A causation mechanism for coal bursts during roadway development based on the major horizontal stress in coal, very specific structural geology causing a localised loss of effective coal confinement and newton's second law

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A CAUSATION MECHANISM FOR COAL BURSTS DURING ROADWAY DEVELOPMENT BASED ON THE MAJOR HORIZONTAL STRESS IN COAL, VERY SPECIFIC STRUCTURAL GEOLOGY CAUSING A LOCALISED LOSS OF EFFECTIVE COAL CONFINEMENT AND NEWTONS’ SECOND LAW

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ABSTRACT: This paper outlines what is considered to be a credible, first-principles, mechanistic explanation for these three current development coal burst conundrums by reference to early published coal testing work examining the significance of a lack of "constraint" to coal stability and an understanding of how very specific structural geology and other geological features can logically cause this to occur in situ, albeit on a statistically very rare basis. This basic model is examined by reference to published information pertaining to the development coal-burst that occurred at the Austar Coal Mine in New South Wales, Australia, in 2014 and from the Sunnyside District in Utah, USA.

The "cause and effect" model for development coal bursts presented also offers a meaningful explanation for the statistical improbability for what are nonetheless potentially highly-destructive events, being able to explain the statistical rarity being just as important to the credibility of the model as explaining the local conditions associated with burst events.

The model could also form the basis for a robust, risk-based approach utilising a “hierarchy of controls”, to the operational management of the development coal burst threat. Specifically, the use of pre-mining predictions for likely burst-prone and non-burst-prone areas, the use of the mine layout to avoid or at least minimise mining within burst-prone areas if appropriate, and finally the development of an operational Trigger Action Response Plan that reduces the likelihood of inadvertent roadway development into a burst-prone area without suitable safety controls already being in place.

INTRODUCTION

In 2017, one of the international authorities on coal bursts, Dr. Chris Mark, published a paper entitled “Coal Bursts that Occur During Development: A Rock Mechanics Enigma”, in which several relevant technical issues were identified, the most pertinent being:

(i) whilst development coal bursts are commonly associated with geological faults, understanding which specific faults result in burst-prone development mining conditions and why, remains undefined.

(ii) conventional wisdom in relation to strong roof and floor geology of the coal seam might be limiting, based on certain burst examples in Colorado.
(iii) development coal bursts can occur without the local ground stresses being substantially elevated from their in situ levels.

The key to understanding the problem of coal bursts during roadway development is in explaining why, at a particular location, does many tonnes of coal in an otherwise stable mining environment, suddenly and without warning become unstable and rapidly accelerate horizontally into a mine roadway without the obvious influence of excessive gas pressures, to the point that the event itself can be heard many hundreds of metres away in the mine. As an industry, the answer to this question appears to remain largely incomplete.

Based on published case histories and information, coal bursts that occur during roadway development without the influence of multi-seam stress interactions, statistically at least, appear to be the underground coal-mining equivalent of a lightning strike. However, at least with lightning strikes, even if their exact timing and location cannot be predicted, the general atmospheric conditions under which they are most likely to occur are well-understood so that effective safety measures can be enacted. Mark 2017 suggested that as recently as mid-2017, the general conditions under which development coal bursts were most likely to occur, remained unresolved.

This paper attempts to address the following:

- provide a possible causal explanation linked to the specific stress conditions under which development bursts can occur, and hence define where they are most likely to occur,
- link this explanation to the statistical rarity of such events more generally, and
- briefly consider how the explanation can lead to a structured development of coal burst management approach based around a Hierarchy of Controls.

The paper is a first-principles-based review of public-domain information from the coal burst at the Austar Mine in 2014, along with published information from the Sunnyside District in Utah.

Definitions

A general review of the literature relating to coal bursts quickly reveals an obvious lack of consistent terminology across bursts, bumps and gas outbursts, it being acknowledged by many that some of the recorded historical coal “bursts” in the USA were more likely to have been gas outbursts. Today a myriad of descriptive terms are seemingly in use in an attempt to classify many different types of events, such as “rock burst”, “strain burst”, “pressure burst”, “coal burst”, “pillar burst”, “shakedown”, “pressure bump/bounce”, “coal bump” and “pillar bump”. The problem with this type of classification is that it is based on the observed manifestation of an event, rather than the source of the energy and the mechanism by which it was released. A good example is found in Gale 2018 whereby it is stated that “a coal burst is defined as a rapid expulsion of coal (and potentially gas) from the boundary of the roadway. The volume of a burst can be variable, but volumes above 10-50m³ are noted and cause significant disruption to operations”. Such a definition, whilst being accurate in a descriptive sense, is actually not helpful when attempting to understand causal mechanisms, therefore another classification method is judged to be required.

Figure 1 contains a basic Venn diagram approach to defining different types of “high energy release” events based on the source of the released energy. Bursts are taken to be those events whereby the energy released is strain energy from within the coal seam, bumps are those related to strain energy release from either the overburden above or floor below the coal seam, and outbursts are primarily driven by gas pressures within the coal seam. This is not to then say that an overburden bump cannot result in a violent expulsion of coal into the mine workings, simply that the energy source involved is not from within the coal seam.
Figure 1: Suggested classification of high energy release events in underground coal mining based on energy source

Figure 1 also recognises that some events can be combinations of two or more energy sources, although from an investigative perspective it may be wise to first understand events based on single energy sources and mechanisms, rather than increasing the complexity by attempting to understand multiple-energy source events.

Figure 2 provides a schematic illustration of how an overburden or floor "bump" might manifest from an energy release perspective, due to horizontal stress-induced shear slip within a thick, massive strata unit along a mid-angled fault plane. There are other possible source mechanisms for overburden bumps, but a simple energy source and release mechanism representation such as that in Figure 2, allows first-pass bump hazard-ranking to be undertaken, based on (a) the presence or absence of thick, massive strata units in proximity to the coal seam, (b) the presence or absence of mid-angled fault planes that extend through such massive units, and (c) the major horizontal stress being aligned sub-perpendicular to the fault plane.

Figure 2: Overburden and floor bump causal mechanisms due to horizontal stress-induced shear slip along mid-angled fault planes

Whilst it is not the focus of this paper, if one accepts the event definitions contained within Figure 1, it is immediately apparent that some events that have been classified by others as coal bursts or pillar bursts, are almost certainly bumps, and vice versa. Without the correct
classification of individual events according to the energy source and release mechanism, the
search for understanding as to cause and effect is likely to remain elusive.

**DIFFICULTIES IN DEFINING A CREDIBLE DEVELOPMENT COAL BURST CAUSATION MODEL**

Determining “cause and effect” is fundamental to developing improved engineering solutions to
problems, yet despite 100 years of coal bursts occurring during roadway development (albeit
on a statistically rare basis), according to Mark 2017 the problem remains an “enigma”, this
being “something that is difficult to understand”, rather than one that cannot be explained.

If one examines other geotechnical problems in coal mining such as pillar design and roadway
roof control as examples, current understanding and associated control practices commonly
emanates from combined industry experience as encapsulated in both empirical databases that
have been statistically analysed, and detailed monitoring studies of changes in relevant
conditions during mining. It is through the resulting insights that mechanistic cause and effect
models have been developed that allow improved hazard identification and engineering
solutions to be applied in current mining operations.

With development coal bursts, there are (a) so few events that have been well-documented
that an industry database approach would be flawed from the outset, and (b) as a very rapid
“lightning strike” type event whose timing and location were unknown prior to the event, no
targeted monitoring data typically exists to help define exactly what occurred and in what
sequence during the event. Therefore, from an analysis perspective, one is forced to take a
“first-principles” approach, the credibility of which then must be judged against whatever case
history details are available, the 2014 Austar incident being the only Australian example on
record not accompanied by a significant release of gas as far as can be determined.

**Loss of confinement hypothesis**

Babcock and Bickel 1984 investigated the idea that coal bursts could be directly caused by “a
loss of constraint”, which would then allow other ground stresses in the coal itself to cause a
c coal burst. They proved the concept in the laboratory by rapidly removing the lateral confining
pressure on coal samples that were already highly stressed in the perpendicular direction,
finding that violent failures occurred in 15 different types of coal material. They also showed
that with lateral confinement being removed, the coal failure type and severity was dictated by
the contact conditions between the coal cubes and the steel platens of the test machine, this
typically being defined by zero cohesion (i.e. steel onto coal) and minimised friction as per
standard rock testing specimen preparation.

Having tested coal from 15 mines in 11 seams in 6 US states with 13 being made to burst when
lateral confinement was removed, Babcock and Bickel 1984 concluded as follows:

“we believe that many, if not most, coals can be made to burst given the necessary
conditions of stress and constraint. In cases where the strength is largely produced by
constraint, the sudden loss of this constraint can produce bursting”, and

“strain energy can produce bursts without the help of gas pressure”

Their work demonstrated that most coals would burst due to the release of internal strain energy
if stressed in one direction without adequate constraint in the others, thereby taking the
emphasis away from the strength of the coal and more towards the ground stresses acting
within the coal seam and variations thereof. This is the focus of this paper.

**Identifying the development coal burst energy source**
If a development coal burst is taken as being caused by an energy release from within the coal seam itself, then there are only four possible energy sources:

(i) gas pressure
(ii) major horizontal stress
(iii) minor horizontal stress
(iv) vertical stress

If it is further accepted that an event driven by gas pressure is a gas outburst as defined in Figure 1, then the event source mechanism for a development coal burst (ignoring multiple-energy source events for now) must inevitably focus on the three principal ground stresses, with the confining or constraining influence of two needing to be overcome by the third, as postulated by the general Babcock and Bickel 1984 model.

Recent work reported by Gale 2018 includes the statement that “Computer modelling indicates that, once confinement and cohesive strength develops in the ribside, the resistive energy becomes much larger, and significantly greater energy is required to create a burst within the confined material”. This is generally consistent with the findings of Babcock and Bickel 1984 albeit that the focus of Gale 2018 is to identify and justify the source of the “greater energy” within the coal seam that is required to cause a coal burst in a confined state. The focus of this paper is to understand how confinement of the coal can locally be lost in two of the three principal stress directions, thereby allowing normal strain energy within the coal seam to drive a coal burst in the remaining direction.

Taking this one stage further, it is instructive to consider the stored energy due to the major horizontal stress within a section of a coal seam, and the resultant acceleration of the coal should that energy become unstable and be released in the manner of an unloading spring. It is noted that strata behaving as a spring under load is also discussed in Gale 2018, whereby he states that “it can be visualised by viewing the rock as a spring, which is compressed by the in situ stresses. The stored energy is the amount required to have compressed the strata (spring) to the in situ state”.

If a coal mass accelerates horizontally when it bursts, it will be assumed as a starting assumption that it is the major horizontal stress that is the primary event driver. For a major horizontal stress of 5 MPa acting with a 3 m high by 3 m long and 3 m wide (i.e. 27 m$^3$) block of coal weighing some 38 tonnes (i.e. 27 m$^3$ x 1.4 = 38 tonnes), the stored horizontal force = stress x area = 5 x 100 tonnes/m$^2$ x 3 m x 3 m = 4,500 tonnes of horizontal compressive force or stored energy.

If that stored energy was to become unstable, based on Newton’s Second Law, the resultant acceleration = force/mass = 4,500/38 = 118 m/s$^2$ = 11.8 g. This acceleration results in a velocity for 38 tonnes of coal = 22 m/s ≈ 80 km/hr at a distance moved of only 2 m. The mechanics and destructive potential of 38 tonnes of coal moving at 80 km/hr requires no further comment herein, suffice to state that this confirms the assertion of Babcock and Bickel (1984) that a normal level of ground stress in a coal seam is more than sufficient to cause a very destructive coal burst if it becomes unstable due to a loss of constraint. How such a state can come about in situ prior to mining is therefore the focus of the remainder of this paper.

The normal or typical state of In Situ Stress

If one accepts for the moment that development coal bursts are both (i) driven by the major horizontal stress in the coal seam becoming unstable due to a loss of effective constraint, and (ii) statistically very rare, then the normal or typical state of the in situ stresses must be such that coal bursts on development cannot possibly occur. Therefore, the starting point for this
discussion is to consider the normal or typical state of *in situ* stress in coal mining and whether it potentially allows development coal bursts to occur or not.

Referring to Figure 3, the pre-mining 3D stress state in coal measures has three principal components, one vertical and two typically being horizontal. Based on the previous discussion with regard to development burst causation, for the major horizontal stress to become “unstable”, it needs to be able to overcome the combined constraining or stabilising influence of both the vertical stress and minor horizontal stress. Therefore, the sources of the minor horizontal and the vertical stresses need to be defined, so that how they may be overcome by the major horizontal stress can be considered further.

![Figure 3: Schematic illustration of assumed pre-mining principal stresses](image)

The *in situ* vertical stress is well established as being caused by the weight of the overburden, as illustrated in Figure 4. No other explanation is required in this regard.

![Figure 4: International vertical stress measurement summary (Hoek and Brown 1980)](image)

The link between the major horizontal stress in coal mining and plate tectonic effects is well established and does not need repeating herein. However, the very strong relationship that is almost always found between the measured magnitudes of the major and minor horizontal stresses is less well known, as outlined in more detail in Colwell and Frith 2012. Figure 5 shows...
an example of such a relationship from mine site stress measurements, the finding being that as the major horizontal stress increases in magnitude, so does the minor horizontal stress, typically being between 50 to 60% of the magnitude of the major horizontal stress. The reasons behind this commonly found relationship are irrelevant to the objectives of this paper, suffice to state that the minor horizontal stress typically acts to stabilise the major horizontal stress, rather than allow it to become critically unstable.

Figure 5: Sample stress measurement data showing a strong linear correlation between the major and minor horizontal stresses

With the vertical stress being driven by cover depth and the major and minor horizontal stresses tending to increase and decrease linearly with each other, this offers a credible explanation for the statistical rarity of development coal bursts, as the typical or normal \textit{in situ} ground stresses in coal mining do not obviously conform with the Babcock and Bickel 1984 hypothesis whereby one principal stress becomes unstable due to a loss of effective constraint from the other two.

This then raises two key questions:

1. mechanismically how, on a very rare basis, the constraining influence of both the minor horizontal and vertical stress can be lost or overcome by the major horizontal stress, thereby allowing the major horizontal stress to be the energy source for a development coal burst, and

2. is there any credible evidence indicating that such conditions were present at known development coal burst sites?

These two questions will now be considered further.

Loss of the minor horizontal stress with the major horizontal stress being maintained

The one obvious scenario whereby one principal stress can be reduced in magnitude back to zero, and the other maintained and even intensified, is the stress re-distribution that occurs in 2D around an excavation, as illustrated in Figure 6 for a circular excavation under hydrostatic stress conditions. If one considers Figure 6 in plan, rather than section, so that the two stresses being analysed are horizontal, it is evident that at the boundary of the excavation, the tangential stress (i.e. that acting parallel to the excavation boundary) is intensified as a result of the excavation being formed, whereas the radial stress (i.e. that acting perpendicular or normal to the excavation boundary) drops to zero at the boundary. The question that therefore follows is whether there is a credible scenario that allows such an excavation or void to form via natural processes prior to mining, so that a local modification to the \textit{in situ} pre-mining horizontal
stresses is induced, consistent with the minor horizontal stress being lost and the major horizontal stress maintained?

Figure 6: 2D elastic stress redistribution around a circular excavation under hydrostatic stress conditions

Figure 7 is taken from an underground coal mine in South Africa and demonstrates that open voids via open defects (e.g. joints, cleats or faults) can, and do indeed develop pre-mining, the horizontal stress acting perpendicular to an open defect inevitably being zero at the boundary of the defect. However, for the development coal burst causation model to be credible, a mechanistic explanation for the formation of substantial pre-mining voids within an otherwise bi-axial compressive horizontal stress environment needs to be developed.

Figure 7: Example of an open vertical joint in an underground coal mine

Figure 8 is taken from Hatherly et al 1993 and illustrates the formation of new fractures (as marked in red) at the tail end of a section of horizontal shear movement along a major fault plane driven by the major horizontal stress (NB these new fractures are termed as “wing cracks” in structural geology parlance). It is noted that Hatherly et al 1993 was in part based on structural mapping conducted at Ellalong Colliery, which is part of the larger Austar Mine complex.
The following quotation is taken from Hatherly et al 1993: (emphases added by authors):

"Strains near re-activated fractures and new fracture propagation. Re-activation of pre-existing fractures creates additional strains which leads to the development of new fractures through the TENSILE FAILURE of intact material. These fractures tend to curve into an orientation sub-parallel to the major compressive stress".

The excerpt from Hatherly et al 1993 describes the exact characteristics required by the development coal burst model for a local modification to the major and minor horizontal stresses within the coal seam, namely that the major horizontal stress is maintained (parallel with the tensile/open fracture), whilst the minor horizontal stress is inevitably eliminated (perpendicular or across the tensile/open fracture) as shown in Figure 9, if the aperture or width of the tensile fracture is sufficient to accommodate the necessary strata relaxation.
Loss of the constraint from the vertical stress to the major horizontal stress

Whilst a causation mechanism has been identified that can explain the local loss of the minor horizontal stress whilst the major horizontal stress is maintained or even intensified, the same cannot be applied to the vertical stress due to it being driven by the weight of overburden, which cannot be so easily relieved, if at all. Therefore, another mechanism and set of circumstances is required to explain how the constraint to the major horizontal stress from the vertical stress can be overcome.

The solution is straightforward and is found by considering the resistance to horizontal shear movement along a horizontal plane, as illustrated in Figure 10. For a large mass of coal to be rapidly ejected sideways out into a mine roadway, the horizontal driving stress needs to overcome the horizontal shear resistance within the coal seam, which will logically be at a minimum along any discrete and continuous horizontal defects, planes or low strength beds.
Depending upon the cohesion and friction acting along such a plane, it can readily be demonstrated that the major horizontal stress in the coal seam cannot always be effectively constrained by the vertical stress in isolation. For example, for a zero-cohesion horizontal plane having an Angle of Friction of say 10° (which as a comparison represents a slickensided, planar bedding surface), results in only 0.176 MPa of horizontal shear resistance for every 1 MPa of vertical stress. Even in a coal seam containing relatively low tectonic horizontal stresses due to the low Young’s Modulus of coal, such a level of horizontal shear resistance from the vertical stress is insufficient to fully constrain and control the major horizontal stress.

**SPECIFIC CIRCUMSTANCES AT THE AUSTAR INCIDENT SITE**

Various details of the Austar incident have been made publicly available in NSW Department of Industry 2015, NSW Department of Industry 2016 and Hebblewhite and Galvin 2016. Two geological circumstances of the event are believed to be of direct relevance to causation under the hypothetical coal burst mechanism described herein as will now be explained.

Figure 11 shows the reported structural geology of the incident site with key features being highlighted, namely the main “Quorrobolong” fault zone some distance outbye the incident site (shaded in green) and a structure or series of structures projected to be just inbye the incident site (highlighted by the blue dashed line) that are oriented substantially differently to the main fault zone, but project back to the main fault zone just to the south of MGA9 (see Figure 12). The difference in the alignments of these two different structure sets is directly comparable to that shown in Figures 8 and 9 relating to the development of tensile wing cracks due to variations in horizontal stress-driven shear movement along a pre-existing fracture.

![Figure 11: Plan showing layout and some geological features of mg a9 (NSW Department of Industry 2015)](image-url)
If it were to be the case that the structure or structures indicated by the blue dashed line in Figure 11 were in fact tensile wing-cracks developed from horizontal shear movement along the main fault plane, they would provide for the necessary pre-existing strata "void", with the potential ability to locally eliminate the minor horizontal stress, whilst maintaining if not more likely intensifying the major horizontal stress, as illustrated in Figure 9.

Figure 12 shows a photo of the geological structure where it was intersected at the inbye end of the adjacent A Heading (see Figure 11), and under one interpretation it could conceivably be associated with an open void that has subsequently been filled with extraneous material over geological time. It is accepted that the complete nature of the structure(s) just inbye the current headings in MGA9 cannot be defined from Figure 12. However, it is impossible to ignore this structural zone given its different orientation as compared to the main fault zone, what this may signify in terms of its genesis, and the potential for it to have contained a distinct strata void at some point in geological history.

Taking this suggestion a stage further, it is hypothesised that if the major and minor horizontal stresses were locally modified by a substantial strata void within the structural zone, it should result in stark differences in coal rib conditions either side of any nearby roadways, as illustrated schematically in Figure 13. In this regard the following are noted:

(i) roadway rib conditions in proximity to the burst site are described in NSW Department of Industry 2016 as follows:

"Mining conditions in B Heading at the time included some spall of the right hand rib, below the Dosco Band (see Figure 6, for an image of the Dosco Band parting within the coal seam). However the left hand rib was standing straight."
(ii) Post-event geotechnical mapping of the general area as reported in NSW Department of Industry 2016 (see Figure 14), indicates that in the adjacent A Heading, the left-hand rib was mapped as Condition Green which is defined as $< 0.3$ m of rib spall, the small photo of the left-hand rib included in Figure 14 showing a rib that is "standing straight". In contrast, the right-hand-rib is mapped as Condition Red which is defined as $> 1$ m of rib spall and described as "very friable and sugary inbye A2".

(iii) Figure 15 from NSW Department of Industry 2015 shows the right-hand rib in A Heading, which provides a clear indication of the significant levels of rib fracture and spalling, as compared to the left-hand rib that was described as "standing straight".

The conclusion drawn from the available evidence is that inbye the main fault zone, both A Heading and B Heading exhibited quite unusual rib condition variations between the left-hand and right-hand sides of the roadway. One possible explanation for this is an intensification of the major horizontal stress and substantial reduction of the minor horizontal stress within the coal seam, as indicated in Figure 13.
Figure 14: Post-incident geological mapping of area (NSW Department of Industry 2016)
In terms of whether a very weak horizontal plane of weakness was present at the Austar burst site and so acted to allow uncontrolled horizontal shear slip of the coal by reducing the confining influence of the vertical stress below critical levels, the presence of the Dosco Band at the top of the coal section that burst is clearly evident in Figures 16 and 17. This raises the question as to whether the Dosco Band in this location was likely to be characterised as being of zero cohesion and low friction?
NSW Department of Industry 2015 contains the following statement – “The smooth and dominant shear surface presented by the Dosco Band within the Greta Seam, which appears to have acted as a dynamic shear failure plane once some form of triggered loading (or unloading) event occurred”. Hebblewhite and Galvin 2016 provide a more detailed description – “the upper bound of the burst cavity is clearly visible (Fig. 6b) as a very smooth, flat bedding plane within the seam known as the “Dosco Band”. Rib coal above the Dosco band has not displaced at all, whereas all the coal beneath it is part of the burst. The exposed surface of the Dosco Band showed signs of horizontal shearing activity, with a quite distinctive reddish-brown dust coating on much of the surface. Newman (2002) and others have reported similar evidence of reddish-brown pulverised coal particles at burst sites”. These two independent descriptions of the exposed Dosco Band at the Austar incident site clearly confirm it as being a planar or flat surface with little or no cohesive strength and minimal friction.

Another possible source of a planar, zero cohesion, low friction horizontal plane of weakness within a coal seam that could theoretically act in a similar manner to that of the Dosco Band in a coal burst, is the unconformable contact that commonly exists between the top of a coal seam and base of a massive strata unit such as a sandstone. The significance of such a contact is clearly evident in Figure 18 from a US coal burst site, this offering a credible explanation for the commonly observed presence of a strong sandstone roof at coal burst sites, which has potentially resulted in many researchers inadvertently placing the significance of the presence of sandstone on its high strength or modulus, rather than the very specific nature of the contact between the coal and the sandstone.
FEATURES OF THE SUNNYSIDE DISTRICT, UTAH

According to Mark 2017, the Sunnyside District in Utah was the location of the first recorded development coal burst in the USA in 1915, subsequent to which many similar development burst events were recorded.

Figure 19 shows the regional structural geology of the Sunnyside District, which is dominated by the Sunnyside Fault Zone. The Sunnyside Fault Zone is described in Osterwald et al 1993 as under-going horizontal shear-slip due to the action of horizontal stress, as evidenced by the bending of railway lines on the surface following large regional bump events.
Figure 19: Major structural geology of the sunnyside mine area (Osterwald et al 1993)

More specifically in relation to the phenomenon of development coal bursts, several features appear to be consistent with either the structural geology of the Austar incident site or the development burst hypothesis presented in this paper more generally, they include:
(i) the difference in alignment between the main fault zone in Figure 20 and what appears to be another mapped structure extending out from it, with the associated “bump area” being located between the two structures. This is broadly similar to the situation from Austar shown in Figure 11.

(ii) The fact that the main fault zone shown in Figure 20 has one side characterised as being associated with bumps and the other as not being associated with bumps. The application of the wing crack causation model shown in Figure 8 would lead to the inevitable conclusion that a major fault zone would only be coal burst prone on one side at any given location.

Figure 20: Mapping showing relation of faulting to bumping and non-bumping areas in part of the sunnyside No.2 mine (Osterwald et al 1993)

The geological mapping in Figure 21 shows three relevant features in close proximity to the main fault zone, namely one side of the heading being heavily spalled (marked by the red shaded area) as compared to the other side (as suggested from Figure 13 and demonstrated via information from Austar), mapped geological structures at a significantly different alignment to the main fault zone (marked by the green shaded area) and an area described as “broken coal, thrown out from left rib” (marked by blue shaded area) on the side of the heading with the more stable general rib conditions.

The mapped structural geology and varying roadway conditions from the development coal burst-prone mine’s in the Sunnyside District show similar general features to that from the development coal burst location at Austar. Further, the indication that one side of a major fault was burst prone and the other not burst prone, adds further credibility to the wing-crack model, as shear-slip movement driving the formation of new tensile fractures (wing-cracks) would logically only occur on one or other side of a major fault at any given location along its length.
CAUSAL MECHANISM SUMMARY

In the process of developing and illustrating a credible causation model for understanding development coal bursts, questions posed within Mark 2017 were used as a starting point, particularly related to the following two comments:

“coal mines have developed across many faults in Utah and elsewhere. What was so unique about the Sunnyside fault that it contributed to so many powerful bursts over so many years, many in the same place and well outbye any active mining?”

Figure 21: Underground geologic map of right-hand airway at sunnyside fault zone, sunnyside No.1 mine (Osterwald et al 1993)
and why is the area so burst prone, when the coal seams are encased in relatively soft rock?

Furthermore, the work attempted to address the following broader questions pertaining to development coal bursts:

- What is the energy source?
- Is there a mechanistic link between the manifestation of a development coal burst and its severity?
- Can the ground stresses and/or geotechnical conditions which (a) create the energy source and (b) allow it to become unstable (and so is released in an uncontrolled manner) be defined?
- How can such geotechnical conditions come about in an underground mine?
- Is there any evidence that such geotechnical conditions were present at Austar in proximity to the burst site (based on public domain information) and/or other known development burst–prone mines (e.g. Sunnyside in Utah)?
- Does the development coal burst model provide a plausible explanation for the statistical rarity and improbability of development coal bursts in general terms?

Addressing these questions in their entirety, the following summary points are made:

1. The energy source for a development coal burst can demonstrably be simply the major horizontal stress within the coal seam (even at relatively low magnitudes), as evidenced by the application of Newton’s Second Law, providing that the constraining influence of the minor horizontal stress and vertical stress are insufficient.

2. The minor horizontal stress can locally be substantially reduced to as low as zero, with the major horizontal stress being maintained or even intensified via the development of dilated tensile fractures known as wing-cracks at the tail end of horizontal shear-slip along a major fault plane, this being well-established in structural geology.

3. The constraining influence of the vertical stress can be eliminated via the presence of a planar, zero cohesion and low friction horizontal plane, either in the form of an unconformable contact at the top or bottom of a coal seam, or a discrete stone or clay bed within the coal seam that has either been re-worked by horizontal shearing effects over geological time or is naturally very weak and friable. Interestingly, this is consistent with the comments of Babcock and Bickel 1984 in that they observed that once lateral constraint was removed from a coal sample, the style of failure was directly linked to the contact conditions between the coal sample and steel platens of the testing machine.

4. The required geological conditions for a development coal burst, as outlined in points 2. and 3., were seemingly present in direct proximity to the Austar incident site, and more generally in the Sunnyside District in Utah.

5. The horizontal stress conditions and the necessary structural geology under which such stress conditions can form within an otherwise bi-axial compressive horizontal stress environment, combined with the need for a specific horizontal plane of weakness to substantially reduce the constraint provided by the vertical stress, offer a credible explanation for the statistical improbability of development coal bursts across industry in general terms.

The proposed development coal burst causation model outlined in this paper provides what are considered to be credible answers to the various questions listed, remembering that it is founded on well-established physics and structural geology, in combination with known local conditions from the only well-documented development coal burst in Australia, and general
geological conditions within a mining district in the US that was demonstrably prone to development coal bursts.

IMPLICATIONS TO COAL BURST MANAGEMENT

If a Hierarchy of Controls approach is applied to the issue of development coal burst management in mining operations, it inevitably results in the following requirements, in priority order:

1. To eliminate exposure to the hazard if possible.
2. To develop suitable engineering controls that minimise both the exposure to and severity of the hazard if 1. is not possible.
3. To develop effective administrative control measures to prevent the inadvertent exposure of persons to the hazard if 1. and 2. above fail.

With these three statements in mind, the following comments are made for general industry consideration:

a) major geological structures that have undergone a substantial local relative change in horizontal shear-slip magnitude along the structure (i.e. strike-slip motion) under the action of the major horizontal stress (i.e. a very specific local structural influence), might be identified pre-mining from geotechnical borehole exploration data, including variations in the direction and magnitude of the major horizontal stress, as can be inferred from borehole breakout.

b) the critical “danger” area from a development coal burst perspective, is proximity to the “tail end” of substantial horizontal shear slip along a fault plane where new tensile fractures (“wing-cracks”) can form and substantially modify the horizontal stress environment.

c) it is possible that high horizontal stress, coal-burst prone zones might be identified and delineated by longhole drilling. In this regard, Figure 22 shows the pre-development longhole drilling at the outbye end of MGA9, firstly through the Quorrobolong Fault Zone and then inbye towards the what would eventually be the coal-burst site and the geological structure just slightly further inbye. The reason that longhole drilling was stopped as shown was reported “bogging” as stated in Figure 22. The founding reference (NSW Department of Industry 2016) does not offer an explanation as to what this term means in reality, however the comment is made that “Directional longhole drilling was undertaken from the 300 Mains in advance of Maingate A9 development, to establish the presence and nature of some of these projected geological features, as well as to inform on coal seam continuity and gradients ahead of Maingate A9 development. Figure 13 shows the pattern of holes that were drilled in the vicinity. While these holes clearly penetrated the cluster of faults that crossed Maingate A9 between 1 and 2 cut-through, they appeared to have all stopped short of the structures that were encountered beyond 2 cut-through in A Heading, and that were projected to lie just beyond the face of B Heading and the dog-leg heading at the time of the incident”. Without digressing in detail, it is stated that the actual mine workings appear to contain no obvious major geological structure (see Figure 14) that would explain the “bogging” and ceasing of longhole drilling, an alternative potential explanation being intensified horizontal stresses within the coal seam causing excessive coal breakout and hole collapse at this location. The close alignment of the limit of long hole drilling and the inferred “wing-crack” structure just inbye the burst site is intriguing, as is the mapped occurrence of floor heave in A Heading commencing just inbye the limit of longhole drilling (see Figure 14).
Figure 22: Longhole drilling undertaken ahead of maingate A9 development (NSW Department of Industry 2016)

d) zero cohesion and low friction horizontal planes within the working section (i.e. clay bands, re-worked stone bands, sandstone seam roof/unconformity) which substantially limit the constraint generated by the vertical stress, should be identifiable from surface borehole information.

e) items (a) to (c) potentially allow some form of credible pre-mining hazard ranking for development coal burst prone and non-prone areas.

f) the mine layout could be engineered to eliminate exposure to identified burst-prone areas, or at least minimise both the exposure to and severity of the hazard.

g) the development burst causation model leads to the identification of some obvious visible and audible TARP triggers that could be used in operations to identify the onset of development coal burst-prone areas, including stark variations in roadway rib conditions and the identification of certain types of geological structures.

The mechanical engineering and isolation control measures that may allow roadway development in coal-burst prone conditions, such as remote mining, guarding on the CM and/or out-of-seam drivage, are well beyond the scope of this paper. Therefore, no comment as to the likely effectiveness of such measures has been considered or is provided.

CONCLUSIONS

The paper has outlined suggested generic definitions for different types of “high energy” release events that can occur in the underground coal mining based on the location and type of the energy source, rather than the characteristics of the manifestation in the mine workings. This is considered to be fundamental to improving the understanding for each event type and hence, the ability to more reliably predict and manage the associated safety and business risks.

A causation model specifically for development coal bursts has been outlined, founded on the loss of constraint hypothesis that was first postulated by Babcock and Bickel 1984 from their laboratory testing studies. Using published information in regards to development coal bursts at the Austar Mine in Australia and from the Sunnyside District in Utah, USA, a model linking the local structural geology to (a) the loss of the minor horizontal stress and (b) significantly limiting the constraint offered by the vertical stress has been developed, the resulting inevitable uncontrolled release of the major horizontal stress in the coal seam being shown to be more
than sufficient to generate a violent expulsion of coal by reference to Newton’s Second Law of Motion.

The causation model further addresses two key questions raised in a seminal paper on development coal bursts from as recently as 2017, namely faulting system characteristics that are likely to be development burst prone, and how can coal bursts occur within a sequence of otherwise soft measures. Furthermore, it also offers a credible explanation for the statistical rarity of development coal bursts in more general terms, this being due to the improbability of all of the required elements of the causation model coming together at the same location within a mine roadway.

The causation model allows more targeted hazard ranking prior to mining as well as inputting into operational management of the development coal burst hazard. In particular, if the proposed causation model is essentially correct, credible pre-mining hazard ranking for development coal burst prone areas should be achievable using commonly available exploration information such as horizontal stress directions and severity from borehole breakout analyses, and horizontal planes of weakness from lithological logs. Further, there is credible evidence that longhole drilling ahead of roadway development is able to delineate development coal burst-prone zones via the inability to drill into them.

Ultimately, industry will benefit from being able to apply a more targeted Hierarchy of Controls approach to the development coal burst problem, which due to the very high associated safety and business consequences will benefit from being focused on both prediction ahead of mining and detecting the hazard before mine roadways are developed into development burst-prone areas without suitable mitigatory controls in place.

REFERENCES


