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Xiaohan Yang
University of Wollongong

Ting Ren
University of Wollongong

Xuequi He
Univeristy of Science and Technology, Beijing

Lihai Tan
University of Wollongong

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A REVIEW OF ENERGY SOURCES OF COAL BURST IN AUSTRALIAN COALMINES

Xiaohan Yang[1], Ting Ren[2], Xueqiu He[3], Lihai Tan[4]

Abstract: Coal burst, which refers to the violent and catastrophic failure of coal, is a serious safety hazard for underground coalmines. Coal burst has attracted intensive research interest from mining and geological scholars. Due to the shallow mining depth, simple geological condition, advanced mining technology and reasonable geotechnical design, coal bursts has not been identified as a safety hazard in Australia coalmines as there are no documented coal bursts cases in Australia before 2014. However, more recently, the coal burst risk in Australian coalmines was highlighted by coal burst accidents in some coalmines. This paper reviewed the potential energy sources and their influence on past coal burst accidents in Australia. It is believed that the previous coal burst accidents in Australia are more likely to be the dynamic failure of highly stressed coal triggered by small-scale dynamic disturbance. Coal burst propensity index method and micro seismic monitoring technic are recommended to indicate coal burst risk before and during mining activities.

INTRODUCTION

Coal burst, which refers to the violent and catastrophic failure of coal in underground mining, has long been known as a safety hazard in coalmines of Poland, Russian, China and the U.S. (Dou *et al*, 2006b; Mark, 2017; Whyatt, 2008). Even after decades of extensive research made by international mining and geotechnical scholars, the increasing trend of coal burst frequency and severity appeared in these countries and has not been solved. Presumably due to the shallow mining depth, simple geological condition, advanced mining technology and reasonable geotechnical design, coal bursts has not been identified as a safety hazard in Australian coalmines as there is no documented coal burst cases in Australia before 2014. However, following the coal burst accidents that happened in some Australian coalmines, it is believed by mining researchers and engineers that Australian coalmines will face the safety hazards posed by coal bursts in the future (Yang *et al*, 2018a).

During the occurrence of a coal burst, massive stored elastic energy in the coal body will be rapidly released in the forms of noise, coal ejection and seismicity (Bieniawski *et al*, 1969). Intensive researches have been conducted to understand the energy sources of coal bursts. The increased static load resulting from high depth of cover was identified as an important energy source of coal burst by many researchers because of the positive correlation between coal burst frequency and mining depth (Dou and He, 2001). The study delivered by Zhao, *et al.*, (2017) illustrated that major geological structures, such as faults, folds, and coal seam thickness change, can cause the stress and energy concentration. In addition, the experimental result (Vardar O *et al*, 2017) and theoretical analysis (Yang *et al*, 2018a) indicated that surrounding rock stiffness is a dominant factor of energy flow between the coal seam and surrounding rock. The influence of dynamic load on the mechanical behaviour, elastic energy ratio and burst potential of coal had been studied by many researchers as well (Li *et al*, 2016; Okubo *et al*, 2006). The mining experience of the U.S. and China found that many coal burst cases are closely related to the dynamic load caused by seismicity events (Ge, 2005). Hence,

[1] *PhD Candidate, University of Wollongong. Email: xy987@uowmail.edu.au Tel: 0484557784*
[2] *Associate Professor, University of Wollongong. Email: tren@uow.edu.au Tel: 0242214186*
[3] *Professor, University of Science and Technology Beijing. Email: hexq@uow.edu.au Tel: +861062333758*
[4] *PhD candidate, University of Wollongong. Email: lt716@uowmail.edu.au Tel: 0434977792*

the existence of dynamic load in coalmines can encourage the formation of coal burst by providing additional seismic energy.

To better explain the formation of coal burst, Dou, *et al*., (2015) proposed the static and dynamic load superposition theory to illustrate the energy sources of coal burst. As shown in Figure 1, coal burst will occur when the sum of static and dynamic load exceeds the minimum load required for coal burst formation. It also has been widely accepted by other researchers that, in most cases, the dissipated energy of coal burst is provided by the combination of static and dynamic load (Linkov, 1996; Whyatt *et al*, 1900). However, the study on the relationship between coal burst accident happened on 2014 and seismic event in New South Wales delivered by Ahn, *et al*,. (2017) found no clear correlation between seismic events and mining activities, which means dynamic load, or at least seismic events, may not be an important factor for coal burst formation in Australia. This finding is not a general rule as it is just the result based on the coal bursts case that happened in 2014. Further study needs to be conducted to figure out the energy sources of coal bursts in Australia as four more coal burst accidents happened in 2016 and 2018. The aim of this paper is providing a better understanding of the energy sources of coal burst in Australian coalmines. The reminder of this paper reviews the possible energy sources of coal bursts and its potential influence in Australian coalmines the formation of coal bursts.

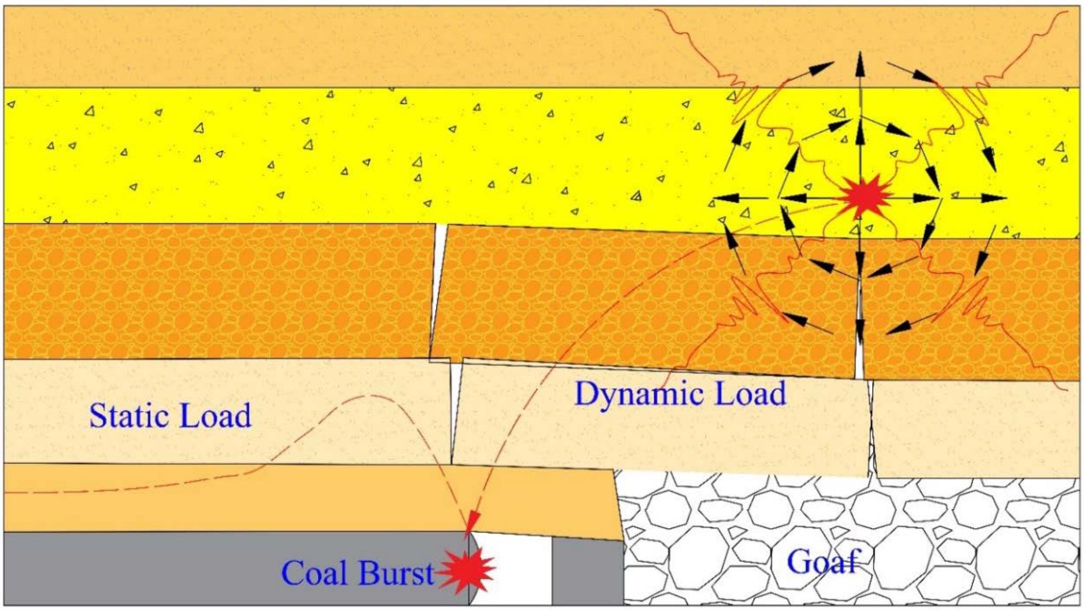

Figure 1: Coal burst induced by static and dynamic load superposition (Wang *et al*, 2016)

STATIC LOAD

Mining depth

Mining depth has been identified as an important factor for the formation of coal burst. According to the analysis of coal burst cases in Poland and China, Dou, *et al*., (2006b) found that the first coal burst accident in coalmines generally happened when mining depth approaches 350m and the frequency and severity of coal bursts sharply increased with mining depth changing from 350 to 600m. Some scholars found that nearly all coal burst accidents in the main coalfields of the U.S. occurred at depths greater than 300m, and most were in exceed of 400m (Mark, 2016). The contribution of mining depth to coal bursts mainly result from the increasing gravitational stress. More strain energy will be stored in coal under high gravitational stress condition (Dou and He, 2001). Besides, for coalmines in China and the U.S., hard sandstone roof seems the common geological feature for deep mining, which can further result in a large accumulation of energy or a catastrophic dynamic load (Agapito and Goodrich, 1999; Yang *et al*, 2018a). The potential influence of hard roof (roof stiffness) also will be discussed in other section of this paper. The mining depth of two coalmines with coal burst accidents in Australia are around 500m (Mine Safety, 2016). Hence, the strain energy accumulation leaded by high gravitational stress plays an important role in the formation of coal burst accidents in Australia as the mining depth of the coalmines is already beyond the mining depth of the majority of burst accidents revealed by international research.

More seriously, almost all coalmines in Australia have plans for deeper mining, which means the stress environments will be more complicated and more energy will be stored in coal seams (Zhang *et al*, 2017).

Geological structures

It has been shown by numerous studies that the complicated geological structures caused by folds, faults and coal seam thickness variation have a noticeable influence on the coal burst occurrence (Iannacchione and Tadolini, 2016). Dou and He, *et al*., (2001) found that 72% of coal burst accidents in Longfeng Colliery were related to faults. The numerical study conducted by Chen, *et al*., (2012) found that stress will concentrate near the coal face when the coal face approaches a fault. Mark (2017) found that coal burst accidents in the U.S have close relationship with faults. Folds, which are created by compressional tectonic stress, may have high residual tectonic stress in the geological structures. Through the stress regression analysis of Huanghuiyan Colliery, Jiang, *et al*., (2018) found that stress concentration tends to exit at the area near the syncline axis. The influence of geological structures on stress distribution is shown in Figure 2.

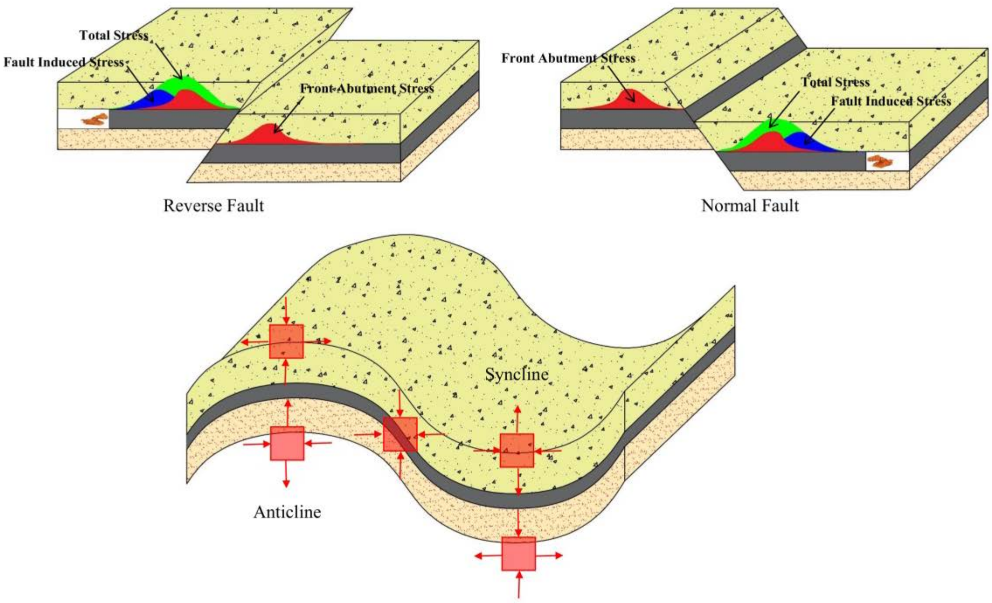

Figure 2: Stress concentration caused by geological structures

Compared with the condition of other chief coal mining countries such as China, the U.S. and Canada, most of the coalmines in Australia are in coal seams with sample geological conditions and covered by gentle and order sedimentary basins. However, evidence shows that complicated geological structures are involved in the coal burst occurrences in Australia as well. According to the investigation reports published by NSW Department of Industry, two coal burst accidents that happened in 2014 and 2016 are both in faulted zones (Bruce and Jim, 2017; Mine Safety, 2016). Besides, as shown in Fig.3, these two coal burst accidents also happened in the area with many large faults. The coal burst accidents that happened on 2

February 2018 and 17 May 2018 are also relevant to the geological problems caused by faults. The latest coal burst accidents occurred in the Bulli seam. In general, as shown in Figure 3, faults are not intense in the Bulli seam while this seam is often associated with folds and the regional geological structure of this seam is a broad syncline (Hutton, 2009). Bulli seam in the area where coal bursts occurred is under bad roof conditions caused by orthogonal joints (Brook, 2016).

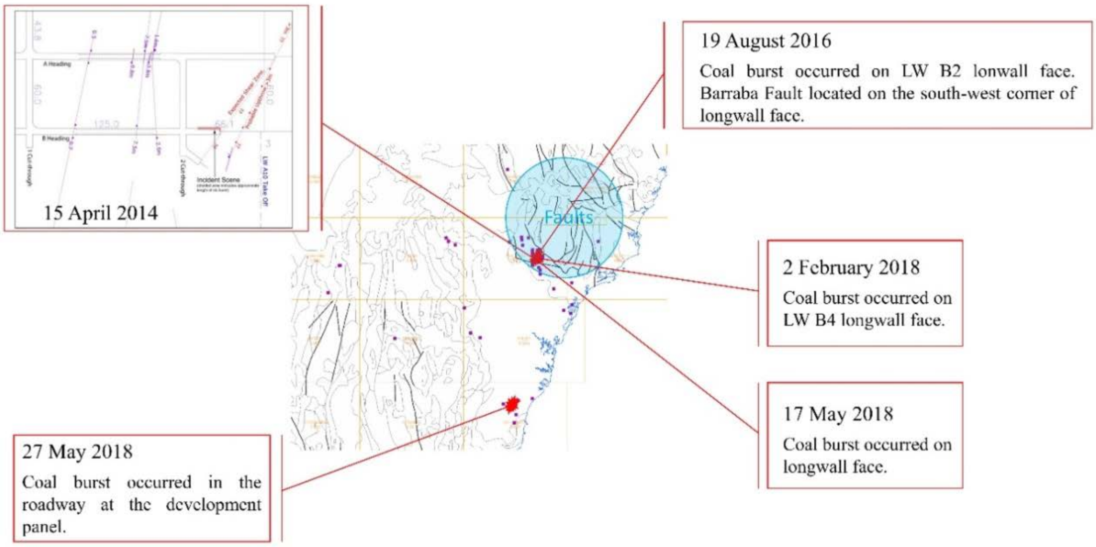

Figure 3: Structural geology of coal burst sites (Bruce and Jim, 2017)

Surrounding rocks stiffness

Stiffness of the surrounding rocks is one of the main factors giving rise to coal burst. Bieniawski found that rock samples are more prone to violent failure under the high stiffness loading machine. The uniaxial compression tests of samples composed of coal and rock found that most elastic energy is stored in the coal part of the compound sample and burst potential of the sample is positively related to the thickness of rock part (Dou *et al*, 2006a; Huang and Liu, 2013). Through theoretical analysis, Yang, *et al*,. (2018a) found that energy will flow from high stiffness material to low stiffness material. Hence, high stiffness of surrounding rocks will enhance the energy accumulation in coal seams. In addition, as shown in Figure 4, the strength of coal tends to rapidly decrease under a high stiffness environment (Vardar *et al*, 2017). Generally, the high stiffness environment is related to the heavy and hard sandstone layer above the coal seam (Whyatt, 2008). Sometimes, the thickness of the sandstone layer can reach tens or even hundreds of meters (Dou and He, 2001).

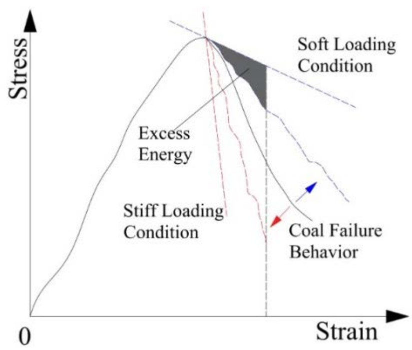

Figure 4: Effect of stiffness of the loading system on the behavior of coal failure (Yang *et al*, 2018a)

As shown in Figure 5, the Branxton Formation, which generally consists of more than 400 meters thick sandstone and conglomerate units, is described as strong and massive roof above the Greta seam (Mine Safety, 2016). The existence of high stiffness roof is a potential factor that can cause massive elastic energy accmalation in Greta seam. However, the Bulli seam in Illawara Measures, which is the coal seam mined at Southern coalfield, is under a weak and highly jointed roof. Hence, there may be no roof above Bulli seam as thick and hard as the Branxton Formation.

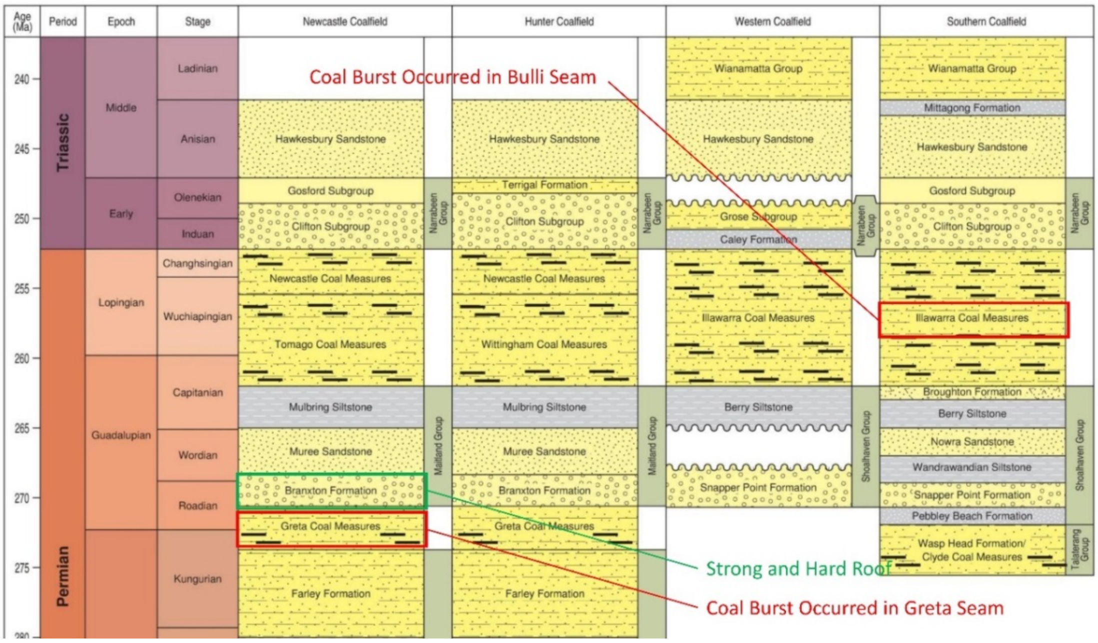

Figure 5: Generalized stratigraphic column for the geological Sydney Basin (Herron *et al*, 2018)

DYNAMIC LOAD

Earthquake

Earthquake, refers to the large-scale seismic events. If they happened in or near coalmines, they can result in a rapid accumulation of seismic energy in coal by applying dynamic stress transferred by vibration waves. Generally, an earthquake is caused by geobody instabilities related to mining activities such as fault slipping and breakage of overburden strata. In 2007, seismic event with local magnitude ML=3.9 occurred in Crandall Canyon coal mine, Utah and the seismic wave was recorded by earthquake monitoring stations operated by the United States Geological Survey (USGS), the University of Utah, and EarthScope (Ford *et al*, 2008). Powerful seismic events related to copper mining activities have been detected in Poland (Lizurek *et al*, 2015). As the largest coal producing country around the world, China has more than 80 reported mining induced earthquake records and the magnitude of most earthquake is around 3 ML (Li *et al*, 2007). The mine earthquakes that happened at Lander and Hector even reached magnitude 7.3 and 7.1, respectively (Gomberg *et al*, 2001).

After the first coal burst accidents happened in 2014, Ahn, *et al,*. (2017) analysed the seismic events that occurred within the New South Wales mining regions from June 2006 to June 2016 and found no clear correlation between coal bursts and the past-recorded seismic events. Geoscience Australia, a preeminent geoscience organization supported by Australian government, operates a high-quality seismograph network that provides ongoing coverage for locating and recording earthquakes that occur within Australia. Using the earthquake monitoring data published by Geoscience Australia, the seismic events that occurred near coal burst spots from March 2014 to June 2018 are drawn in Figure 6. It is clearly illustrated by the seismic data that there were no monitored seismic events near coal burst spots before and after the coal burst accidents. Hence, there was no large-scale mining induced earthquake in mining area when coal bursts were happening.

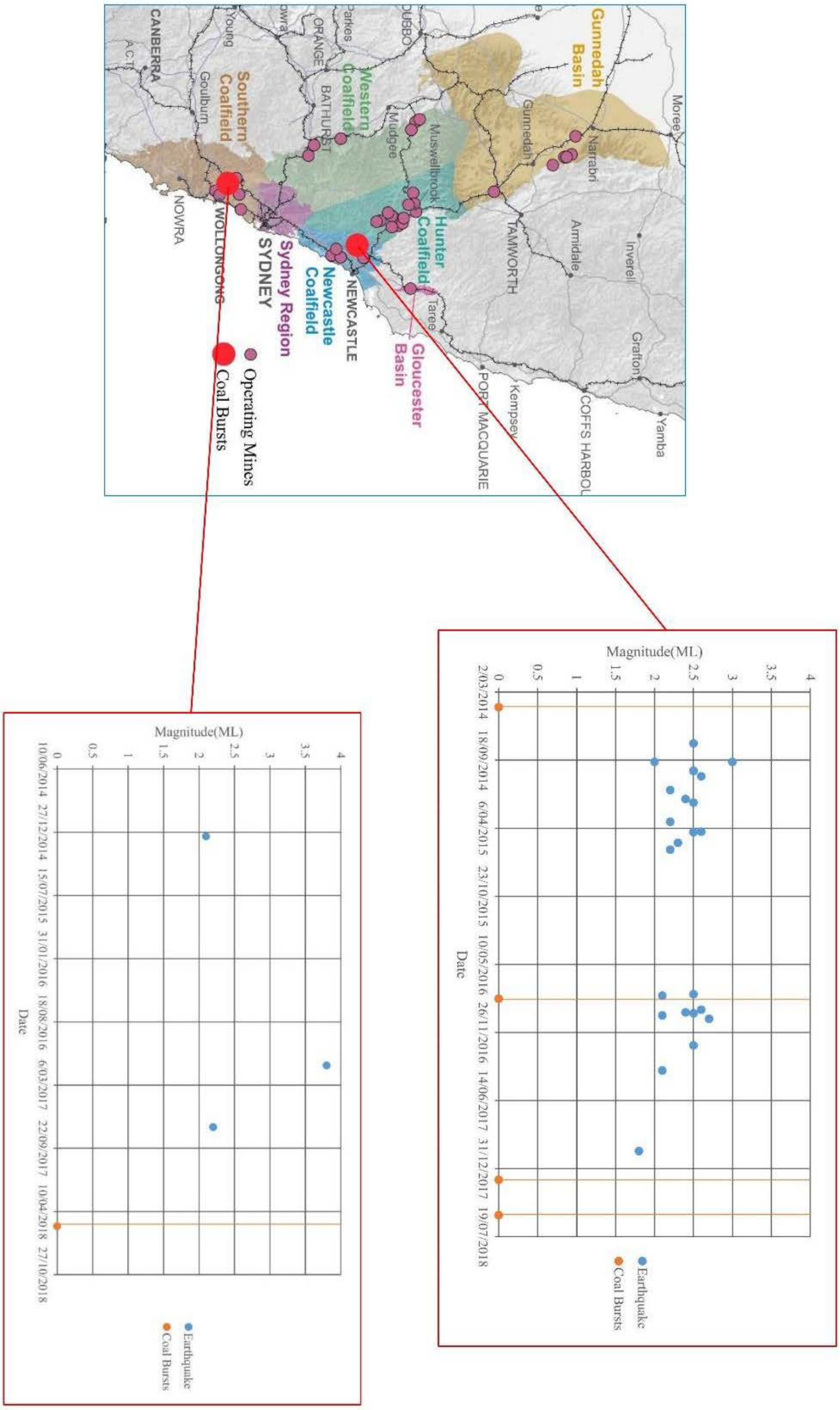

Figure 6: Seismic events occurred near coal burst spots in recent years

Micro seismicity

Micro seismicity refers to the regional small-scale seismic events which are undetectable by earthquake monitoring station due to their small-scale energy compared with earthquakes. However, for underground coalmines, the energy released by micro seismicity is an important energy source for coal burst formation. Intensive micro seimicity has been observed in most of coalmines with high burst risk in Poland, China and the U.S. (Hallo, 2012; Leśniak and Isakow, 2009; Li *et al*, 2018). Micro seimicity can be detected and located by specific micro seismic monitoring apparatus. Deep research has been made by many researchers on the monitoring of dynamic load and identifying high burst potential areas through micro seismic monitoring (Amitrano *et al*, 2010; Ge, 2005; 2010). In 2013, CSIRO established a micro seismic monitoring system at the 2014 coal burst spot to monitor the longwall weighting. The field monitoring results clearly demonstrated the effectiveness of micro seismic monitoring to infer longwall caving and weighting events (Shen *et al*, 2013). However, most of the micro seismic events recorded by geophones were weak.

DISCUSSIONS

The coal bursts that have occurred in Australia possess the general features of coal burst including high mining depth, complicated geological structures or massive roof strata mentioned by Poland, China and the U.S. researchers as well. However, strong dynamic load does not seem to be a factor which leads to coal burst in Australia as there are no reported mining induced seismic events or strong seismic events sensd by mining workers. Coal burst propensity index method, a widely adopted risk evaluation method of coal burst in Russian, China and the U.S., can indicate the coal burst risk from the aspect of energy accumulation and dissipation. The detailed introduction of this method can be found in literature (Yang *et al*, 2018b). As shown in Figure 7, the coal burst propensity index test conducted by Yang, *et al*,. (2018b) also found that the elastic energy storage ability of Australian coal seam with high burst potential is typically high. There is no record of a coal burst happening in Australian coalmines with shallow depth, which also indicates that there is no dynamic load strong enough to trigger coal burst in these coalmines. Dou divided coal bursts into two types including strong dynamic load type (coal is under low static load but coal burst can be induced by strong dynamic load) and high static load type (coal is under high static load while small dynamic disturbance can leads to coal burst) (Dou *et al*, 2015). As analysis above, it is believed that most of the energy released during coal burst accidents that happenned in Australia is provided by high static load. That is, the coal bursts happening in Australia are more likely to be of the high static load type. Hence, the coal burst controlling measures involving blasting operations may not be suitable for Australian coalmines as the further dynamic disturbance caused by blasting may trigger the instability of coal. For other coalmines with great depth, high stiffness strata, and complicated geological structures, the coal burst may be easily trigered by small-scale dynamic load if massive energy has been stored in the coal. The elastic energy storage ability of coal is a dominant factor of coal burst formation. Hence, the coal burst propensity index method can be an effective way to evaluate the burst risk of coalmines as this method can indicate the energy storage ability of coal (Yang *et al*, 2018b). Micro seismic monitoring is also a useful geotechnical tool to indicate coal burst risk by the real-time monitoring and locating of seismic wave released by small-scale dynamic load.

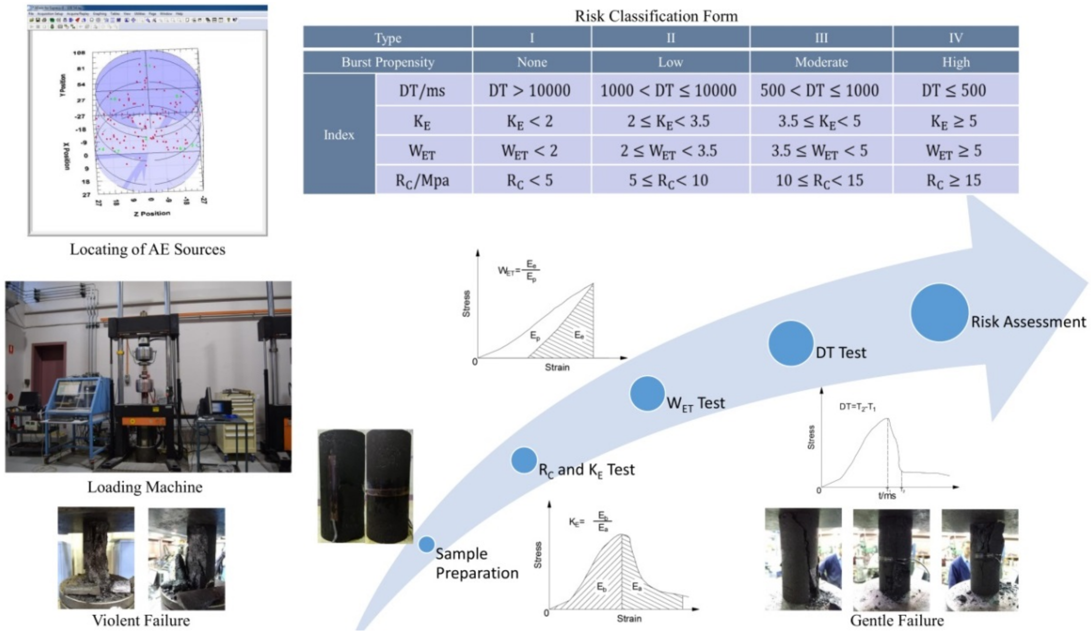

Figure 7: Coal burst risk evaluation with coal burst propensity index

CONCLUSIONS

This paper reviewed the potential energy sources and their influence on coal burst formation of past coal burst accidents that occurred in Australia. Based on the analysis above, the following conclusions can be drawn:

1. High mining depth and complicated geological structures are the common features for coalmines with coal burst history in Australia. According to international experience, these factors can result in stress and strain energy concentration in coal. Hence, coal burst propensity index is recommended to be adopted as a coal burst risk evaluation method for these coalmines.

2. There is heavy and massive strata above the Greta seam while the roof of the Bulli seam is weak and poor. High stiffness roof is one of the potential factors which can cause elastic energy accumulation of the Greta seam. But the strong roof may not be a source of strong dynamic load as there is no reported seismic events related to roof weighting.

3. The coal bursts that happened in Australian coalmines are more likely to be the failure of highly stressed coal triggered by small-scale dynamic loads. In this circumstance, micro seismic monitoring should be considered as a geotechnical tool to indicate coal burst risk by real-time monitoring and locating of small-scale dynamic loads.

However, this is the preliminary conclusion with limited geological and geophysical information. A more quantitative analysis can be conducted with detailed geological mapping and sufficient micro seismic monitoring data around the coal burst sites.

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