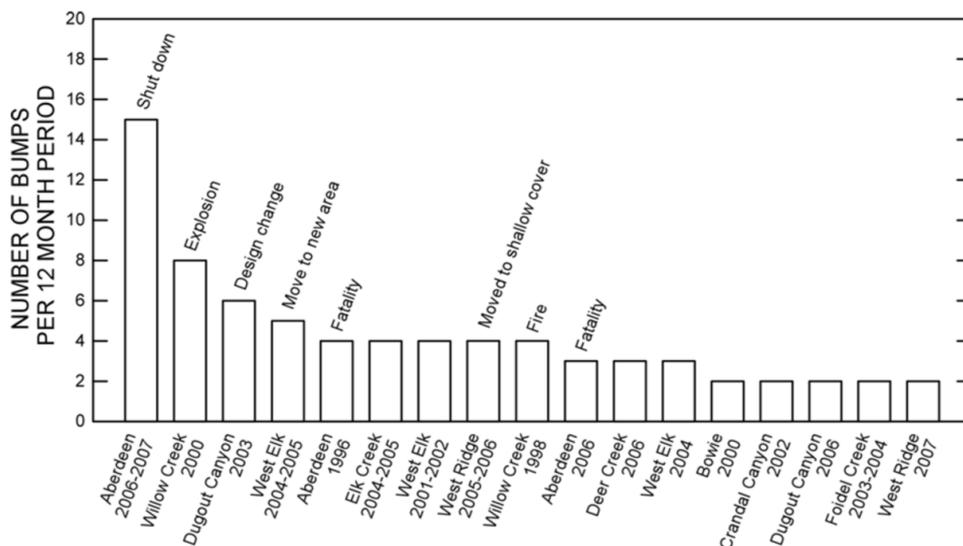
Potvin and Wesseloo (2013) state the seriousness of the risk of mining seismicity in unequivocal terms, "The possibility of experiencing a seismic event resulting in fatalities has arguably become the most important financial risk in underground hardrock mines operating in developed countries. In the two most recent cases in Australia, the entire operation was shut down for a period well exceeding one year while the mining method had to be re-engineered in order to demonstrate to regulators that the seismic risks had been lowered to an acceptable level."

---

<sup>1</sup> Lecturer Mining Engineering, School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW, Australia. E-mail: [jcalleja@uow.edu.au](mailto:jcalleja@uow.edu.au) Tel: +61 242213096,

<sup>2</sup> Honorary Senior Fellow, School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW, Australia. E-mail: [jnemcik@uow.edu.au](mailto:jnemcik@uow.edu.au) Tel: +61 0408711280,

The development of seismic risk is often progressive, as a result of increasing stress and seismicity as mining progresses to increased depths. Lack of recognition and analysis of seismic risk in mine development and planning has led to inappropriate mine designs and inaccurate assumptions around percentage extraction and mining rates, which have led to mines performing at lower profitability, the occurrence of injuries and fatalities and mine closures (Beck and Duplancic 2005). Mining seismicity has been occurring and has caused injuries and fatalities in Australian hard rock mines since the first reported event in 1917 in Kalgoorlie. Mark and Gauna (2015) noted that major bursts in the USA have often been preceded by a pattern of increasing coalburst activity and Whyatt (2008) found that for clusters of three or more bursts in a 12 month period since 1999, one ended with mine closure, two continued without incident, two resulted in a design change or move to a new mining area, one ended with a fatality and one ended with a fire and explosion (Figure 1). It should be noted that Crandall Canyon was on this graph with two coalbursts in the 12 month period, but which later had a pillar burst disaster in August 2007 which caused nine fatalities.



**Figure 1: Reportable coalburst grouped into clusters by mine and 12 month period through to July of 2007 in the USA (Whyatt 2008)**

Table 1 shows the history and occurrence of coalburst internationally. Earliest experiences of coalburst occurred in Europe as a result of long term coal mining and the development of very deep, often multi-seam, coal mines. A great deal of the current understanding of coalburst and its management evolved in Europe and has since been adopted and extended with advancing technology in China and Europe. Whilst 927 fatalities have been reported in time periods which are not overlapping in the references listed, this is by no means a complete record. It is likely that the actual number of fatalities caused by coalbursts internationally is significantly greater.

A number of terms have been used in different countries to describe the same phenomenon, which is referred to as coalburst in this paper. In China, Europe, South Africa, Russia and India, coalburst is described as rockburst of coal and this is the most technically accurate terminology. For the purposes of clarity in this paper, 'rockburst' will be used to describe bursting of non-coal rock and 'coalburst' will be used to describe bursting of coal. In quotations, where a different word is used to mean coalburst that word will be superscripted with 'cb' e.g. rockburst<sup>cb</sup>. Coalburst is sometimes described as 'coal burst' (with a space) internationally, however in Australia, the terms 'rockburst' and 'outburst' are both written without a space and so this practice is also adopted here for coalburst. The singular form of the word 'coalburst' is used as a noun to describe the phenomenon or a single event. The plural, 'coalbursts', is used to describe more than one event.

Many researchers, globally, have defined rockburst and coalburst and there is strong agreement in their descriptions of the phenomena. Kaiser and Ming (2012) defined a rockburst as "damage to an

excavation that occurs in a sudden or violent manner and is associated with a seismic event". Brauner, 1994, wrote that "Every rockburst is accompanied by a loud report and ground tremor – a seismic shock. The rockbursts in coal mines are violent failures of the coal seam, causing ejection of broken coal and often taking the form of an abrupt movement of the face or sidewall.". MSHA (2004) provided the most specific definition of rockburst as a "sudden and violent failure of overstressed rock resulting in the release of large amounts of accumulated energy. Rock burst does not include a burst resulting from pressurized mine gasses."

There are two essential defining factors which allow an event to be categorised as a coalburst. Firstly, there must be sudden and violent ejection of coal. Secondly, the coal failure must be associated with (the cause of, or caused by) a seismic event.

A seismic event is a sudden inelastic deformation within a given volume of rock, i.e. a seismic source that radiates detectable seismic waves. It is defined quantitatively by the seismic moment,  $M$ , and either radiated seismic energy,  $E$ , or stress drop,  $\Delta\sigma$  (Mendecki *et al.*, 1999). A seismic wave is an elastic strain wave which propagates through rock. A simple analogy is that of a ruler, which is clamped on a desk at one end. The other end is free to bend. As the free end is bent further from horizontal, the ruler is straining elastically and storing strain energy. When the ruler breaks, the strain energy is released and the free end of the ruler will vibrate up and down. The clamped end of the ruler cannot move freely, but as the free section of the ruler vibrates it alternately compresses and tenses against the desk, which changes the state of stress and strain in the desk around the ruler in a reverberating manner thus creating a seismic wave in the desk.

**Table 1: Coalburst occurrence and fatalities by country / region**

Country / Region	Earliest known coalburst	Time Period	Number of Coalbursts	Number of Fatalities	Reference
Czech Republic / Poland	1880	1983-2003	190	122	(Ortlepp, 2005)
Ruhr, Germany	1890s	1973-1992	50	27	(Brauner, 1994)
USA	1924	1943-2003		78	(Blake and Hedley, 2003)
USA	1924	1983-2013	337	20	(Iannacchione and Tadolini, 2015)
China	1933	1933-1996	4000	400	(Zhou and Xian, 1998)
China	1933	2006-2013	>35	>300	(Jiang <i>et al.</i> 2014)

### WHAT IS COALBURST?

Any type of rock failure will release some seismic energy, however the amount of seismic energy released by a coalburst will be significantly greater than the seismic energy released by non-violent failure of coal.

Coalburst is distinguished from progressive stress induced failure or gravitational failure by the release of stored elastic strain energy in the form of both seismic energy and kinetic energy in the process, which will propel the failed coal a greater distance from its original position, than could occur as a result of gravity alone (Figure 2).



**Figure 2: Crandall Canyon Pillar Burst Disaster (MSHA 2007)**

Coalburst can occur irrespective of gas content. In cases where the *in-situ* gas content is low, a coalburst will not be associated with a large release of gas into the workings and can be recognised by the monitored or observed seismic event and the distribution of failed coal during or after the incident.

Gas outbursts always occur with a large release of gas into the workings, and the failure of coal from gas pressure will impart kinetic energy and propel the coal into the workings. Ortlepp, 2005, and Brauner, 1994, agree in their definitions that outbursts are events which are generally not regarded as coalbursts and merit a separate classification as very little seismic energy is emitted into the rockmass. In contrast, a number of researchers have considered gas outbursts to be a sub-set of coalburst, whereby the coal failure is instigated by stress and the coal propagation is supported by released gas pressure (Lama and Saghafi 2002). In China, Li *et al.*, (2007) suggested that coalbursts can sometimes lead to outbursts, rather than outburst being a separate non-seismic or independent phenomenon. In addition, Li *et al.*, (2007) wrote, "In coalmines the correlation of gas outbursts and rockbursts<sup>cb</sup> is very strong, especially at depth. A different type of rockburst<sup>cb</sup>, or gas outburst-rockburst<sup>cb</sup> can be triggered by the coupling effect of unloading of confining stress due to mining and desorption and expansion of high-pressure gases. In addition high-pressure gases can contribute to rockburst<sup>cb</sup>. As a result the rockburst<sup>cb</sup> and abnormal gas gush can be used as warning signals interchangeably."

## CAUSES

There are many examples and case studies of coalbursts which demonstrate that they can occur in a range of different circumstances with different causative factors. Coalbursts have occurred out of the face of development headings, as rib bursts out of a development pillar or on the block side of the roadway, out of the longwall face, out of the longwall block or out of the pillar side ribs in longwall gateroads. In addition, outbye pillar ribs and block ribs have burst as well as entire pillars and areas of pillars (pillar burst).

Coalbursts are often triggered by the mining process and usually occur close to an active mining face in development, longwall or pillar mining but can also be triggered by blasting or large scale mining-induced seismic events (e.g. magnitude 1-3). Brady and Brown (1994) defined two broad classes of rockbursts. Type 1 results from fault slip events and Type 2 results from failure of the overstressed rockmass.

'Shakedown' can also occur as a result of mining induced seismicity, however this is a result of already fractured rock or coal collapsing due to shaking and gravity when it is not sufficiently contained by the installed support. Shakedown is an important risk associated with mining seismicity but it is not rockburst or coalburst as the rock failure mechanism is not dynamic (Whyatt 2008).

Iannacchione and Zelanko (1995) reviewed the MSHA coalburst database and found that "pillar retreat mining accounted for 35% of the bumps, barrier-splitting for 26%, longwall mining for 25%, and

development mining for 14%. Of the longwall incidents, 33% affected the longwall face, 19% the tailgate entries, 36% both the longwall face and the tailgate entries, and 6% the headgate entries”.

Brauner (1994) provided illustrative cases of coalbursts which occurred in the Ruhr, Germany. In one case (1000 m depth with a 40 m thick sandstone roof unit) a pre-existing roadway in the longwall block and more than 100 m of the longwall face burst as a result of increasing vertical stress due to the diminishing pillar created as the longwall face approached the roadway. In another case, at 720 m depth and with a 25 m thick sandstone roof, a 35 m length of rib of a roadway adjacent to mined workings in an overlying seam, 57 m above, burst more than 4 months after the longwall face had approached to within 22 m. Another case occurred on the tailgate end of a longwall face at 800 m depth. The tailgate pillar had a yield design (2-7 m wide) and there were thick units of sandstone in the roof and floor (24 m and 28 m). 15 m of the longwall face burst. One miner was killed and nine were injured. After the burst a gap of 15 cm between the seam and roof was evident. The roof and floor remained stable.

Brauner (1994) identified three critical contributing factors which all need to be present for coalburst to occur, they were: high static stress, triaxial loading of the coal (i.e. presence of sufficient confinement) and the presence of a strong thick and massive lithological unit in proximity to the seam. Many researchers have recognised the importance of the combination of mining conditions and geological features in the causation of coalburst (Whyatt *et al.*, 2002). More recently, Mark and Gauna (2015) reviewed the risk factors for coalburst in the USA and internationally. The key factors identified through these works to indicate coalburst risk were:

### High static stress

The level of static stress required to cause coalburst is proposed by Brauner (1994) to probably be in the order of 100 MPa and with the coal subject to triaxial loading conditions. This may occur due to high depth, proximity to goaf and particularly tailgate corners, overlying unmined areas adjacent to workings and/or critical pillar dimensions (width to height ratio between 5 and 20).

- Depth of cover is an important contributor to static stress. Whilst coalburst has occurred at 230 m depth in the USA, and Brauner, 1994, reports a case at 100 m depth, the number of coalburst incidents increases dramatically as depth increases. Almost half of the mines operating over 600 m experience coalburst.
- Pillar design plays an important role in concentrating vertical stress. Critical pillars with a width to height ratio greater than 4 - 5 and less than fifteen, have been identified as high risk, as they are too large to fail under low loads in a static way (as yield pillars do) but create higher stress concentrations than larger abutment pillars (Iannacchione and Tadolini 2015). Brauner (1994) shows cases of coalbursts with width to height ratios between five and twenty, however, Brauner's work and other international evidence indicates that there is no safe pillar size above the yield pillar range which will not burst (e.g. longwall blocks). Yield pillars are designed to fail prior to longwall abutment loading and redistribute stress away from the critical maingate and tailgate roadways. However, this has, at times, led to high vertical stresses being concentrated on the longwall block and longwall face leading to coalbursts.
- On a larger scale, mine layout is important in creating vertical abutment loading. More than 80% of bursts have occurred on retreat longwall or pillar mining, and only 20% have occurred on development. Modifying the mine layout to avoid creating corners surrounded by goaf or infrequent goaf failure can be used to reduce stress concentrations. Avoiding cutting into highly stressed pillar cores in pillar mining and reducing mining rates to allow progressive failure around the excavation reduce the risk of coalburst.
- Remnant coal left after other seams have been mined will create stress concentrations which have been a factor in many cases of coalburst in the USA and internationally. The distance between the previously mined seam and current workings, as well as the geometry of previous workings has a significant effect on the level of risk. When more than one seam has been previously mined and remnants overlap particularly high stress concentrations can develop.

- Structures, such as faults, can also act to prevent stress transfer and distribution, allowing high static stresses to be concentrated around them, either from a tectonic or mining induced origin.
- Rapid changes in depth of cover have been associated with coalbursts, however the exact role they play has not been determined. It may be due to stress concentration under incised valleys, otherwise undetected structural features which resulted in the development of steep topography, increased vertical stress from increased depth of cover or some other unidentified cause.

### Lithology

- The presence of strong, thick and rigid strata more than 5 m thick and close to the seam (within 10 m) is an important risk factor. Brauner (1994) wrote that, "Burst tendency decreases or vanishes as soon as the main roof gives way". The identification of high risk strata can be achieved by exploration or underground borehole geotechnical characterisation using coal mine roof rating unit ratings combined with rock testing results (Calleja 2006). High risk units would be expected to have a unit rating of 50 or more (Calleja 2008).
- Sandstone channels of 1.5 m within 1.3 m of the seam have been found to cause coalbursts (Hoelle 2009). Sandstone channels are also known to occur at Astar (NSW Mine Safety Investigation Unit, 2015). Seam rolls are an additional feature which have been associated with coalburst.
- Seam thickness – 4 m - 6 m thick seams appear to be the most burst prone, although Brauner (1994) suggested that this was due to the mining methods used in those cases. An increased risk of coalbursts in 4 - 6 m thick seams has been observed in China, and Astar is an Australian mine with coalburst which supports this as a risk factor.
- Coal properties – many different researchers have found that almost any coal can burst, and coal strength and other properties cannot be used to rule out coalburst risk. In saying that, the elastic properties of coal are measured in the Czech Republic coal mines to indicate coalburst propensity (Ptacek 2015).

### Dynamic loading and Seismic Events

A number of coalbursts have happened at the time of shotfiring at a distance within 30 m or more. There are mines which have numerous mining-induced seismic events but are free from coalburst, however coalburst prone mines may have coalbursts triggered by external seismic events. Faults which can be unlocked by local or regional mining induced stress changes can slip and cause seismic events which can trigger coalbursts.

### History of coalburst

Most of the worst coalburst incidents were preceded by less severe coalburst events. As such a history of coalbursts within the seam being mined is considered a moderate risk for coalburst, and a history of coalbursts at the mine is considered a high risk.

One case study from the USA is particularly interesting, from a longwall mine in Eastern Kentucky (Hoelle 2009). Coalbursts were experienced at a minimum depth of 358 m and with many occurring in the 400-600 m depth range. Major coalbursts occurred in the tailgate abutment pillars and the tailgate end of the longwall face with seismic events of magnitude 2 to 4.3. Initially, the presence of sandstone channels (1.5 m thick) at the top of the seam were identified as causative. However coalbursts also occurred where the sandstone channels were not present, but the immediate roof consisted of sandstone or siltstone with UCS of 100 – 177 MPa and Young's Modulus of 20-33 GPa.

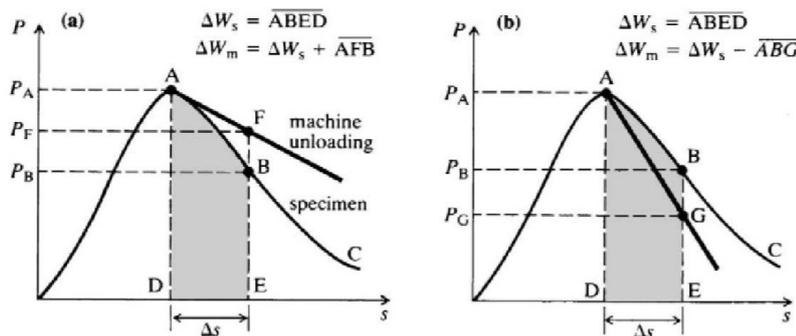
### MECHANISMS

Rockburst has traditionally been described as being the combined action of shearing and subsequent splitting resulting in sudden detachment of rock slabs with a high velocity and is usually observed in

brittle hard rocks (such as unweathered igneous or siliceous sedimentary rocks), which have a sudden loss of strength following little or no plastic deformation (Vutukuri and Katsuyama 1994). Brady and Brown (1994) provided a more detailed analysis of the failure process of rockburst, defined as “the release and transmission of seismic energy from the zone of influence of mining. It is well known that impulsive loading of a structure member results in transient stresses greater than the final, static stresses in the system rockbursts may be best studied through methods which account for energy changes in the system”. Rockburst is known to occur as a result of differences in the post-peak stiffness of the rock and the loading environment as a result of the accidental bursting of rock samples in the laboratory before the advent of servo-controlled testing machines.

In the laboratory, rocks, such as coal, which show strain-softening behaviour (brittle rock) after failure under uniaxial loading continue to deform with rapidly decreasing load. If the loading environment is softer (less steep gradient on the stress / strain curve) than the specimen, then the strain energy released by the loading environment is greater than strain energy which can be absorbed by the rock. The excess energy is converted to seismic and kinetic energy and results in bursting. Where  $\Delta W_m > \Delta W_s$  in Figure 3 a) the excess energy results in rockburst.

This analytical approach to understanding sample bursting in the laboratory can be extended to a larger scale, where, if the stiffness of surrounding rock which is loading a pillar or ribline is lower than the post-peak stiffness of the pillar or the ribline, then it will burst. Specifically, rockburst or coalburst will occur if the surrounding rock is able to deform and continue to apply higher loads than the failing rock can absorb.



**Figure 3: Post Peak unloading using machines that are a) soft, and b) stiff, with respect to the specimen (Brady and Brown 1994)**

Based on this conceptual approach, the key factors required for rockburst are that:

- 1) The rock is in an intact state prior to failure, in order for there to be stored elastic energy which can be released,
- 2) Has been sufficiently stressed to exceed its peak strength,
- 3) Its post-peak behaviour is strain-softening, and
- 4) It continues to be loaded by the surrounding rock with a higher load than it can absorb as it fails.

Iannacchione and Tadolini (2015) defined three coalburst mechanism categories: excessive stress, seismic shock, and loss of confinement.

The majority of coalburst cases reviewed by Iannacchione and Tadolini (2015) were due to the excessive stress mechanism, which typically occurred at depths greater than 500 m in retreating partial or full extraction mining, close to a pillar line, when advancing beneath overlying remnant pillars or at a mining face which had not been successfully de-stressed. The excessive stress mechanism occurs when coal, which was stable on development is exposed to rapidly increasing vertical stress. This failure mechanism is reasonably explained by the laboratory failure mechanism in Brady and Brown (1994).

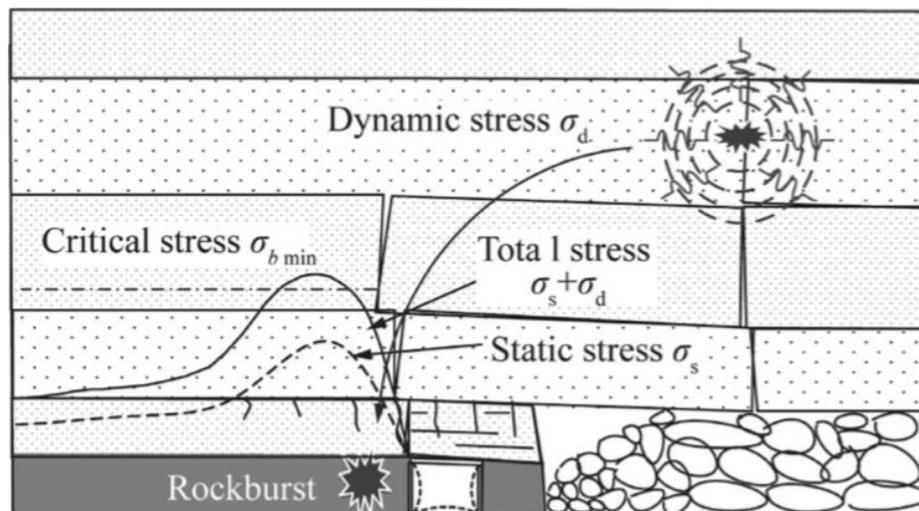
The Crandall Canyon disaster in 2007 is a widely known, well documented example of this mechanism (Figure 2).

The occurrence of both rockburst and coalburst events as a result of large scale mining induced seismicity has been well documented. Brady and Brown (1994) discussed the importance of dynamic loading in the following terms, "it is well known that impulsive loading of a structural member results in transient stresses greater than the final, static stresses in the system...the amount of energy that a particular member can store or dissipate is frequently an important criterion in mechanical design". However, understanding the role that dynamic loading and seismic events have on excavations requires more than just analysis of impulsive loading, and it is not explained by the post-failure stiffness model. It requires consideration of the transmission of seismic waves and energy in rock.

The fundamental issues which can explain seismic triggered rockburst and coalburst rely on defining the impact of seismic waves in the excavation boundary and the rapid stress changes and deformations they produce. It has been hypothesised that seismic shock bursts can be triggered by the shear failure of rigid strata during goafing and subsidence

(Figure 4) and by the sudden failure of massive spanning strata in longwalls or pillar extraction (Rice 1935). In addition, there have been many cases of rockbursts and coalbursts occurring in response to the seismic events created by slip along pre-existing geological structures. This has occurred at distances of up to 100-120 m from the structure in coal mines in the USA (Heasley *et al.*, 2001). Seismically triggered bursts are suggested to cause significant dynamic shear stresses in the coal resulting in dynamic failure of the coal (Iannacchione and Tadolini 2015). However, it is suggested that the coal failure mechanism with seismic shock is actually more complex.

Dou *et al.*, (2009) explained the cause of seismic events triggering coalbursts as a function of strong-soft-strong strata. When there is stiff, strong massive strata, it is capable of transmitting seismic energy very efficiently, with minimal energy loss or absorption. When a seismic wave passes from a strong stiff unit into soft strata, the soft strata does not transmit the seismic energy as efficiently and acts as an energy absorber.



**Figure 4: A simplified explanation of the seismic shock mechanism (Wang *et al.*, 2015)**

The loss of confinement mechanism, identified by Babcock and Bickel (1984), occurs as a result of the rapid loss of coal pillar confinement between the coal and roof or coal and floor or by reducing the confinement on highly stressed coal by mining into a pillar core in burst prone strata. This mechanism was demonstrated in their own laboratory tests on coal samples. Their findings are consistent with similar results presented by Brauner (1994) which demonstrated that bursting would occur around a hole (Figure 5) drilled into a sufficiently triaxially loaded sample of coal (between 156-41 MPa). For this mechanism to occur high stresses need to be present on the excavation boundary and this typically

requires high shear strength between the coal and roof or floor, which is known to occur in burst prone mines with rough irregular contacts between the coal and sandstone in the USA. "Red coal" (mylonite) is often observed on the failure planes which are left, following a coalburst.



**Figure 5: Borehole coalburst, an example of the loss of confinement mechanism (Brauner 1994)**

### CONCLUSIONS

One thing which is clear from the international experience of coalburst and mining seismicity, is that once it starts to occur it is not something which will go away. It is a risk which causes injuries and fatalities, and the survival of individual mines which experience seismicity is purely a function of the rapid response to the risk through adequately resourcing and establishing technical expertise in order to implement high quality management and engineering controls. At this point in time, in Australia, where we have very little experience and technical expertise in coalburst management, this is likely to prove a formidable challenge. However, the Australian coal industry has demonstrated an exceedingly low tolerance for fatal risk and an internationally enviable safety record (Harris *et al.*, 2014). Substantial research and development funding is already being committed to address the risk through the Australian Coal Industry Research Program (ACARP). The success in managing outburst is clear evidence of the capability of the Australian coal industry to address the risk of coalburst without having similar multiple fatality mining disasters which have occurred overseas.

### ACKNOWLEDGEMENTS

The first author would like to acknowledge A/Prof Jun Han, Liaoning University, China, for his dedicated efforts in reviewing this paper.

### REFERENCES

- Babcock, C O and Bickel, D L, 1984. Constraint - the missing variable in the coal burst problem. *In proceedings of the 25th US Symposium on Rock Mechanics*, 25-27 June, Evanston, Illinois, USA. (American Rock Mechanics Association).
- Beck, D A and Duplancic, P, 2005. Forecasting performance and achieving performance indicators in high stress and seismically active mining environments. *In proceedings of the 6th International Symposium on Rockburst and Seismicity in Mines*, 9-11 March, Perth, Western Australia, Australia. (Eds Potvin, Y and Hudyma, M) pp 409 – 418 (Australian Centre for Geomechanics).
- Blake, W and Hedley, D G F, 2003. *Rockbursts: Case studies for North American hard rock mines*. ISBN 0-87335-232-7, 121 p, (Society for Mining Metallurgy and Exploration Inc., Colorado USA).
- Brady, E H G and Brown, E T, 1994. *Rock mechanics for underground mining (Second ed.)*. ISBN 0-412-47550-2, 571 p (Chapman and Hall, London, UK).
- Brauner, G, 1994. *Rockbursts in coal mines and their prevention*. ISBN 90-5410-158-X, 144 p (A A Balkema, Rotterdam Netherlands).
- Calleja, J, 2006. Rapid Rating using coal mine roof rating to provide rapid mine roof characterisation from exploration drilling. *Proceedings of the 2006 Coal Operators Conference Wollongong, Australia*. Illawarra Branch, The Australian Institute of Mining and Metallurgy, pp 20 – 27 (Ed. Aziz, N), <http://ro.uow.edu.au/coal/32>.

- Calleja, J, 2008. CMRR practical limitations and solutions. *Proceeding of the 2008 Coal Operators Conference*, 14-15 Feb, Wollongong, Australia. Illawarra Branch, The Australian Institute of Mining and Metallurgy, pp 92 – 103 (Ed. Aziz, N), <http://ro.uow.edu.au/coal/489/>.
- Calleja, J and Porter, I, 2016. Coalburst control methods. *Proceedings of the 2016 Coal Operator's Conference*, 10-12 Feb, Wollongong, Australia. Illawarra Branch, The Australian Institute of Mining and Metallurgy, (Ed. Aziz, N), <http://ro.uow.edu.au/coal/>.
- Dou, L, Lu, C, Mu, L and Gao, M, 2009. Prevention and forecasting of rock burst hazards in coal mines. *Journal of Mining Science and Technology*, 19 (2009), 0585–0591.
- Hargraves, A J, 1980. Keynote address – A review of instantaneous outburst data, in *The Occurrence Prediction and Control of Outbursts in Coal Mines Symposium*, Southern Queensland, pp 1-18 (The Australian Institute of Mining and Metallurgy).
- Harris, J, Kirsch, P, Shi, M, Li, J, and Gagrani, A 2014. Comparative analysis of coal fatalities in Australia, South Africa, India, China and USA, 2006-2010. *In proceedings of the 2014 Coal Operator's Conference*, Wollongong, Australia. Illawarra Branch, The Australian Institute of Mining and Metallurgy, pp 399 – 407 (Ed. Aziz, N), <http://ro.uow.edu.au/coal/535>.
- Heasley, K A, Ellenberger, J L, and Jeran, P W, 2001. An analysis of rock failure around a deep longwall using microseismics. *In proceedings of the 20th International Conference on Ground Control in Mining*, Morgantown, West Virginia. pp 280-286 (Ed. Peng, S S) <http://icgcm.conferenceacademy.com/papers/detail.aspx?subdomain=icgcm&iid=741>.
- Hoelle, J, 2009. Coal Bumps in an Eastern Kentucky USA Longwall Coal Mine 1989 to 1997. *In proceedings of the 2009 Coal Operator's Conference*, Wollongong Australia. Illawarra Branch, The Australian Institute of Mining and Metallurgy, pp 236 – 245 (Ed. Aziz, N), <http://ro.uow.edu.au/coal/105>.
- Iannacchione, A T, and Tadolini, S C, 2015. Occurrence, prediction, and control of coal burst events in the U.S. . *In proceedings of the 34th International Conference on Ground Control in Mining*, Morgantown, West Virginia. pp 1 - 11 (Ed. Peng, S S) <http://icgcm.conferenceacademy.com/papers/detail.aspx?subdomain=icgcm&iid=2470>.
- Iannacchione, A T and Zelanko, J C, 1995. Occurrence and remediation of coal mine bumps: a historical review. *In proceedings of the Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines*. pp 27-67. <http://www.cdc.gov/niosh/mining/userfiles/works/pdfs/oaroc.pdf>.
- Jiang, Y, Pan, Y, Jiang, F, Dou, L and Ju, Y, 2014. State of the art review on mechanism and prevention of coal bumps in China. *Journal of China Coal Society*, Vol 39(2), pp 205-213, doi: 10.13225/j.cnki.jccs.2013.0024 in Chinese.
- Kaiser, P K and Ming, C 2012. Design of rock support system under rockburst condition. *Journal of Rock Mechanics and Geotechnical Engineering*. Vol 4(3), 13. pp 215 – 227. <http://www.rockgeotech.org/en/dqml.asp>.
- Lama, R and Saghafi, A, 2002. Overview of gas outbursts and unusual emissions. *In proceedings of the 2002 Coal Operator's Conference*, 6-8 Feb, Wollongong, Australia. Illawarra Branch, The Australian Institute of Mining and Metallurgy, pp 74 – 88 (Ed. Aziz, N), <http://ro.uow.edu.au/coal/543/>.
- Li, T, Cai, M F and Cai, M, 2007. A review of mining-induced seismicity in China. *International Journal of Rock Mechanics and Mining Sciences* 44(2007), pp 1149-1171 (Ed. Zimmerman R) [doi:10.1016/j.ijrmms.2007.06.002](https://doi.org/10.1016/j.ijrmms.2007.06.002), <http://www.sciencedirect.com/science/article/pii/S1365160907000810>
- Mark, C and Gauna, M, 2015. Evaluating the risk of coal bursts in underground coal mines. *In proceedings of the 34th International Conference on Ground Control In Mining*, Morgantown West Virginia. pp 1 - 7 (Ed. Peng, S S) <http://icgcm.conferenceacademy.com/papers/detail.aspx?subdomain=icgcm&iid=2466>.
- Mendecki, A J, Aswegen, G V and Mountfort, P, 1999. A guide to routine seismic monitoring in mines. In A. J. Jager and J. A. Ryder (Eds.) *A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines* (pp. 35). Cape Town, South Africa: Safety in Mines Research and Advisory Committee, Department of Minerals and Energy of South Africa, Creda Communications.
- MSHA, Mine Safety and Health Administration, 2004. *Definitions for surface and underground metal and nonmetal mines* [online], (30 CFR Parts 56 and 57). Arlington Virginia, USA: Available from <<http://www.msha.gov/regs/fedreg/final/2004final/04-14698.asp>> [Accessed: 18 January 2016].
- MSHA, Mine Safety and Health Administration, 2007. *Crandall Canyon fatal accident report Appendix O* [online],. (CAI-2007-15-17, 19-24). Virginia USA: Available from <<http://www.msha.gov/fatals/2007/CrandallCanyon/CrandallCanyonreport.asp>> [Accessed: 18 January 2016]
- NSW Mine Safety Investigation Unit, 2015. *Report into the deaths of Jamie Mitchell and Phillip Grant at the Austar Coal Mine, Paxton* [online],, NSW on 15 April 2014. Available from <[http://www.resourcesandenergy.nsw.gov.au/data/assets/pdf\\_file/0006/583125/Investigation-Report-Austar.pdf](http://www.resourcesandenergy.nsw.gov.au/data/assets/pdf_file/0006/583125/Investigation-Report-Austar.pdf)> [Accessed: 18 January 2016]

- Ortlepp, W D, 2005. RaSiM Comes of Age—A Review of the contribution to the understanding and control of mine rockbursts SRK Consulting. *In proceedings of the 6th International Symposium on Rockburst and Seismicity in Mines*, 9-11 March Perth , Western Australia, Australia. (Eds Potvin, Y and Hudyma, M) pp 3 – 20 (Australian Centre for Geomechanics).
- Potvin, Y and Wesseloo, J, 2013. Keynote Lecture: Improving Seismic Risk management in hardrock mines. *Proceedings of the 8th International Symposium on Rockbursts and Seismicity in Mines (Rasim8)*, Saint Petersburg, Moscow, Russia. [http://pts.mi-perm.ru/rasim8eng/?page\\_id=1522](http://pts.mi-perm.ru/rasim8eng/?page_id=1522)
- Ptacek, J, 2015. Rock bursts prevention system in Ostrava-Karvina Coalfield (OKR). Presentation provided to author via personal communication, 7/9/2015. Institute of Geonics of the Czech Academy of Sciences.
- Rice, G S, 1935. Bumps in coal mines of the Cumberland Field, Kentucky and Virginia- causes and remedy. *U.S. Bureau of Mines Report of Investigations 3267*, 1935, 36 pp. (R1 3267)
- Vutukuri, V S and Katsuyama, K (Eds.), 1994. *Introduction to rock mechanics*. 275 p (Industrial Publishing and Consulting Inc. Tokyo Japan).
- Wang, G, Gong, S, Dou, L, Cai, W and Mao, Y, 2015. Evolution of stress concentration and energy release before rock bursts: two case studies from Xingan Coal Mine, Hegang China. *Rock Mechanics and Rock Engineering*. Dec 2015, DOI: 10.1007/s00603-015-0892-x
- Whyatt, J, 2008. Dynamic failure in deep coal: recent trends and a path forward. *In proceedings of the Proceedings of the 27th International Conference on Ground Control in Mining*, Morgantown, WV. (Ed. Peng, S S)  
<http://icgcm.conferenceacademy.com/papers/detail.aspx?subdomain=icgcm&iid=339>
- Whyatt, J, Blake, W, Williams, T and White, B, 2002. 60 years of rockbursting in the Coeur D'Alene district of Northern Idaho, USA: lessons learned and remaining issues. *109th Annual Exhibit and Meeting, Society for Mining, Metallurgy, and Exploration*. Phoenix, Arizona.  
<http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/yorit.pdf>
- Zhou, X and Xian, X, 1998. Research advances in the theory and engineering application of rockburst in coal mines. *Journal of Chongqing University (Natural Science Edition)*, 21(1), in Chinese.