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A discussion on causation mechanisms for overburden bumps as distinct from coal bursts

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A DISCUSSION ON CAUSATION MECHANISMS FOR OVERBURDEN BUMPS AS DISTINCT FROM COAL BURSTS

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ABSTRACT: The entire subject area of micro-seismic events due to stored strain energy, as distinct from gas-driven coal outbursts, can be readily sub-divided into firstly events with their energy source from within the coal seam (termed "bursts") and secondly, event with their energy source outside of the coal seam in either the overburden and/or floor strata. The reason for sub-dividing micro-seismic events in this manner is that if the causation mechanisms and associated geotechnical conditions are materially different, then effective pre-mining predictions and subsequent operational controls may also differ. Attempting to explain a multitude of micro-seismic event types without consideration of varying source mechanisms will inevitably lead to inadequate causal explanations and effective controls.

The paper outlines several different causal mechanisms for bumps emanating from both the overburden and/or floor of a coal seam by reference to both theoretical treatments and known associated case histories. These include massive pillar collapses (including the Coalbrook disaster in 1960), large-scale shear slip along fault planes/other geological discontinuities, the compressive failure of thick and strong strata units and finally, multi-seam stress effects.

The objective of the paper is to provide an initial "*cause and effect*" list of geological and geotechnical circumstances that can and indeed have resulted in large magnitude micro-seismic events during underground coal mining activities, being able to predict the likely propensity for such significant events prior to mining being the first requirement in an effective prevention or consequence mitigation process.

INTRODUCTION

In relation to the specific phenomenon of development coal bursts, as distinct from overburden and/or floor bumps, Frith and Reed (2019) outlined a first-principles causation mechanism and specific geological circumstances related to the 2014 Austar tragedy and more general features of the reported development coal-burst prone, Sunnyside Mine in Utah, USA. A clear distinction was made between generic "bursts" whereby the energy source is within the coal seam, as distinct from "bumps" whereby the energy source is within the overburden or floor of the seam (this being the definition of the term "bump" herein), and "outbursts" which are gas-pressure driven. These three fundamental event types were represented as a Venn diagram (Figure 1), the potential for hybrid events with more than one energy source involved being recognised, but in no way proven in the field.

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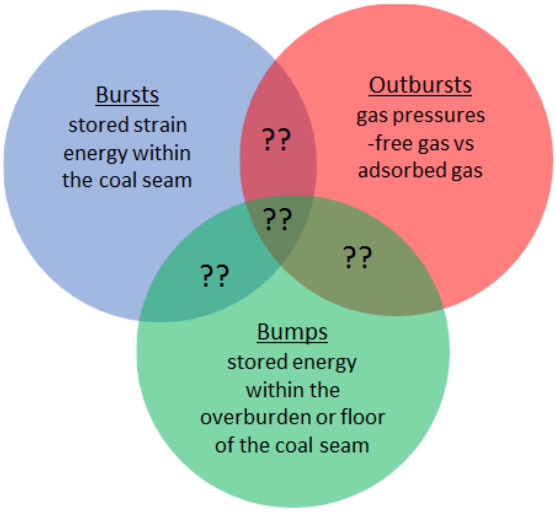

FIGURE 1: Suggested Classification of High Energy Release Events in Underground Coal Mining (Frith and Reed 2019)

Frith and Reed 2019 made the statement that "*a general review of the literature relating to coal bursts quickly reveals an obvious lack of consistent terminology across bursts, bumps and gas outbursts*…", the point being that without clear definitions of event type and in particular, associated causation mechanism, there might be a tendency to categorise individual events incorrectly, this potentially leading to increased confusion rather than clarity. This was to a large degree demonstrated in the recent ACARP-sponsored coal burst workshop in Australia whereby international experts from several countries were invited to share their knowledge, the vast majority of which related to overburden bumps or gas outbursts, rather than development coal bursts of the type that occurred at Austar. This is not to diminish these contributions, simply to indicate that there clearly remains general confusion as to what constitutes a "burst" as distinct from a "bump" in terms of causation.

It is hypothesised that part of the confusion may be a disjoint between the observation of an event manifestation, as compared to the source of and release mechanism of the driving energy. How an event may be experienced by persons in the mine or the resultant altered conditions of the mine workings following an event (e.g. violent coal rib failure, rapid floor heave, significant closure of an excavation etc.) may be similar for a range of different energy-release event types. As such, attempting to define and understand energy sources and release mechanisms using the resultant impact on the mine workings may be less than reliable, hence the confusion along the lines just described.

This paper seeks to provide an improved level of clarity by considering potential energy sources and release mechanisms from overburden and/or floor bumps rather than their direct impact on the mine workings, this being based on both a theoretical problem treatment and the use of selected case histories.

GENERIC BUMP MECHANISMS AND ENEGRY RELEASE MECHANICS

When discussing mining-induced seismicity and "rockbursts" Brady and Brown 2005 consider that two distinct source mechanisms may be involved, one related to shear-slip along pre-existing geological discontinuities, the other due to crushing of the rock mass, noting also that the study of such events may be best facilitated by accounting for energy changes within the system. These basic principles are at the core of the discussion herein relating to "bumps" in underground coal mining.

The bump causation mechanisms outlined herein are based on the following generic principles:

(i) Two of the three distinct failure mechanisms of a linear arch.
(ii) Stress-driven shear slip along large-scale pre-existing planes of weakness.

Examples of these general behavioural mechanisms using coal mining field experience will be provided, prior to which it is necessary to briefly summarise the governing principles of a linear arch or Voussoir beam, as well as stress-driven shear slip along a pre-existing plane of weakness. It is also useful to have a frame of reference for energy release magnitudes when considering bump causation mechanisms at a fundamental level.

Governing Principles

The Linear or Voussoir Arch is outlined in detail in Brady and Brown 2005. The general beam configuration and the associated internal compression arch, as originally put forward by Evans 1941, is shown in Figure 2, the critical characteristic being that such a beam can fail in one of three distinct modes – (a) vertical abutment shear, (b) horizontal compression at or close to the crown of the beam or (c) uncontrolled buckling. On the basis that buckling is generally not associated with a rapid significant energy release, the discussion herein will focus on vertical abutment shear and compressive failure of intact material as two potential coal mine bump causation mechanisms.

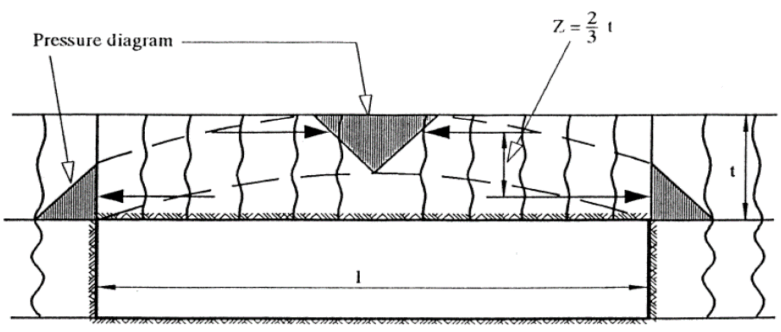

FIGURE 2: Linear Arch Concept (Evans 1941)

Stress-driven shear slip along pre-existing major geological discontinuities such as faults, is well established in the seismology literature, the application herein relating to mining seismicity on a smaller-scale than that involved in regional earthquakes for example. The basis for stress-driven shear-slip along a plane of weakness involves two distinct aspects – (i) resolving the acting ground stresses into shear (parallel), and normal (perpendicular) components relative to the plane, and (ii) assessing whether the resultants will result in shear slip along the plane using a Mohr-Coulomb representation. Figure 3 is taken from National Research Council 2013 and illustrates the basic problem as just described, including the potential influence of pore pressure, p, if relevant.

Both the linear arch and stress-driven shear slip along a plane of weakness are simple to understand and analyse, the applicability of both to coal mine bump propagation being considered in more detail later in the paper.

If one accepts the hypothesis that a bump is a direct consequence of energy release from either the roof or floor strata, it is useful to start with the general equation for a changing mechanical or potential energy state of any system (kinetic energy being ignored in this instance), namely:

$$\text{Initial Total Stored Energy } (TSE_i) + \text{work done} = \text{Final Total Stored Energy } (TSE_f) \quad (1)$$

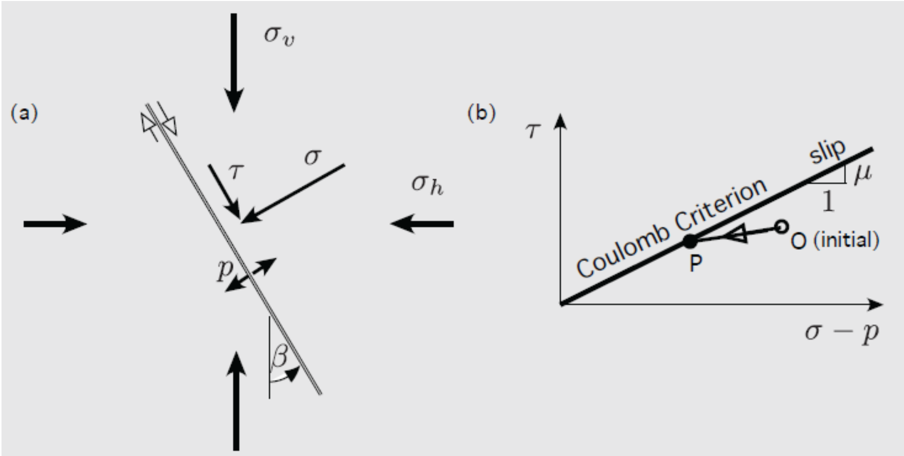

FIGURE 3: Shear and normal stress components along a plane of weakness and a Mohr-Coulomb shear strength sepresentation (National Research Council 2013)

In other words, the energy released should TSE_f end up being less than TSE_i can be considered as "negative work", the general equation for work being given by:

work = force x distance (or in this case stress x area x strata displacement) (2)

Equation 2 identifies three distinct components of work or energy release that should be relevant to the bump problem, namely (i) ground stress magnitudes, (ii) the area from which ground stresses are released, and (iii) the magnitude of strata displacement before equilibrium is re-established. The greater the magnitude of ground stress that is dissipated or relieved over a larger area and the further that the strata moves before an equilibrium condition is re-established, the greater the work done, hence the greater the energy release. In seismology, this defines a seismic event's *magnitude*.

Table 1 is taken from a larger table contained within USGS 2014 and outlines the links between event magnitude (Richter Magnitude), equivalent energy released (in Joules) and interestingly for context, a description in practical "explosion" terms. In terms of the manner by which a bump event is experienced in the mine workings (termed *intensity*), either audibly, via strata damage levels or via physical shaking of the excavation, the dissipation of energy with increasing distance from the epicentre of either a seismic or in this case, a micro-seismic event is of direct relevance. How seismic events are experienced at any given location (i.e. their intensity) is a highly complex subject and was initially addressed via an empirical scale known as the "*Modified Mercalli Intensity Scale*" which is similar to Mohs Scale of Hardness in that it contains 10 distinct categories with no numerical relativity relationship between the categories.

Analysing seismic event intensity numerically involves a whole range of technical considerations that are well beyond the scope of this paper and are in fact, uniquely the realm of the professional seismologist. However, for the purpose of this paper it is sufficient to state that seismic event intensity generally decreases as a direct function of increasing distance from the event epicentre, the energy decay commonly being quoted as being exponential (i.e. proportional to 1/r where r is the distance from the epicentre). Therefore, distance from the mine workings to the epicentre of a bump event is the fourth variable to be aware of.

TABLE 1: Seismic Event General Descriptions (extract from USGS 2014)

Approximate Richter Magnitude	Equivalent TNT for Seismic Energy Yield	Joule Equivalent	Example
0.0	15 g	63 kJ	
0.2	30 g	130 kJ	Large hand grenade
1.5	2.7 kg	11 MJ	Small construction blast
2.1	21 kg	89 MJ	West fertilizer plant explosion

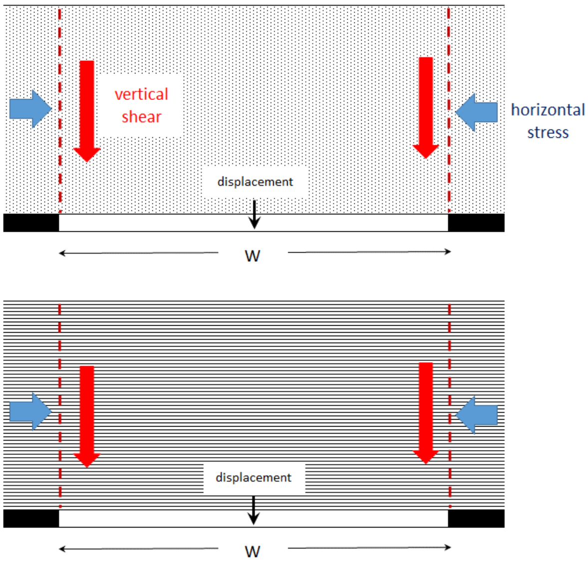

FIGURE 4: Thought-Experiment Representations: Massive and Laminated Overburdens Including Vertical Joints and Horizontal Stress (Frith and Reed 2018)

Vertical Abutment Shear

Frith and Reed 2018 described an overburden stability model for coal mining that is fundamentally consistent with that of vertical abutment shear within the linear arch model, in that it recognises that one mode of large-scale overburden instability is linked to the horizontal stress acting across vertical joints being overcome by vertical shear, as illustrated in Figure 4.

A "blocky" overburden collapse mode can be demonstrated by reference to overburden extensometry data from longwall extraction. Willey *et al* 1993 report surface extensometry data from the extraction of LW4 at Cook Colliery in QLD, the measured outcomes being contained in Figure 5. The data indicates that with the longwall face less than 40 m past the borehole extensometer location, an almost instantaneous large-scale vertical "slip" event occurred, for all of the anchors that were still operating at that time, in the depth range from at least 50 m to 218 m.

Figure 5 shows similar surface extensometry data for a longwall face at shallower depth (90 m) with the overburden containing more than 50 m of dolerite material immediately above the coal seam. Again, there is clear evidence of large-scale blocky overburden collapse within credible measurement data, as might logically be expected.

In terms of whether this type of overburden collapse mode might have the ability to cause a high energy release and so drive an overburden bump, is demonstrated by reference to two documented coal pillar collapses, the first being that at Coalbrook in 1960, the second being a highwall mining pillar collapse at Ulan Mine in New South Wales.

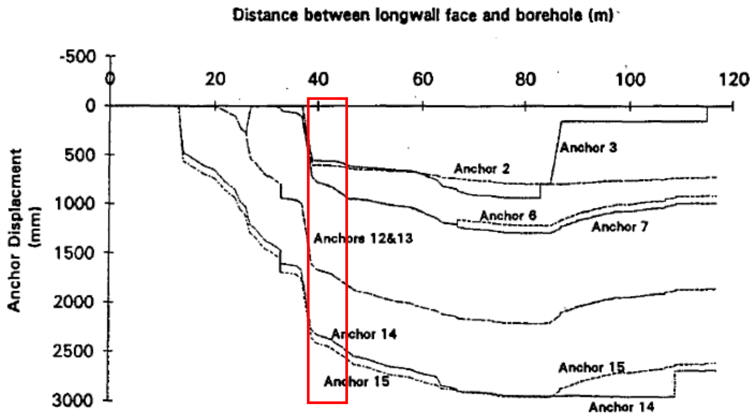

FIGURE 5: Crossline Subsidence Profile, Castor Seam Longwall 4 (Willey *et al* 1993)

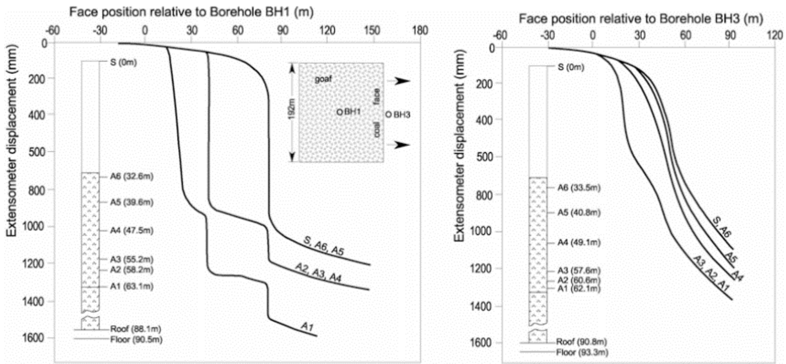

FIGURE 6: Graphs Showing Progressive Step-Failure of a Dolerite Sill as Recorded using Surface to Seam Borehole Extensometers (reproduced from Galvin 2016)

Van Der Merwe 2006 describes the circumstances and experience of the Coalbrook disaster, in particular the major event in early 1960 following the local "*experiment*" collapse in late 1959. The following quotations are taken from that paper:

> *At about 16:00, the miner in charge of a section which was then working just West of Section 10, was alarmed by loud shot-like noises coming from the direction of Section 10 and pillar spalling.*
>
> *At 16:20, the miner in charge of a gang working just South of Section 10 also became aware of problems in Section 10 by a strong wind blast from that direction and sounds like heavy thunder.*
>
> *Sometime after 19:00, the men replacing the ventilation stoppings South of Section 10 became aware of increasing thunder-like noises from Section 10 and increasing methane emissions. They withdrew but before they could reach a safe place, were "overtaken by a hurricane of dust laden air accompanied by crashing like thunder".*
>
> *The following seismic events were recorded that can be connected to the collapses:*
>
> *28 December at 19:16, Richter Magnitude 0.5*
>
> *21 January at 16:45, Richter Magnitude 0.3*
>
> *21 January at 19:26,Richter Magnitude 1.0*

The events on 28 December and at 16:45 on 21 January exhibited single amplitude peaks while the one at 19:26 on 21 January lasted for 5 minutes, with three distinguishable amplitude peaks during that period. Comparison of the times at which the seismic events were recorded to the times at which wind blasts and other observations indicating collapse underground were made, leads to the conclusion that the seismic events were caused by the collapse and were not minor earthquakes leading to the collapse.

The mine collapse at Coalbrook was demonstrably accompanied by a significant amount of seismic activity that was both audible in the mine workings and measurable via seismic networks. This raises the obvious questions as to (a) the source of the energy released during the collapse and (b) the associated release mechanism.

Frith and Reed 2018 examined the key question of whether, in a pillar collapse, it is the pillars or the overburden that fails first, the conclusion being that it is almost certain that the coal pillars go post-peak strength well before the overburden become critically unstable *en masse*. Therefore, it logically follows that the Coalbrook seismic events almost certainly emanated from the overburden eventually becoming critically unstable and collapsing, rather than coal pillar failures. In this context, it is judged that the energy source and associated release mechanism was more likely comparable with that illustrated in Figure 4, namely one of vertical abutment shear when the stabilising influence of horizontal stress was eventually overcome by the super-incumbent weight of an unstable overburden mass and so rapidly released.

The highwall mining collapse at the Ulan Mine is documented in CSIRO 2001 with the following statement being of relevance to this paper:

> *On 18th of March, 2000, a highwall panel failure occurred in HW3 Trench encompassing up to an estimated 119 entries. The failure occurred quickly at 6 a.m. There were no injuries nor was any equipment damaged. The failure was recorded as a seismic event by the Australian Geological Survey Organisation who calculated a local magnitude of ML = 3.8 for the event. This is approximately equivalent to a 1000 tonne "mine blast".*

Whilst not from the same mine, Figure 5 shows a HWM pillar failure from distance, the propagation of vertical abutment shear through substantial portions of the overburden below near-surface weathered material being self-evident.

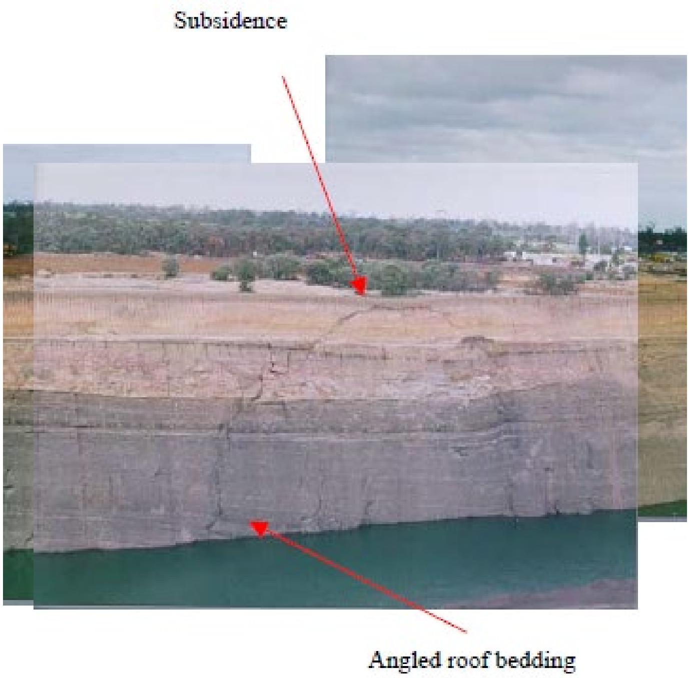

FIGURE 5: Photograph of overburden above a HWM pillar failure, Yarrabee Mine (CSIRO 2001)

A 3.8 Richter Magnitude event is broadly equivalent to an energy release (or work done) in the order of 30 GJ. Using Equation 2, this can be achieved via a combination of (a) a 2 MPa horizontal stress reduction, (b) a vertical shear displacement of 0.5 m and (c) a shear area

30,000 m^2, which is the equivalent of a perimeter of 300 m (i.e. 100 m + 100 m + 100 m) and a sheared interval of 100 m thickness, which is judged to be credible for a HWM layout. In other words, it is easily conceivable than even in a low horizontal stress environment at shallow cover depth in proximity to an open cut highwall, a substantial energy release event can occur in conjunction with a coal pillar collapse.

The preceding discussion has attempted to demonstrate that even relatively small-scale pillar collapses have the potential to develop substantial micro-seismic energy events via the release of horizontal stress from the overburden due to a vertical abutment shear mechanism.

Compressive Failure of Intact Material

Frith and Creech 1997 reported the results of micro-seismic monitoring from West Wallsend Colliery in NSW, specifically related to the narrowing of a longwall face beneath a known thick, massive, near-seam conglomerate unit with the inferred potential to cause significant periodic weighting effect and associated face instability if allowed to “weight” and cave in an unrestricted manner.

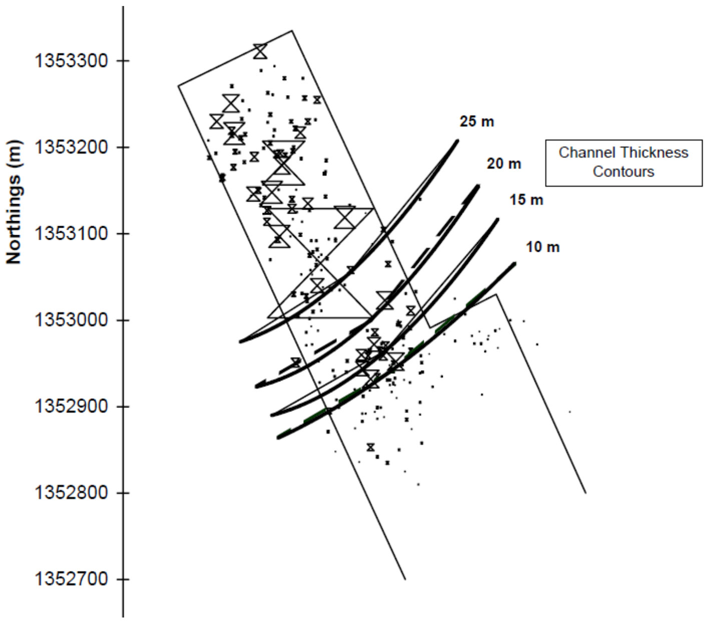

FIGURE 6: Location and Magnitude of Events in Relation to Panel and Channel Geometry, LW12 West Wallsend Colliery (Frith and Creech 1997)

Figure 6 contains the plan location and associated magnitude of measured micro-seismic events associated with initially narrowing of the longwall face from 240 m wide to 150 m and subsequently the thickening up of the massive conglomerate channel from 10 m to in the order of 25 m outbye. As described in the research report, not only did the event magnitudes dramatically increase (the largest single event had a calculated Richter Magnitude in the order of 2), the associated source mechanism was found to be compressive rather than shear (as was almost entirely the case for measured events at the full face width of 240 m), with the location of large compressive events at 150 m panel width being generally behind rather than ahead of the longwall face.

This monitoring data fully demonstrates that with the necessary thick, massive and strong overburden conditions and an extraction width that results in spanning of strata via the development of a substantial compressive linear arch across the extraction width, large magnitude micro-seismic events can be generated during active mining, this being consistent with the horizontal compression failure mode of a linear arch.

Stress-Driven Shear Slip Along Pre-Existing Planes of Weakness

For the purpose of illustration, reference will be made to the significance of mid-angled discontinuities in uncontrolled roadway roof instability, the associated theoretical basis then being increased in scale to that of major faults and broader ground stress considerations.

The critical geotechnical characteristic of a mid-angled discontinuity in relation to overburden bumps, is exactly the same as its ability to cause large-scale roadway roof falls with little or no obvious pre-cursor warning signs (as discussed in detail in Frith 2016), the reason being that under certain conditions, such a plane of weakness becomes naturally unstable under the action of horizontal stress, so that uncontrolled stress-driven shear-slip occurs along the plane, thereby dissipating horizontal stress and so rapidly leading to a major roadway roof collapse unless adequately supported. The problem of shear-slip along a mid-angled plane of weakness under the action of horizontal stress (the vertical stress having been removed due to the formation of the mine roadway below), is illustrated in Figure 7, with the necessary condition for shear-slip being that the Friction Angle (Φ) along what is an assumed cohesionless plane of weakness, must be less than 90-θ where θ is the inclination of the fault plane to the horizontal.

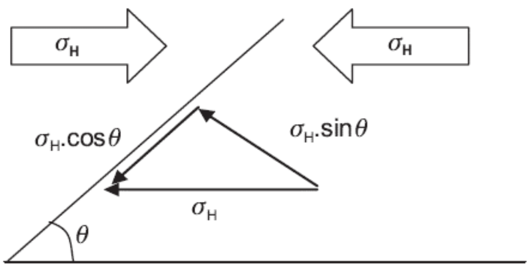

FIGURE 7: Arrangement of Horizontal Stress Across a Mine Roadway, an Inclined Discontinuity and Resolving Horizontal Stress Along the Discontinuity (Frith 2016)

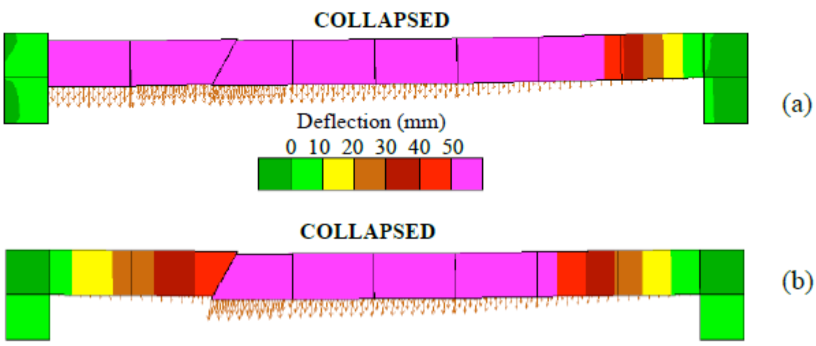

FIGURE 8: Deflection Contours for Single Steeply Dipping Joint (dip 60º): (a) σ_h = 0 MPa; (b) σ_h = 4 MPa (Oliveira and Pells 2014)

For a mid-angled fault plane with an inclination of 60° to the horizontal, the plane will inevitably be unstable under the action of horizontal stress for an Angle of Friction of < 30°, this being one of the reasons why mid-angled faults can result in highly unstable roadway roof conditions, Friction Angles < 30° being readily achievable along fault planes having undergone significant displacement. This critical mechanistic aspect of mid-angled discontinuities under the action of horizontal stress, is fully confirmed in Oliveira and Pells 2014 whereby they analyse tunnel roof stability containing a cohesionless plane of weakness inclined at 60° to the horizontal, with an assumed Friction Angle of 30°, the stability outcome being shown in Figure 8, the "strong" and "weak" sides of the discontinuity being obvious. This suggested fault-slip overburden bump mechanism is fully consistent with that shown in Figure 9 from the Yima Mine in China.

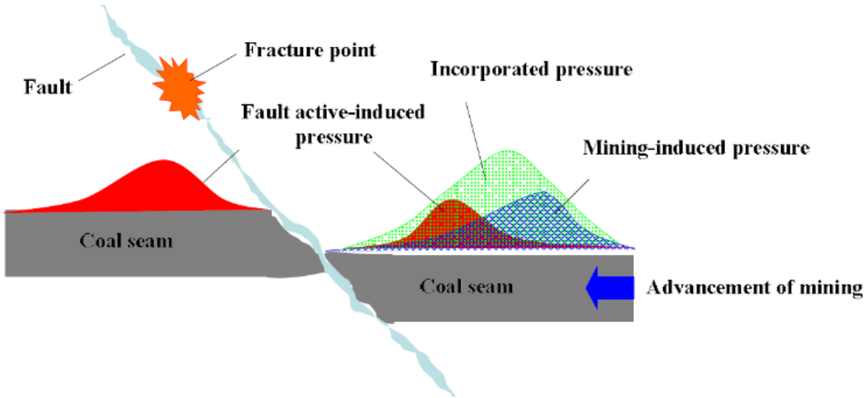

FIGURE 9: Tectonic Structure in Yima Coal Mine, China (CSIRO 2016)

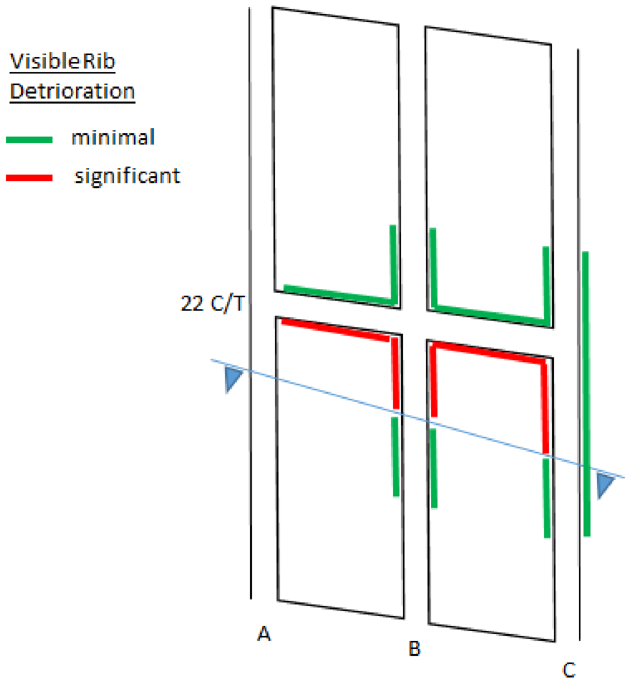

FIGURE 10: Observed Roadway Rib Conditions in Proximity to a Development Bump-Prone Mid-Angled Fault Plane

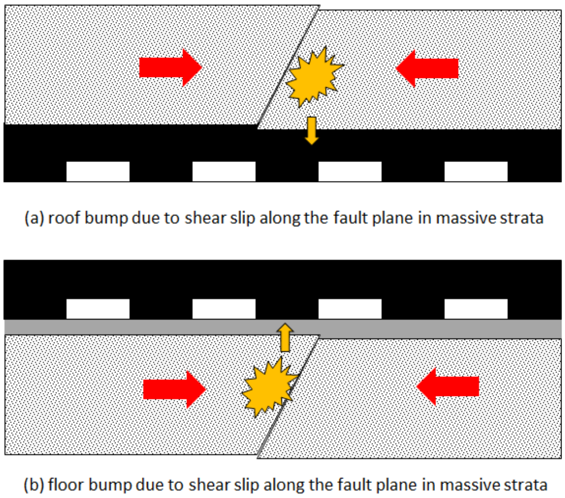

FIGURE 11: Schematic Illustration of Overburden and Floor Bumps Due to Horizontal Stress-Driven Shear Slip Along a Mid-Angled Fault Plane

Figure 10 shows the result of rib condition mapping on the under-hade side of a mid-angled fault plane under the action of a very high level of major horizontal stress that proved to be bump-prone (but not burst-prone) during roadway development. The substantial rib damage on the under-hade "weak" side as compared to the over-hade strong side, is self-evident, the logical conclusion being that both the bumps and deteriorated ribs were directly due to horizontal stress-driven shear slip on the under-hade side of the overlying mid-angled fault.

The combination of a mid-angled fault plane with a significant magnitude of horizontal stress acting perpendicular to the strike of the fault, may also give rise to the phenomenon of floor bumps, as the strong side of a mid-angled fault plane in the roof above the coal seam, is actually the weak side in the floor, as illustrated in Figure 11.

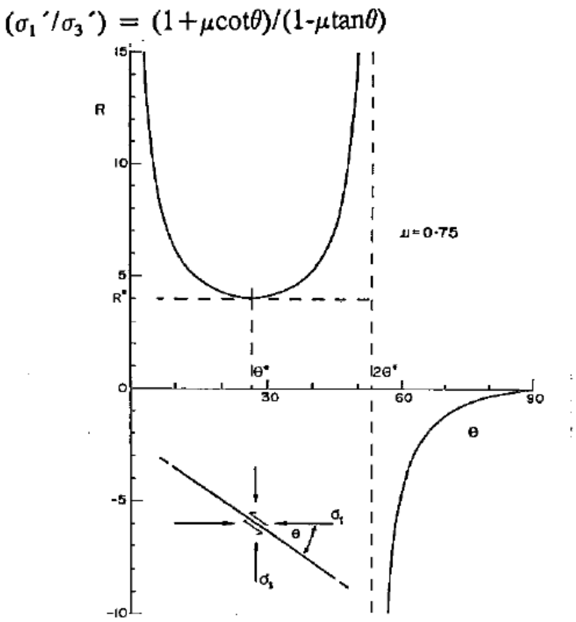

FIGURE 12: Stress Ratio (R) Required for Frictional Re-Activation (Hatherly *et al* 1993)

The same type of stress-driven shear slip analysis can also be undertaken on vertical fault systems by considering the alignment of the major horizontal stress with the strike of the fault plane and the friction acting along the plane, this being illustrated in Figure 12. The basic mechanism of horizontal-stress driven shear slip along a major fault plane is actually fundamental to the development coal burst model for Austar and Sunnyside mines outlined in Frith and Reed 2019, the reported experience from Sunnyside Mine being one of many substantial overburden bumps (as distinct from coal bursts) during active mining that resulted in noticeable offsetting of surface railway lines, this being interpreted as evidence of horizontal shear movement along pre-existing fault planes.

It is evident based on a theoretical treatment supported by mining experiences, that the major horizontal stress can, under certain circumstances, drive significant shear-slip events along major fault planes during active mining, resulting in substantial energy releases that manifest as reported overburden or floor bump events.

Multi-Seam Events

Mark 2017 describes two pillar burst events at the Manalapan 17 Mine in Kentucky, which are worth considering in the context of how multi-seam mining appears to be far more pillar-burst prone than virgin conditions. Cover depths involved were in the order of 510 m with the overlying seam being worked at the time of the pillar bursts being in the order of 50 m above the pre-existing lower seam workings. As an example of many such layout plans that have been viewed, Figure 13 contains the layout plan for the two separate incidents at the Manalapan 17 Mine.

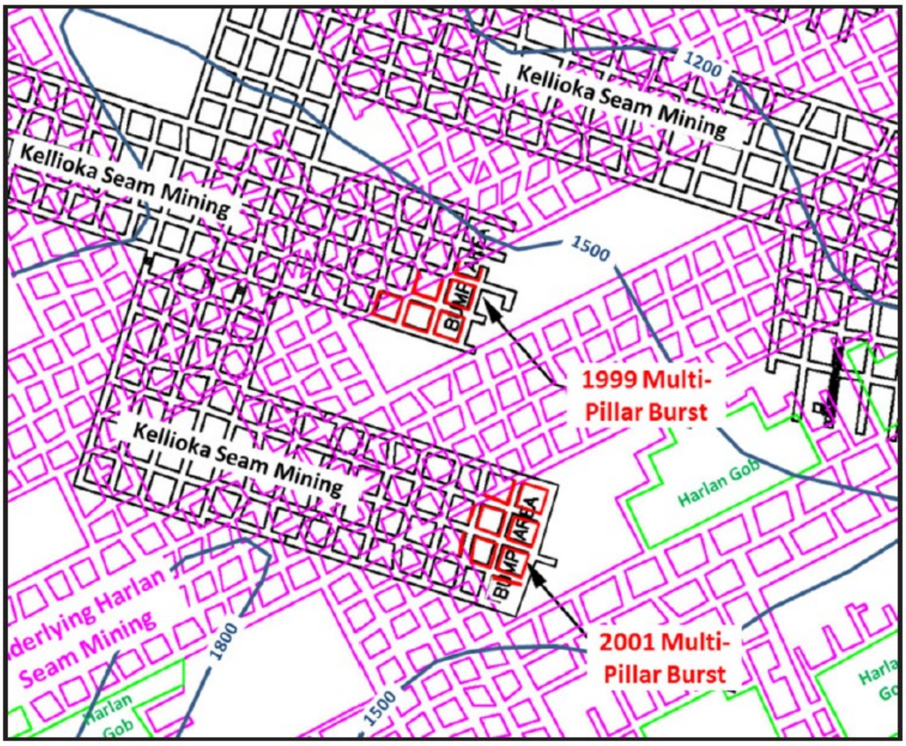

FIGURE 13: Locations of Burst Events in the Manalapan No. 17 Mine (Black) Relative to Underlying Harlan Seam Workings (magenta and green) – Mark 2017

For the purpose of this paper, only two observations need to be made, namely that:

(i) the areas of defined "burst" coal are above solid remnant pillars in the underlying seam, rather than areas of either standing production pillars or extraction. Therefore, given the technical discussion herein as to the various source mechanisms of overburden and/or floor bumps and with no major geological structures being identified in the direct vicinity, it is seemingly self-evident that the reported pillar bursts cannot be a direct consequence of any form of overburden bump event.

(ii) the cover depth involved is not extreme, as compared to coal mining in Germany for example at well in excess of 1000 m, which is understood is pre-dominantly coal-burst prone due to multi-seam mining effects rather than high cover depth in isolation.

The required mechanics for a large-scale pillar burst is beyond the scope of this paper, a detailed discussion being planned for publication in the near future, the critical role of low overburden stiffness and elevated pre-mining vertical stresses due to pre-existing mine workings, whether due to multi-seam effects or from within the same seam being considered in first-principles level detail.

SUMMARY

The paper has described several potential source-mechanisms for overburden bumps based on fundamental structural models and selected case-histories, all but one being directly linked to stress-driven shear-slip along pre-existing planes of weakness, this being entirely consistent with one of the well-stablished large-scale earthquake causation models. It has further demonstrated the hypothesis presented in **Frith and Reed 2019** that overburden bumps are mechanistically distinct from development coal-bursts, as per that which occurred at Austar in 2014, due to the location of the primary energy source (coal seam or overburden/floor) and the associated mechanism(s) of energy release.

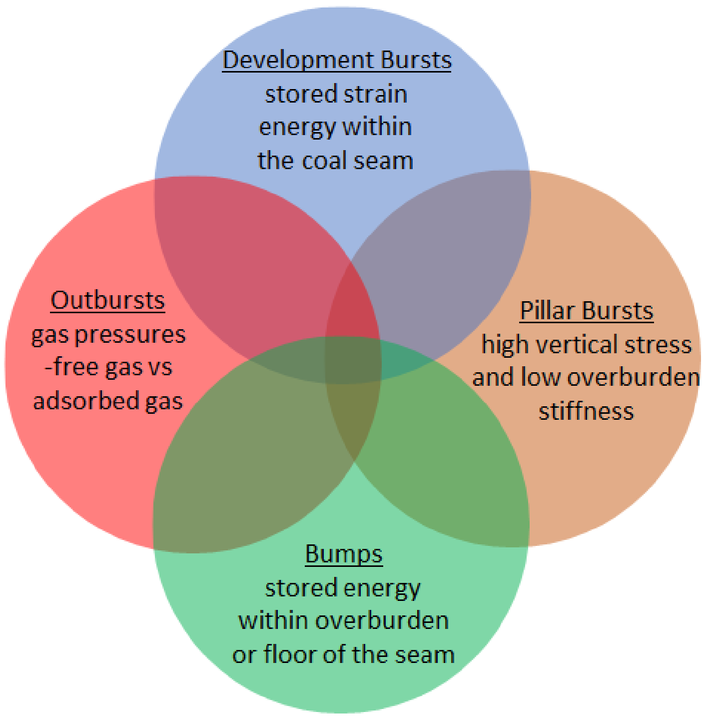

FIGURE 14: Suggested Classification of High Energy Release Events in Underground Coal Mining for 4 Fundamental Event Types

The paper has also briefly considered published case-histories for coal-pillar bursts, concluding that they cannot be directly explained by either the development coal burst or overburden bump causation models, hence there must be a further event-type to be identified and analysed, this to be the subject of a future technical paper. However, this does require that the Venn diagram representation of Figure 1 be updated to include four fundamentally different event types, as shown in Figure 14, the need to understand event-types in isolation from each other being even more critical than with only three in Figure 1.

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