

## Review Article

# Analysis of the Coal and Gas Outburst Mechanism from the Perspective of Tectonic Movement

Qingyi Tu,<sup>1,2,3</sup> Yuanping Cheng ,<sup>2</sup> Sheng Xue,<sup>1</sup> Ting Ren,<sup>3</sup> and Xiang Cheng <sup>1</sup>

<sup>1</sup>State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines, Anhui University of Science and Technology, Huainan 232001, China

<sup>2</sup>Faculty of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China

<sup>3</sup>School of Civil, Mining & Environmental Engineering, University of Wollongong, NSW 2522, Australia

Correspondence should be addressed to Yuanping Cheng; [ypccumt2015@outlook.com](mailto:ypccumt2015@outlook.com)

Received 9 March 2021; Accepted 15 June 2021; Published 5 July 2021

Academic Editor: Guozhong Hu

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Coal and gas outburst is the extreme instability caused by stress, gas, and coal. In this review article, dominant factors and inducing factors of outburst were summarized; geologic features of typical outburst cases and the effects of tectonic movement on outbursts were analyzed; the outburst stages with considerations to geologic factors were divided. It was found that inducing factors, including buried depth, tectonic movement, gas composition, coal seam conditions, overlying/underlying rock conditions, and mining mode, control the outburst by influencing the dominant factors (stress, gas, and coal). Among them, tectonic movement is the key of outburst. Influenced by tectonic movement, the primary structure of coals is damaged/pulverized due to the tectonic stress and unique tectonic mode, resulting in the formation of tectonic coals. When external dynamic factors are changed, tectonic coals are crucial to outburst control for its evolution of porous structure as well as the unique mechanical behaviors and gas flowing responses. Besides, the preparation stage of outburst includes the tectonic process and mining process. The former one refers to the restructuring process of the original coal-bearing strata by tectonic movement, while the mining process is the prerequisite of outburst and it refers to the disturbance of human mining activities to the initial coal seams. It is suggested that more work is required on geological factors of outburst, and a few research areas are proposed for future research.

## 1. Introduction

Coal and gas outbursts (hereinafter referred to as outbursts) are a kind of sudden dynamic disaster in underground coal mines which have complicated processes [1, 2]. Since the catastrophe process is accompanied by considerable failure effect, outbursts are a great threat to safety exploitation of coal resources, thus becoming a wide concern around the world [3]. In particular, outbursts during coal mining in China are more serious, which is determined by the extremely complicated occurrence environment of coal resources in China [4]. Meanwhile, high-intensity exploitation (>30 billion tons) over years leads to gradual exhaustion of shallow coal resources, thus increasing the coal mining depth year by year [5]. Increasing mining depth implies the continuous worsening of coal mining environment. Coal mining is going to face with a series of challenges, such as

more complicated tectonic movements, high gas, high ground stress, low strength, and low-permeability coal mass. Therefore, studying the basic theory and control technology of coal and gas outbursts is still one of the important links in safety production of coal mines [6, 7].

Due to the complicated mechanism of outbursts, mechanisms of outbursts under different geological conditions are difficult to be explained by the uniform theory. Many studies have summarized the mechanism of outbursts as the collaborative consequence of stress, gas, and properties of coals [8, 9]. Moreover, the process of outbursts is divided into the outburst preparation stage, sudden instability stage of coal mass, continuous instability development stage toward deep coal mass, coal transportation stage in the mining space, and outburst termination stage [10, 11]. In addition, many studies focus on the role of stress and gas in coal instability, continuous instability development, and coal transportation

[11–13] but pay few attentions to the effect of properties of coals on the outburst process, especially on outburst preparation, continuous instability, and coal transportation. Nevertheless, many cases of outbursts have demonstrated that most outburst accidents occur in tectonic zones (e.g., fault, fold, and overthrusting tectonics), which is attributed to the following reasons. These tectonic zones change the stress and gas environment in coal seams [2, 14–16]. More importantly, tectonic zones alter microstructures (e.g., matrix, pore, and fracture) of coal, thus changing properties of coals. Influenced by tectonic movements, soft and highly crushed tectonic coals are observed in many fields of outburst accidents [14].

Under one-stage or multistage tectonic movements, the primary structure of coals develops different degrees of embrittlement, crushing or ductile deformation, or overlying failure, thus leading to the sharp reduction of matrix size of coals and even causing changes in internal chemical composition and structure [17]. As a result, tectonic coals are formed. Moreover, a small-sized matrix of tectonic coals undergoes the secondary shaping under the effect of ground stress, forming polymeric tectonic coals [18]. Tectonic coals are compacted under the in situ stress state, manifested by high closure of the fracture-pore system and extremely low permeability of coals [14]. According to field statistical data, permeability of tectonic coals in typical tectonic coal mines of China is lower than 0.1 mD [14, 19–21]. Such low-permeability coal mass restricts gas flow in coal seams, thus resulting in uneven distribution of gases and local gas enrichment in coal seams [22]. Nevertheless, tectonic coals show extremely weak antidisturbance, and their mechanical behaviors and gas flow become unique upon changes of external factors. Under this circumstance, tectonic coals are extremely easy to be crushed into abundant scattered small particles, in which gas is released at extremely high speeds [23].

Existing studies on geologic causes of outbursts mainly focus on statistical analysis of cases. However, it lacks a systematic study on the changes of the ground stress field and gas field in the original coal-bearing stratum caused by tectonic movements and the physical and chemical changes that coals have undergone under the effect of tectonic movement to form tectonic coals.

In this study, relevant factors were summarized and analyzed systematically. The specific topics reviewed in this study include the following:

- (1) Dominant factors and inducing factors of coal and gas outbursts as well as relations of these causes
- (2) Geologic features of typical outburst cases and the effects of tectonic movement on outbursts
- (3) Reconstruction of the stress field, gas field, and coal structure of the original coal seams caused by tectonic movement
- (4) The outburst process and stage division with considerations to geologic factors

At last, discussion on the current research status and future research areas is performed.

## 2. Key Factors of Coal and Gas Outbursts

*2.1. Dominant Factors of Coal and Gas Outbursts.* Due to complexity and variability of outburst, there are many influencing factors of outbursts. Moreover, influencing factors vary for different outburst cases. However, studies over years demonstrate that there are three dominant factors of outburst, namely, stress, coal seam gas, and properties of coals.

*2.1.1. Stress.* Most outbursts occur at ends of roadways or working faces, where there are mining disturbances and prevalent stress concentration [16]. Stress is the power and energy source of coal/rock failure in the outburst process. Stress participates in preparation, triggering, and development stages of outbursts [9, 11]. In the preparation stage of outburst, stress (tectonic stress) is the dominant factor that determines the occurrence state of coal seams, and it is also an important influencing factor of gas occurrence in coal seams [24, 25]. In the triggering stage of outbursts, it is generally necessary to damage rock pillar/coal pillar in front of outburst coals, which is caused by stresses [26]. In addition, damage of outburst coals before separation in the development stage is also mainly attributed to the dominant role of stress [11, 27]. Therefore, the risk of outbursts is increased significantly in some regions with abnormal stresses or in high-stress environment in the deep mining stage.

Stress which dominates the outburst includes not only in situ stress of the coal seam but also disturbed stress. Specifically, in situ stress is the collaborative consequence of tectonic stress, gravity or thermal effect, and residual stress of tectonic effect [28]. These components cannot be distinguished independently during practical measurement of in situ stress. Disturbed stress involves additional stress caused by mining activities (e.g., vibration and blasting). More importantly, the stress balance of primary rocks is broken by mining activities, thus resulting in stress transfer and forming stress concentration [29].

According to the literature review, the stress state at any point in underground coals and rocks can be determined by three principal stresses, and there are two principal stresses on or close to the horizontal plane in most regions [30]. Besides, the maximum horizontal principal stress in shallow strata is generally higher than the vertical stress, which is attributed to the control of tectonic stress. Liu et al. [30] carried out a statistical analysis on in situ stress in coal seams in 74 formations in the Huanan Coal Mine in the buried depth of 350–1100 m. The maximum principal stresses of 59 formations were on the horizontal plane, but maximum principal stresses of only 15 formations were on the vertical plane, and the measuring points with the maximum horizontal stress higher than the vertical stress accounted for 79.7%. Obviously, in situ stress of coal seams in the Huainan Coal Mine is controlled by tectonic stress significantly.

Li et al. [31] measured in situ stress (buried depth: 230–424 m) of coal seams surrounding the Mafangquan fault in the Julishan Coal Mine, Jiaozuo Mine. They found that the maximum and minimum principal stresses at 5 measuring points were 12.4–18.3 MPa and 4.9–9.2 MPa, respectively. The maximum and minimum principal stresses at all

measuring points were nearly horizontal, while the middle principal stress was nearly vertical. Due to the existence of the Mafangquan fault, the direction of in situ stress was changed. Specifically, the maximum principal stress far away from the fault zone was NNW-strike, while the maximum principal stress near the fault turned to NS-strike. Besides, Han et al. [32] measured in situ stress of coal seams in several typical outburst mine areas in China through the stress relief method and found that the maximum and minimum principal stresses were on the horizontal plane, but middle stress was on the vertical plane. The maximum and minimum principal stresses in these mining areas were significantly higher than those in other mining areas, and the tectonic stress in these mining areas was remarkable. Hence, the control effect of tectonic stress on outbursts cannot be ignored under current coal mining depth.

Moreover, the initial balance state of in situ stress is broken due to the sudden unloading on one direction and disturbed stress on other directions caused by mining activities [33]. However, these stresses do not disappear but transfer to coals/rocks in front of the exposed surface, thus causing redistribution of the stress state on coals/rocks [34]. Generally, redistribution of stress shows two different laws along the mining direction (radial) and perpendicular to mining direction (tangential) [35]. Firstly, stress along the horizontal mining direction (radial) increases from 0 to the original state gradually. Secondly, stress perpendicular to the mining direction (tangential) transfers inward from the exposed surface, and a stress concentration occurs at a position in front of the exposed surface. Such stress distribution mode, composed of radial stress unloading and tangential stress concentration in coals/rocks in front of the exposed surface, favors the coal/rock damage, which is also vital to the occurrence of outbursts [36].

*2.1.2. Coal Seam Gas.* As another power and energy source of outbursts, coal seam gas (hereinafter referred to as gas) is also crucial to the occurrence of outbursts. Effects of gas on outbursts are manifested by two aspects. Firstly, gas can change mechanical properties of coals and participates in mechanical failure of coal masses [37, 38]. Secondly, gas provides power to the transportation of outburst coals/rocks, which is one of the requirements for continuous development of outbursts [39–41]. Generally, gas which participates in outbursts is divided into free gas and adsorbed gas. The former one exists in coal fractures and large pore spaces as free phases, while the latter one is adsorbed onto the pore space surface of coals [42, 43]. Due to different occurrence states of free gas and adsorbed gas in coals, the complexity of their participation mode and processes in outbursts varies significantly, thus making it greatly difficult to determine their proportions in outbursts [44, 45].

Free gas participates in outbursts through expansion energy and decreasing effective stress of coal mass [46]. Free gas changes mechanical properties of coals since it decreases effective stress of coal mass, which can be explained by Terzaghi effective stress laws [47]. With the increase in free gas pressure, effective stress of coal mass decreases gradually, thus decreasing confined pressure of coal mass and thereby weakening mechanical strength of the coal [48].

According to literatures [49, 50], free gas in fractures and large pore spaces makes expansion energy immediately once pressure of external gas declines. However, there is still dispute over whether the expansion process of the free gas is an adiabatic process or an isothermal process [42]. Scholars who agree that the expansion process is an adiabatic process pointed out that outbursts occur in a very short period, during which heat exchange between coal-gas and external world is very rare. Hence, the outburst process can be viewed as an adiabatic process [51]. Scholars who advocate the isothermal process deemed that heat exchange in the outburst process cannot be ignored since the heat exchange area between coal-gas and external world is large, but temperature changes of coals and gas in this process can be ignored [52]. At present, most scholars accept that the expansion energy is an adiabatic process and the theoretical formula of swelling energy of gas has been deduced.

The participation mode and process of adsorbed gas in outbursts are more complicated than those of free gas [53]. Some stated that adsorbed gas decreases the surface energy of coal mass, thus changing mechanical properties of coals [38]. The gas adsorption on coals is essentially attributed to surface energy of coals. The gas adsorption is a process that coals change from an unstable state to a stable state, during which surface energy of coals is decreasing gradually [54, 55]. According to the crack growth theory of Griffith, the critical stress for crack expansion declines with the reduction of surface energy, thus decreasing mechanical strength of coals [56, 57].

Moreover, the prerequisite for adsorbed gas to participate in outburst is that adsorbed gas is transformed to free gas quickly during the occurrence of outburst. The participation process of adsorbed gas in outburst involves three stages: desorption of adsorbed gas from the pore surface, diffusion of gas in pores, and gas seepage in the fracture system [41]. These three stages are controlled by different influencing factors, and correlations among these factors are very complicated [58, 59]. Hence, it is very difficult to determine practical amount of adsorbed gas participating in outbursts. Nevertheless, some scholars have concluded that adsorbed gas makes remarkable contributions to outbursts, and it is an important energy source of outbursts [53, 60]. Sobczyk [61] carried out a simulation test of outbursts based on  $N_2$  and  $CO_2$  which have different adsorbability. He found that  $CO_2$  with the stronger adsorbability could induce outbursts under a relatively low gas pressure and the outburst duration in the  $CO_2$  test was longer than that in the  $N_2$  test under the same gas pressure. Test results reflected the effects of adsorbed gas on critical condition and strength of outbursts intuitively. Gale [60] believed that adsorbed gas in coals contained a lot of outburst potentials, but the amount of adsorbed gas which could be released to participate in outbursts was determined by a series of factors. From the perspective of energy transformation of outbursts, Zhao et al. [41] found that limited free gas was inadequate to meet energy demands for outbursts and rapid desorption of adsorbed gas in a short period was an essential condition for continuous development of outbursts. They also found that in the Zhongliangshan outburst, the adsorbed gas had

to supply about  $5.61 \times 10^8$  J expansion gases for transportation of outburst coals/rocks, which was nearly 6.3 times of energies that free gas could provide.

With respect to gas participation in damage of outburst coals, some study has pointed that gas dominates tensile fracture of coal masses in the outburst process [62, 63]. Based on an outburst simulation test and theoretical calculation, Shi Ping et al. believed that sudden reduction of gas pressure on exposed surface may cause gas seepage in the side coals, forming a gas pressure gradient and generating a tensile stress to destroy coal mass [62]. Ding et al. [62] found that initial failure and continuous failure of coals were mainly caused by seepage of free gas. Hu [9] pointed out that there is a great gas pressure gradient near the exposed surface after sudden exposure of coals, which was related to the gas flow in coal pores and fractures. Such gas pressure gradient would generate a drag force to coals, so that coal powders which were not bonded with the coal matrix tightly would be brought out of coals along the gas flowing path. Additionally, some studies mentioned that crushed coals would be further smashed by the expansion energy of desorbed gas during transportation, which, however, lacks more detailed studies [64].

*2.1.3. Properties of Coals.* As the main carrier of coal and gas outbursts, coal is the acting object of all outburst energies [45]. Therefore, the importance of properties of coals in outbursts is beyond doubt. Properties of coals are also one of dominant factors that control outbursts. Nevertheless, there are a lot of properties of coals. According to literatures [2, 65], mechanical properties, pore structural features, and gas occurrence/flow characteristics of coals are major control factors of outbursts.

Mechanical properties of coal are important features that determine the risk of coal outbursts. Mechanical strength and failure mode of coals are major parameters that influence outbursts [1]. However, physical properties (e.g., elasticity, plasticity, brittleness, and creep properties) vary significantly in different coals due to the structural differences of coals. Moreover, mechanical strength also is significantly different among different coals [66]. According to literature records, an in situ strength test and laboratory strength test are the main testing method of mechanical strength of coals at present [67, 68]. According to test results, uniaxial mechanical strength of tectonic coals with reconstruction structure is generally lower than 3 MPa [69–72], but the uniaxial compressive strength of intact coals with relatively complete structure is higher than 10 MPa [68, 73, 74]. [65] pointed out that the width of the stress releasing zone in front of the exposed surface increases with the decrease in coal strength when advancing into the roadway. On the one hand, widening the stress releasing zone could increase the resistance of outbursts. On the other hand, it could lead to rapid releasing of adsorbed gas. However, rapid releasing of adsorbed gas often occupied the dominant role in the occurrence of outbursts, thus resulting in extremely high risk of outbursts in the soft coal seams.

Moreover, macroscopic morphological differences after the failure also influenced outburst risks of coals. The mechanical strength of intact coals is generally high, accom-

panied by strong brittleness [75, 76]. Hence, intact coals mainly develop shear failure along to a certain angle of shear fracture along the native weak surface. The lumpiness of broken blocks is relatively large [75, 76]. Nevertheless, tectonic coals show strong plasticity under high confined pressure and damage expansion after failure, and tectonic coals are extremely easy to be broken into abundant pieces with small size [69, 77]. Therefore, tectonic coals are extremely easy to be broken during the occurrence of outbursts, and broken tectonic coals are easier to release adsorbed gas quickly [69, 77]. The existence of tectonic coals can decrease conditions for the occurrence and development of outbursts.

As a complicated porous medium, coal not only contains a great deal of micropores to provide a large specific surface area for gas adsorption but also has big pores and microcracks as channels for flowing of gases in coal seams [78]. The formation process, occurrence environment, and experienced tectonic movements all vary among different coals, thus resulting in different pore sizes and morphologies [17, 79–81]. It has been proven by literatures that pore structure of coals has different variation laws due to influences by metamorphism and tectonic effects [82–84]. According to pore classification standards proposed by IUPAC, volume and specific surface areas of big pores and mesoporous in coals are generally “high at ends and low in middle” with changes of vitrinite reflectance [84–89]. Besides, volume of larger pores in coals increases significantly under strong tectonic effect. However, smaller pores in primary pores are damaged by tectonic effect, thus decreasing pore volume accordingly for smaller pores. This explains to some extent that tectonic effect promotes fracture of macromolecular chains or the aromatic layer greatly, which is conducive to disordering development of molecular structures in coals, finally increasing pore volume [18, 23, 85, 90, 91].

Pore structural features of coals are decisive factors of adsorption/desorption, diffusion, seepage, and other laws. According to literatures, the Langmuir volume of coals to methane adsorption presents a trend of “high at ends and low in middle” with the increase in the metamorphic grade of coals [88, 92–95]. In other words, the Langmuir volume decreases from low-rank coals to middle-rank coals, and it reaches the minimum in the low-rank coals. Subsequently, it increases gradually from the middle-rank coals to the high-rank coals.

Pore structures and crushing degree of coals are developed and increased as a result to the tectonic effect, which brings a larger adsorption space to the coals and makes coals reach the adsorption balance state more quickly [93, 96]. In addition, since diffusion mainly occurs in pores of the matrix, different pore structures of coals cause different diffusion properties of gas in the matrix. According to existing research conclusions, no quantitative relations have been established yet between the pore structure of coals and gas diffusion characteristics [97, 98]. According to testing results of different scholars, the discreteness of the methane diffusion coefficient of coals is very high, crossing several orders of magnitudes [99–103]. Influenced by tectonic effect, the methane diffusion coefficient of coals generally increases [104–106]. On the one hand, this determines that coals which

undergo tectonic effect often have high initial ability to quickly desorb gas [107, 108].

Moreover, gas occurrence capacity in coals determines the outburst gas potentials of coals [40]. Coals shall be able to release gas very quickly in order to transform outburst gas potentials into effective outburst energy during the occurrence of outbursts [49, 109]. Hence, initial gas desorption capacity of coals is an important guarantee to gas supply in the outburst process.

**2.2. Inducing Factors of Coal and Gas Outburst.** Based on the above literature review, three dominant factors of outbursts, namely, stress, gas, and properties of coals, are also influenced by some factors. These factors might influence a dominant cause independently or together. These influencing factors generally are inducing factors of outbursts. Combined with the literature review, this section summarizes important inducing factors and their influences on outbursts.

**2.2.1. Buried Depth.** According to literature records [110, 111], mining activities of human nowadays still concentrate in strata where the buried depth is lower than 800 m. However, there are some mines with mining depth higher than 1000 m. For example, the mining depth of the Suncun Coal Mine of the Shandong XinWen Mining Group reaches 1350 m. Variation of buried depth will surely trigger changes of occurrence environment for coal seams. In particular, it can influence stress environment of coal seams [30, 112]. Influenced by overlying rock thickness, vertical stress of coal seams increases significantly with the increase in buried depth [30, 113].

Variations of occurrence environment/stress environment in coal seams have been proven an important influencing factor of outburst risks in coal seams. However, it has been reported by literatures [1, 110, 114–117] that the lowest buried depth of outbursts is 80 m (outbursts in the Cezar Zofia Mine in Poland, 1894) and the highest buried depth is higher than 1100 m (outbursts in the Yubari Mine in Japan, 1981). So far, most outbursts occur in the buried depth of 300–700 m. It seems that there are no general laws of the relationship between outbursts and buried depth [16, 116, 118]. Some scholars believe that outburst frequency increases with the increase in buried depth, while some scholars get the opposite conclusions. This might be because that occurrence environment/stress environment of coal seams is influenced by factors except buried depth more significantly [16].

**2.2.2. Tectonic Movement and Tectonism Types.** The mechanisms of gas outbursts, under different geology backgrounds and mining conditions, are still unresolved, but it is generally recognized that stress, gas, and properties of coal play an important role in outburst [11]. Meanwhile, these three factors are controlled by other factors, such as tectonic movement, mining method, and coal formation process [110, 119].

Shepherd et al. [16] integrated the novel aspects of stresses, gas, and geological structure in a worldwide review of the problem of outbursts and considered that tectonic movement is the main factor of outburst. He also pointed out that thrust, fault, and fold are especially outburst prone,

while these structures cause tectonic (sheared) coal to be present due to differential compaction. Taylor [120] observed that north England coalfield outbursts occurred in the immediate vicinity of tectonic disturbances and that the outburst coal comes from the soft coal seam. Yan et al. [121] discussed the relationship between gas outburst in  $E_{9-10}$  coal seams and tectonic movement in the Pingdingshan 10<sup>th</sup> Coal Mine and found that there were thick tectonic coals as well as uneven gas distribution due to the control effect of NW-NWW-strike folded tectonic belts.

Therefore, geologic factors play an important role in the formation process of outbursts. However, unfortunately few geological details were given for many outbursts, even though these were premier information for the study of outburst that occurred. Table 1 summarizes the limited record for outbursts and their geological information from different countries in literatures. These literatures [14, 16, 110, 114, 117, 119, 122–126] show that geological factors (such as fault, fold, thrust, roll, coal seam thickness changes, and dip) are a common feature associated with outburst, and some of them point that outbursts occur in the vicinity of tectonic (soft) coal pinched by geological factors.

Effects of these geologic factors on outbursts are manifested in two aspects [127]. Firstly, geologic factors influence the occurrence and geometric shape of coal seams, including variation of coal seam thickness and inclination [1, 110]. This is mainly manifested by changes of stress environment, increasing gravity effect, gas, and energy gathering. Secondly, geologic factors can cause sudden disturbances to coal seams [1, 110]. This is mainly manifested by changes in geometric forms of coal seams and physical-chemical properties of coals, which directly favor the occurrence of outbursts and undergo sudden changes. Specifically, the existence of tectonic coals (soft coal) in many geological tectonic zones deserves extensive attentions.

Tectonic coals are the product of geologic factors (especially tectonic movement). Under extremely high stress conditions, tectonic coals are the product of continuous pulverization of primary coals and changes of physical-chemical properties under high stress conditions (Figure 1) [18]. The distribution of coal seams depends on complicated geological genesis. Bed sliding is the main controlling factor for the regional distribution and stratified distribution of tectonic coal, which are mostly caused by folds (Figure 1(b)) and bedding faults (Figure 1(c)). The local distribution is mostly caused by faults cut by vertical coalbeds, as shown in Figure 1(d). Tectonic coals show significantly different macroscopic mechanical properties, microscopic pores, and fracture structures with intact coals [105]. The formed tectonic coals have extremely low fracture resistance, which is similar to reconstructed coals [1]. Compression of fractures leads to low permeability of coals, which creates conditions for gas enrichment [24]. The low permeability of tectonic coal seams has been proven in many engineering cases of difficult gas extraction in tectonic coal seams [128, 129]. However, tectonic coals can be broken into abundant pieces with small size after failure, during which gas is released very quickly [105, 130]. Therefore, the tectonic movement zone is extremely more susceptible to outbursts than normal zones

TABLE 1: Outbursts and their geological information from different countries [14, 16, 110, 114, 117, 119, 122–126].

Country	Location	Numbers of outbursts	Geological description
England	Gwendraeth Valley coalfield	192	In all these cases, there were geological disturbance and soft coal in the vicinity
Russia	Abashevskaya and Pervomayskaya mine, etc.	19	9 were coincident with faults, and 10 were unspecified
Kazakhstan	Kazakstanskaya and Lenina mine, etc.	7	4 were coincident with faults, 2 occurred in thrust, and 1 was unspecified
Turkey	Kozlu and Karadon mine, etc.	20	8 were coincident with faults, 5 occurred in fold, 1 was located in the coal seam thickness change zone, and 6 were located in the crushed zone
New Zealand	Mount Davy mine	6	4 were coincident with faults, 1 occurred in fold, and 1 was located in thrust
China	Songzao, Diandong, and Jiaozuo coalfield, etc.	31	4 were coincident with faults, 17 occurred in the dip zone, 2 were located in thrust, 3 were located in the crushed zone, and 5 were unspecified
Canada	Crowsnest coalfield	4	2 were coincident with faults, 1 occurred in roll, and 1 were located in the crushed zone
Canada	Canmore coalfield	45	12 were coincident with faults, 1 occurred in roll, 10 were located in the coal seam thickness change zone, and 5 were unspecified
Canada	Cassidy coalfield	260	Outbursts occurred as mining approached soft coal pinched by rolls
France	Cevennes coalfield	1	Outburst occurred at the junction between hard and soft coal, and a fault was found close by
Japan	Ishikari coalfield	13	Outbursts tended to occur where normal or reverse faults were intersected with throws of a magnitude similar to the thickness of the coal seam
Australia	Metropolitan mine in the southern coalfield	25	Outbursts associated with soft coal, dykes, faults, or combinations of these
Australia	Collinsville in the Bowen Basin	6	All outbursts associated with faults
Australia	No. 2 mine in the Bowen Basin	1	Outburst occurred in thrust
Australia	Leichhardt mine in the Bowen Basin	37	Outbursts originated by the interaction of high stresses, induced cleavage, and face cleat
Australia	Appin, Bulli, and Corrimal mine in the southern coalfield		Outbursts occurred along strike-slip faults
Australia	West Cliff mine in the southern coalfield		Outbursts only occurred in the vicinity of strike-slip faults
Spain	8th coalbed of the Riosa-Olloniego unit		Some outbursts could be related to faults or changes in coal seam thickness
Belgium	Charleroi coalfield		Coal seams were strongly deformed by thrusts and normal faults
Poland	Ruben mine in the Walbrzych coalfield		There were wide zones in which the beds of the coal were rolled out and were very deformed
Poland	Wenceslaus mine in the Walbrzych coalfield		Outbursts occurred along longwall faces wherever faults or clusters of faults occurred
Germany	Nordrhein-Westfalen coalfield		Outbursts were related to a particularly porous sandstone to areas where gas was under high pressures of around 6 MPa
Ukraine	Donetsk coalfield		The shear zones existed in the part of the coal seam

due to the unique properties of coals, high stress, and gas concentration.

**2.2.3. Main Components of Coal Seam Gases.** Under general conditions, coal seam gas is the generic term of toxic and harmful gases, mainly  $\text{CH}_4$ . These  $\text{CH}_4$ -centered coal seam gases are mainly formed by decomposition of cellulose of ancient plants and organic matters by anaerobion in early piling and formulation of coals, or  $\text{CH}_4$  is generated continuously from physical and chemical effects of coals in high-temperature and high-pressure environments during the

formation of coals [14].  $\text{CH}_4$ -centered coal seam gases have very extensive distribution in coal seams. Most coal seams are mainly occupied by  $\text{CH}_4$ . As a result, most coal and gas outbursts which have been reported are mainly caused by  $\text{CH}_4$ -centered gases in coal seams.

However, high-concentration  $\text{CO}_2$  is the major gas component in some unique coal seams. The no. 2 coal seam of the Yaojie Coal Mine in Gansu Province, Northwest China, is a typical  $\text{CO}_2$ -occupied coal seam. The  $\text{CO}_2$  concentration in coal seam gases in the eastern region reaches as high as 18.79-96.6% [131]. The  $\text{CO}_2$  concentration in the no. 2 coal

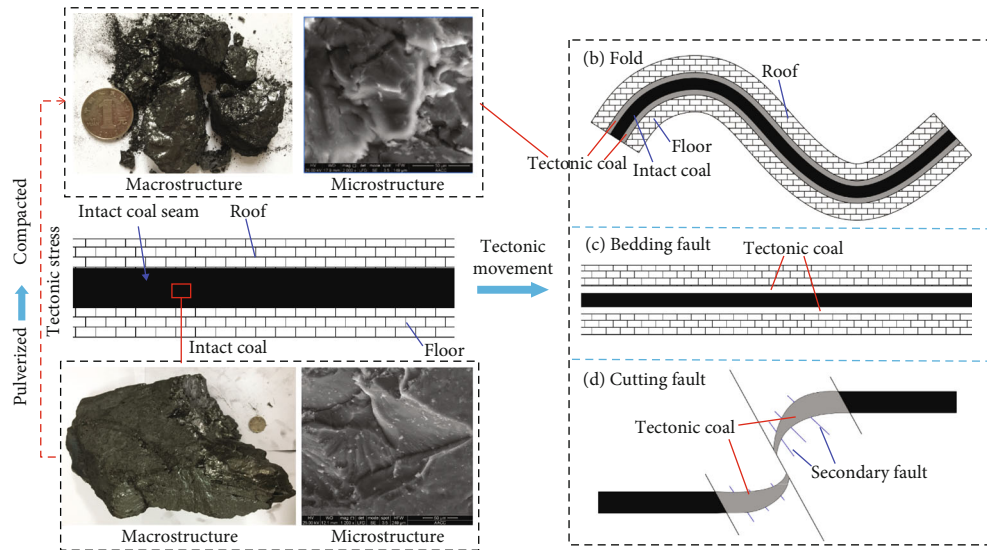


FIGURE 1: Physical restricting of the intact coal seam under tectonic effect [14].

seam of the Haishiwan Coal Mine in deep regions of the Yaojie coalfield reaches 34.1-98.64%, and coal seam gas pressure is 1.0-7.5 MPa [132]. According to literatures [131-133], high-concentration  $\text{CO}_2$  in coal seams has several potential sources, including magmatism, mantle degassing, and spontaneous combustion of coal seams. Among them, volcanic activities and magmatism are important sources of high-concentration  $\text{CO}_2$ . A lot of  $\text{CO}_2$  are generated due to thermometamorphism of carbonates during volcanic activities and magmatism [134, 135]. Meanwhile, fault serves as pipelines, barriers, or mixed effect against transportation and sealing up of  $\text{CO}_2$  in coal seams [136, 137]. In particular, fault plays an important role in the formation of high-concentration  $\text{CO}_2$  in coal seams.

High-concentration  $\text{CO}_2$  can induce outbursts as well. The Yaojie coalfield has experienced several  $\text{CO}_2$  outbursts since 1977 [132], and similar  $\text{CO}_2$  outbursts have been reported in the Cevennes Basin (France) and Sydney and Bowen Basin in Australia [1, 117].

However,  $\text{CH}_4$  outburst and  $\text{CO}_2$  outburst cannot be compared directly due to complexity and nonrepeatability of outbursts. According to the laboratory test, the  $\text{CH}_4$  adsorption capacity of coals is lower than the  $\text{CO}_2$  adsorption capacity [138]. Due to different adsorption capacities, the swelling effect of coals after  $\text{CO}_2$  adsorption saturation is significantly stronger than that after  $\text{CH}_4$  adsorption saturation [139], which can influence permeability and mechanical properties of coals [58, 140, 141]. Besides, gas potentials of coals after  $\text{CO}_2$  adsorption are higher than those after  $\text{CH}_4$  adsorption under the same gas pressure [27]. These potentials will contribute to the occurrence of outbursts once there are conditions for releasing. However, the relationship between the main components of coal seam gas and outbursts still has to be discussed deeply by using similar simulation test means.

#### 2.2.4. Coal Seam Conditions and Overlying/Underlying Rock Conditions.

The influence of the occurrence environment of

the coal seam on outburst is complex, which is necessary to comprehensively consider the coal seam dip, thickness, and overlying/underlying rock conditions.

Due to different sedimentary environments and different geological movements in the late period, occurrences and thickness vary significantly in different coal seams. According to the coal seam dip, existing coal seams can be divided into near-horizontal coal seams ( $<8^\circ$ ), gently inclined coal seams ( $8^\circ$ - $25^\circ$ ), inclined coal seams ( $25^\circ$ - $45^\circ$ ), and sharply inclined coal seams ( $>45^\circ$ ) [9]. Nevertheless, the coal seam dip often changes suddenly and even there is inversion of coal seams during mining practices. According to literatures [142-144], influences of gravity stress of coal seams on outbursts are intensified with the increase in the coal seam dip, thus increasing the risk of outbursts in coal seams. Sudden changes of the coal seam dip or inversion of coal seams is generally related to tectonic activities, and these regions are often high-risk regions of outbursts [16]. Moreover, thickness of the coal seam also can influence outburst risks. Some outbursts may occur in positions with sudden thickening of coal seams or in the soft layer of coal seams [110].

Mudstone or various sandstones are common overlying/underlying rock properties of coal seams. Since these differences of gas permeability and thickness of rock strata can influence the occurrence of coal seam gases, some unique overlying/underlying rock strata can influence outburst risks in coal seams significantly [145, 146]. [147] studied influences of overlying red bed in the Xutong and Zhaoji Coal Mine of the Huaibei Coalfield on the occurrence of coal seam gases. They found that red bed was a kind of porous layer with high permeability and high diffusion and it was inferior to other rock strata in terms of sealing capacity of coal seam gases. As a result, coal seam gases can escape through the overlying red bed. The overlying red bed can be viewed as a symbol of low coal seam gas.

Additionally, a magmatic stratum is viewed as the main controlling factor of several outbursts in the Haizi Coal Mine and Wolonghu Coal Mine in the Huaibei Coalfield, China.

Specifically, there were 11 outbursts below the 120 m thick magmatic rocks in the Haizi Coal Mine and 2 outbursts in the circular closed zone of magmatic rocks in the Wolonghu Coal Mine [148]. The control effect of the magmatic stratum over outburst also exists in the Tiefsa coalfield in Northeast China [149]. Such control effect is mainly manifested in influences on coal seam gases. The magmatic stratum has thermal evolution and sealing effects [4]. Firstly, the thermal evolution of the magmatic stratum promotes secondary hydrocarbon generation of coal seams and changes the metamorphism degree of coal seams and pore/fracture structure of coals, thus increasing content and pressure of coal seam gases [150]. Secondly, the significantly thick and dense magmatic rocks can seal up coal seam gases and prevent escaping of coal seam gases effectively [4].

**2.2.5. Mining Mode.** Mining activity influences outburst as a man-made additional factor. Mining activities not only provide additional energy to outbursts but also break the original balance of coal seams, thus inducing the occurrence of outbursts [8]. According to statistics on frequency and strength of outbursts, rock crosscut coal uncovering is the most favorable condition for the occurrence and development of outbursts compared to coal seam roadway advancing, raise advancing, downhill advancing, and coal face, thus increasing numbers of typical high-intensity outbursts [9]. Mining techniques (e.g., blasting and fully mechanized coal mining) and mining speed are often viewed as influencing factors of outbursts. Outbursts have been reported for several times after blasting of the working face [9]. Excessive mining speed is very easy to break the dynamic balance of coal/rock, stress, and gas, thus making it easy to induce outbursts.

Besides, the advancing direction of the working face and time-space relationship of the primary rock stress field in coal seams are very important to outbursts. [29] carried out a numerical simulation of outburst risks on the working face of roadways under different primary rock stresses by using FLAC3D. When the maximum principal stress is perpendicular to the axis of the roadway, the roadway is the easiest to suffer outburst. Moreover, the outburst risk of the roadway reaches the peak when the recovery cycle is in the position of stress concentration peak. Advancing safety in the roadway is improved when the maximum principal stress is parallel to the roadway [151].

**2.3. Review of Relationship between Dominant and Inducing Factors of Outbursts.** According to above analysis, three dominant factors and 5 inducing factors have different contributions to outbursts. Moreover, there are complicated relations among these 8 factors (Figure 2).

Outburst is the extreme instability under the collaborative effect of stress, gas, and coals. Stress, gas, and properties of coals are all vital to outbursts. Stress and gas are the power and energy source of outbursts. The former one dominates coal-rock damage, while the latter one provides supply to transportation of coals and rocks and intensifies coal-rock damage. Coal is the acting object of power and energy of outbursts, and it determines the power and energy requirements of outbursts. All five inducing factors influence outbursts by

changing stress and gas of coal seams or properties of coals. For example, vertical stress of coal seams increases with the increase in buried depth. Tectonic stress formed by tectonic movement is an important factor of outbursts, while increasing the coal seam dip can intensify influences of gravity stress of coal seams on outbursts. With respect to the occurrence of coal seam gas, gas is difficult to escape due to the thickening overlying strata caused by the increase in buried depth. Gas sealing condition was created by tectonic movement and the existence of the overlying thick and dense magmatic stratum. Heat effect of the overlying/underlying magmatic stratum is going to increase gas generation. Gas occurrence capacity of coals is increased by changing structures of coals. Moreover, tectonic movement also can trigger restructuring of coal seams, thus changing the basic properties of coals.

According to comparison of five inducing factors, there are no general laws in outburst and buried depth. The increasing vertical stress of coal seams and overlying strata thickening caused by the increase in buried depth can seal up gases, which influences the outburst risks of coal seams to some extent. Field conditions of CO<sub>2</sub> outburst and CH<sub>4</sub> outburst are not comparable. At present, it can only conclude according to experiments that CO<sub>2</sub> outburst might be more serious. Hence, the key inducing factors of outburst mainly include tectonic movement, occurrence condition of coal seams, and mining mode. Among them, mining mode is an artificial factor caused by mining activities of human. Rock crosscut coal uncovering, blasting, and high mining speed often cause insufficient unloading of stress and insufficient release of gas, thus inducing outbursts. Unreasonable design of the mining direction may intensify stress concentration. However, tectonic movement is often viewed as closely related to outbursts, and it is the key factors that influence the occurrence of outbursts and together variations of stress, gas, and properties of coals. Moreover, it has been proven that the thick and compact magmatic stratum in overlying/underlying rock strata in coal seams can control some outbursts.

### 3. Coal and Gas Outburst Case Study

**3.1. Outbursts in the Xiangshui Coal Mine.** A serious coal and gas outburst occurred in the Xiangshui Coal Mine, Guizhou Province, on November 24<sup>th</sup>, 2012. This outburst occurred on the working face of the 1135 transport roadway. The elevation and buried depth of the outburst point were +1225 m and about 203 m, respectively. The outburst occurred on the no. 3 coal seam with an average thickness of 2.67 m and a coal seam dip of 10~30°. The measured gas and gas pressure at the no. 3 coal seam were 13.9 m<sup>3</sup>/t and 1.65 MPa, respectively (elevation of the measuring point was +1237.5 m).

According to field investigation, the outburst hole was at about downward inclined 45° in front of the 1135 transport roadway advancing face, which had a small mouth and large cavity. The mouth width of the outburst hole was 3.58 m, and the depth was about 12~15 m.

There were bedding faults at two sides of coal seams in the 1135 transport roadway, and there was obvious rock bed dislocation at the left and right sides of the outburst hole. In addition, the coal seam near the outburst point was



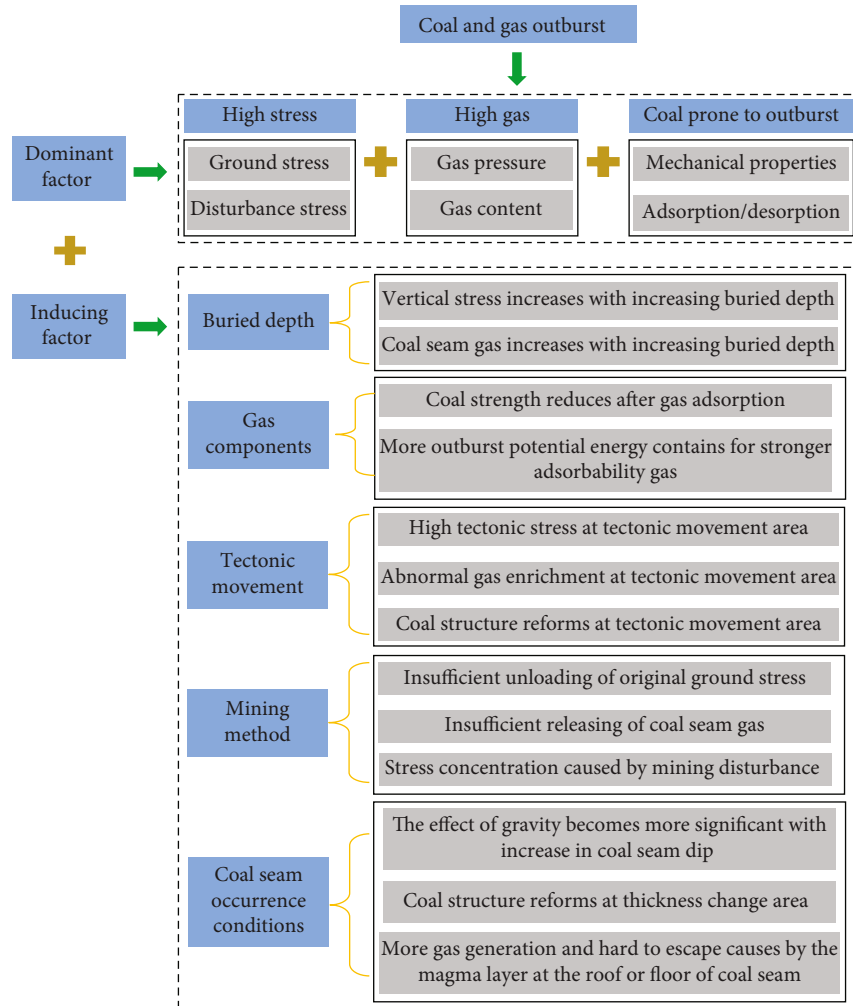


FIGURE 2: Analysis of internal relations of factors of coal and gas outbursts.

thickened, accompanied by evident changes in properties and structure of coals. Coals, which are 163 m away from the outburst point, are bright and hard and presented characteristics of intact coals. However, coals became dark and softened near the outburst point and presented typical characteristics of tectonic coals, as shown in Figure 3.

In a word, stress conditions of the outburst point, gas conditions, and properties of coals determined the occurrence of this outburst together. However, it is difficult to have stress conditions in the outburst region for high smashing or pulverization of intact coals during the outburst process according to the buried depth [127]. Moreover, coal restructuring is the most prominent changes of coal seams near the outburst point, and there are abundant tectonic coals near the outburst point. Such tectonic coals were crushed/pulverized continuously in the tectonic movement process (mainly bedding fault), thus requiring no abundant outburst energies in the outburst process. Once outburst conditions were met, tectonic coals were outburst by the collaborative effect of gas and stress. Hence, tectonic movement played the key role in this outburst.

3.2. *Outburst in the Bailongshan Coal Mine.* A serious coal and gas outburst occurred in the Bailongshan Coal Mine of

Yunnan Diandong Energy Company on September 1<sup>st</sup>, 2013. This outburst occurred on the gas drainage roadway advancing face in the 17+805 working face floor. The outburst coal seam was no. C<sub>7+8</sub> coal seam (thickness of coal seam: 2.76 m), which was at 6.9~7.0 m on the roof of the gas drainage roadway. The buried depth and vertical ground stress at the outburst point were about 500 m and 12.5 MPa, respectively. Besides, gas pressure and gas in the no. C<sub>7+8</sub> coal seam were 1.57 MPa and 16.42 m<sup>3</sup>/t, respectively. Protodyakonov’s coefficient (*f*) of coals was 0.3.

According to field investigation (Figure 4), the gas drainage roadway in the 17+805 working face floor had complicated geological conditions, and more than 10 minor faults were discovered during advancing in the roadway. Besides, a reverse fault with a drop height of 6 m was found at the corresponding outburst position of the gas drainage roadway in the 17+803 working face floor. Moreover, a fault with a drop height of 20 m was found between the 23307 geological prospecting hole and 4233 geological prospecting hole, which was adjacent on the gas drainage roadway advancing face in the 17+805 working face floor.

According to comprehensive deduction, there is a reverse fault with a drop height of 4-6 m in front of the gas drainage

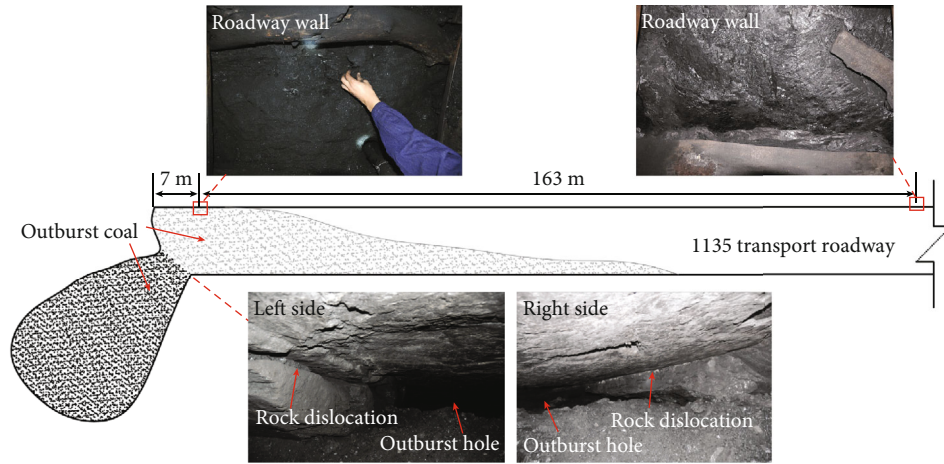


FIGURE 3: Field investigation features of outbursts in the Xiangshui Coal Mine.

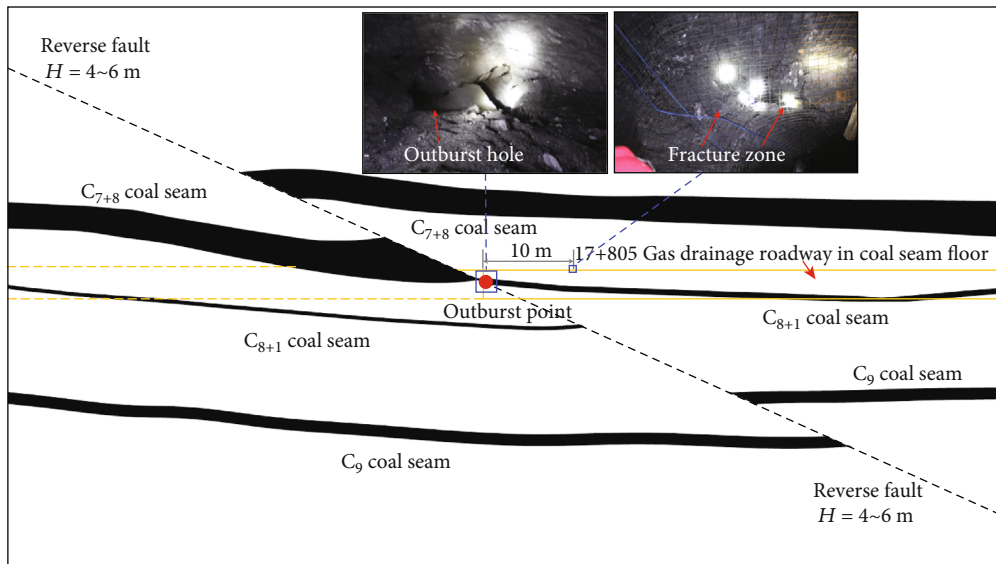


FIGURE 4: Field investigation features of outburst in the Bailongshan Coal Mine [78].

roadway advancing face. Strike, tendency, and dip of this fault were  $110^\circ$ ,  $20^\circ$ , and  $30^\circ$ , respectively (Figure 4). Influenced by faults, the positional relation between the advancing face and no.  $C_{7+8}$  coal seam changed. The no.  $C_{7+8}$  coal seam of the hanging wall of fault lifted up by extrusion, while the no.  $C_{7+8}$  coal seam of the footwall of fault moved downward and approached to the advancing face suddenly. Besides, the tectonic fracture zone was observed near the advancing face, and rock strata on the roof of the roadway 10 m away from the working face were smashed. The outburst coals at the external side of the mouth were crushed and even pulverized.

To sum up, the coal seams near the outburst point in this case had high gas and high ground stress, which were important factors to the occurrence of outburst. Nevertheless, tectonic movement was crucial to this outburst. The reverse fault changed the positional relation between the advancing face and no.  $C_{7+8}$  coal seam, thus making the no.  $C_{7+8}$  coal seam move downward and approach to the advancing face

suddenly. This created conditions for disclosing the outburst coal seams. Besides, the tectonic fracture zone was developed near the outburst point due to tectonic effect, thus resulting in breakages of rock strata on the roadway roof. As a result, coals in the outburst coal seams were crushed and even pulverized, showing low strength. Therefore, these changed the initiation conditions of outburst.

**3.3. Outburst in the Xinyi Coal Mine.** An outburst occurred after blasting in the belt roadway of the 11090 working face in the Xinyi Coal Mine on May 22<sup>nd</sup>, 2018. In this outburst, 1917 t of highly pulverized coals was outburst. According to field investigation, the buried depth of the 11090 working face was 361.9~400.6 m. In this region, there are simple tectonic movement and development of small folds, generally showing monoclinic morphology. The outburst hole was on the left side of the belt roadway, and it was blocked by pulverized coals. The coal seam roof in the outburst hole was flat,

and no roof failure was observed (Figure 5). According to these phenomena, there are no sufficient overlying stress and tectonic stress near the outburst point. In addition, the existing gas data showed that the measured maximum gas pressure of the outburst coal seam (no. 2<sub>1</sub> coal seam) was 1.40 MPa (buried depth of measuring point: 701.71 m) and the maximum gas was 12.84 m<sup>3</sup>/t (buried depth of measuring point: 700 m). Combined with relevant research conclusions, coal seam gas near the outburst point cannot meet energy conditions for high pulverization of intact coals [127].

Therefore, properties of coals play the key role in this outburst. This outburst is a typical outburst case in the tectonic coals. The no. 2<sub>1</sub> coal seam in the 11090 working face belongs to III-V coals and tectonic coals. Besides, the outburst point was in the coal seam thickening zone, and there is a synclinal axis on the left floor of the belt roadway along the advancing direction, thus making tectonic coals highly crushed/pulverized under the original state.

## 4. Discussions

*4.1. Effects of Tectonic Movement in Outburst.* Combined with key factors of coal and gas as well as geological features of the typical outburst case, tectonic movement can control outburst, as shown in Figure 6. This is mainly realized by changing three dominant factors of outburst.

- (1) Tectonic movement will change ground stresses in the tectonic zone. Therefore, ground stresses in the tectonic zone are sensitive to tectonic stress in addition to overlying stress. In particular, tectonic stress influences ground stresses significantly at present mining depth for most coal resources. Ground stresses are changed with tectonic movement, thus resulting in abnormal ground stresses in the region and forming high ground stresses
- (2) Some unique tectonic movements formed by tectonic effects can control the occurrence and migration of coal seam gases. For example, a closed fault can seal up coal seam gases, and a compact magmatic stratum can block the migration of coal seam gas. In addition, high ground stresses in the tectonic zone induce low permeability of coal seams, restricting the migration of gas along the coal seam which can lead to the abnormal occurrence of coal seam gas in the zone, thus forming gas enrichment
- (3) Nevertheless, attentions shall be paid to influences of microstructure changes of coals caused by tectonic movement on outburst. In the long-time tectonic movement process, the primary structure of coals is damaged/pulverized due to the high tectonic stress and unique tectonic mode, which decreases the matrix size of coals sharply. In addition, pulverized coals are compacted by tectonic stress to form tectonic coals. Physical structures of tectonic coals are significantly different from those of intact coals. As a result, mechanical behavioral responses of tectonic coals to changes of external stress are altered. Tec-

tonic coals are generally damaged and expanded under low stress conditions, which can influence the matrix-fracture structure of tectonic coals significantly. During the formation of tectonic coals, internal micropores of coals vary as a response to decreasing matrix size of tectonic coal particles, so that pore structure in coals is further developed, thus influencing the occurrence and diffusion space of gas in the pore structure. Therefore, tectonic coal particles have high initial gas desorption capacity

Besides, physical structure of tectonic coals determines their low permeability under high ground stress [152], which restricts gas flow in tectonic coals and results in abundant gas residues in tectonic coals. However, the matrix-fracture structure of tectonic coals is changed after stress disturbance, and gas flowing in fractures is accelerated. Therefore, rapid gas releasing becomes one of the outburst energy sources.

*4.2. Outburst Process considering Geologic Factors.* The outburst process is generally divided into the preparation stage, triggering stage, development stage, and termination stage. Based on previous studies, the relationship between tectonic factors and outburst was further reviewed, and the outburst process was further described (Figure 7).

All four stages are introduced in the following text:

### (1) Preparation stage

The preparation stage includes the tectonic process and mining process. The former one refers to the restructuring process of the original coal-bearing strata by tectonic movement. In the long-time geological process, coal-bearing strata might experience one-phase or multiphase tectonic movements, which change ground stresses and gas conditions in original coal-bearing strata, resulting in local high ground stresses and gas enrichment. Tectonic coals are the accompanying products of tectonic movement. Physical structures not only determine the properties of tectonic coals but also cause unique mechanical behaviors of tectonic coals and gas flow when external factors change. These are crucial to the preparation of outburst. Nevertheless, the mining process is the prerequisite of outburst, and it refers to the disturbance of human mining activities to the initial coal seams. The mining process breaks the structural balance of initial ground stresses of the coal seam, gas, and coals, causes migration of stress, gas flow, and structural evolution of coals, triggers quasistatic damage of coals, and reaches the critical conditions of outburst gradually. In other words, the preparation stage includes that gas pressure reaches the critical threshold for the occurrence of outburst.

### (2) Triggering stage

This stage is a process of instantaneous instability when a critical condition is met under the collaborative effect of stress, gas, and properties of coals. As the triggering point of outburst, the triggering stage often can cause rapid failure and throwing of outburst obstacles (e.g., rock pillar and coal pillar) and form the initial outburst hole and initial exposed

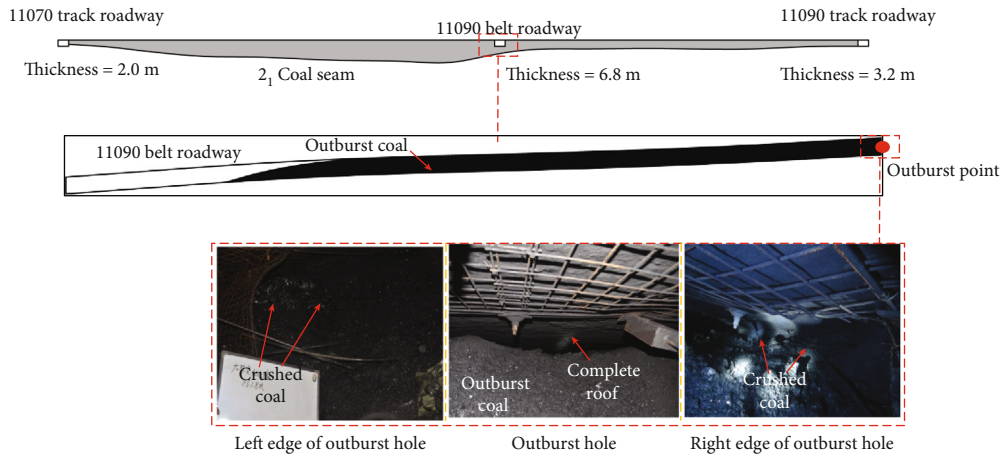


FIGURE 5: Field investigation features of outburst in the Xinyi Coal Mine.

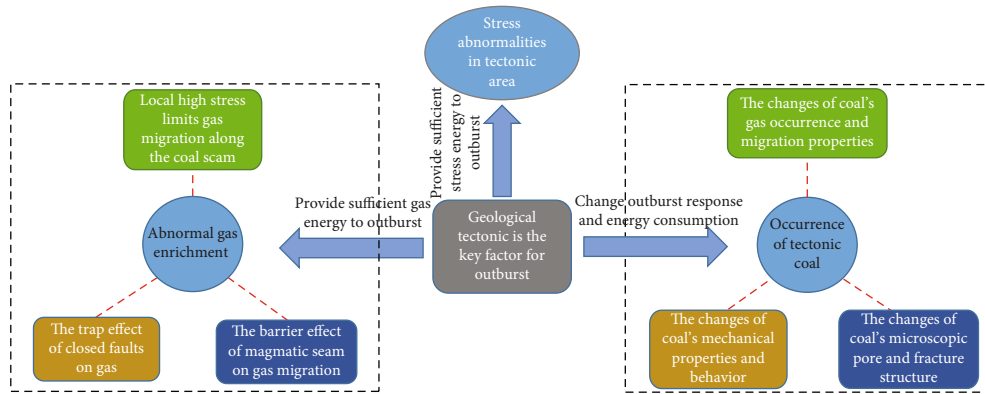


FIGURE 6: Key effects of tectonic movement in outbursts [31, 43, 107, 119, 124, 127].

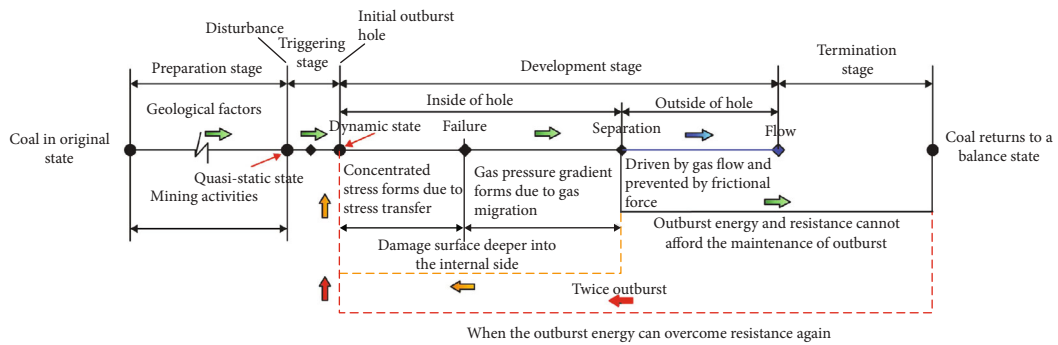


FIGURE 7: Dynamic stages of coal and gas outburst.

surface. These provide a large space conditions for the subsequent development of outburst. Besides, more coals with high stress and gas pressure will be exposed after the formation of initial pores, thus providing favorable conditions for continuous failures.

(3) Development stage

The development stage starts after the triggering stage, and it contains the whole process from acceleration to stability and finally to attenuation. Spatially, it can be divided into the

inside and outside of the hole. Mechanical failure of coals in the outburst hole involves the following processes: (1) concentrated stress dominates fracture development of coals and the expanded plastic failure process. (2) A high gas pressure gradient is formed near the exposed surface, which causes tensile fracture of coals and makes fractures expand through the spalling parallel to the exposed surface. (3) Given the continuous influences of high-pressure gas, spalling breaks and then is separated and outburst. (4) The exposed surface migrates to the deeper positions, and it enters into the next failure cycle.

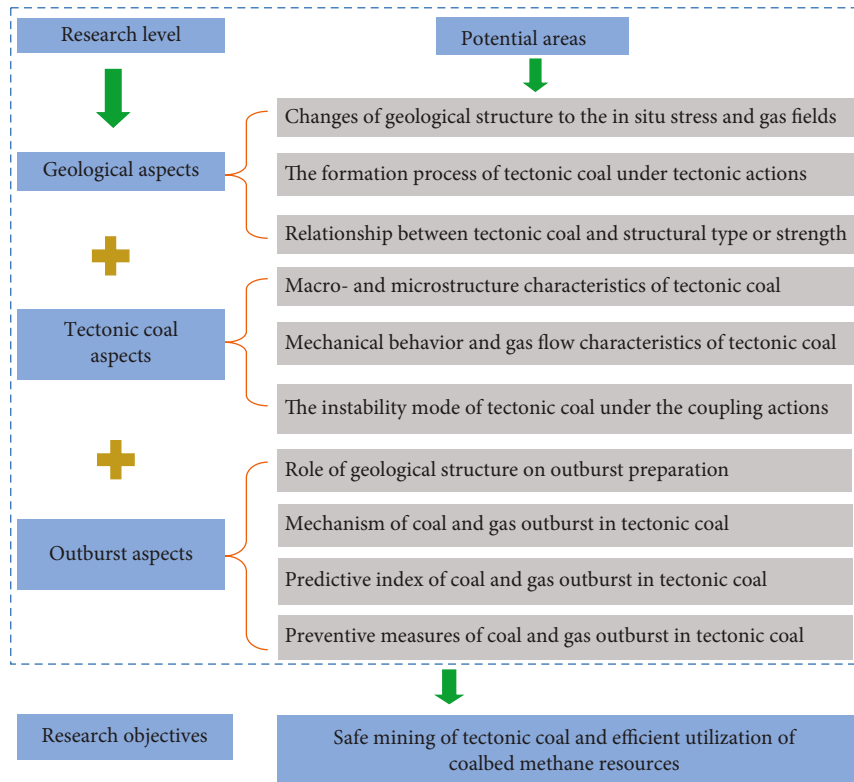


FIGURE 8: Potential research direction of geological factors of outburst.

Outburst coal migration by gas flow occurs outside of the outburst hole, during which outburst coal experiences acceleration, deceleration, and final static under the power and frictional resistance provided by gas. In this process, outburst coal is further crushed and even pulverized due to friction, impact, and swelling effect of desorption gas.

(4) Termination stage

With the development of outburst, gas energy and stress energy of outburst are consumed continuously. Meanwhile, a lot of outburst substances block the outburst hole and mining space, thus increasing the outburst resistance. Finally, the outburst energy and resistance are inadequate to maintain the outburst, and the outburst terminates. When the outburst energy gathers again and it is enough to overcome the outburst resistance, twice outburst might occur, or the outburst terminates directly. Coal-rocks return to the static balance.

4.3. *Potential Research Directions.* Based on the previous analysis of effects of tectonic factors on outburst, there might be potential theoretical and experimental research directions with respect to geologic aspects and process of outburst (Figure 8).

In the geological aspects of outburst, the effects of tectonic factors on the ground stress field and gas field of the original coal-bearing strata have to be further studied. Attentions and further studies are needed on physical and chemical changes that coals have undergone during tectonic movement to form tectonic coals as well as the relations

among tectonic movements, tectonic strength, and types of tectonic coals.

For properties of tectonic coals, a deep study on macro-/microphysical structures of tectonic coals is the premise to master the basic characteristics of tectonic coals. The unique mechanical behaviors and gas flow of tectonic coals when external factors change as well as instability mode of tectonic coals under the coupling effect of stress and gas also shall be further explored.

In addition, the internal relations between tectonic coals and preparation and development of coal and gas outburst shall be studied deeply. The occurrence mechanism of coal and gas outburst in tectonic coals is built, and predictive indexes of outburst in tectonic coals are established to evaluate outburst risks. Specific multigrade and multilevel measures shall be adopted to eliminate outburst risk of tectonic coals, which also needs to be further studied.

Finally, it is expected to further disclose the formation mechanism and process of outburst under tectonic movement. It has important scientific significance to study the outburst mechanism and control.

**5. Conclusions**

- (1) Outburst is the extreme instability caused by stress, gas, and coal. Inducing factors, including buried depth, tectonic movement, gas composition, coal seam conditions, overlying/underlying rock conditions, and mining mode, control the outburst by influencing the dominant factors. Tectonic movement will change the

stress field, gas field, and structural characteristics of coals in the tectonic zone, and it is the key of outburst. Most outburst cases have proven the close relationship between outburst and tectonic movement

- (2) Influenced by tectonic movement, tectonic stress can change ground stresses and gases in the tectonic zone, thus resulting in abnormal ground stress and gas enrichment in the region. The original structure of coals is damaged/pulverized due to the tectonic stress and unique tectonic mode, resulting in a sharp reduction of matrix size. Crushed/pulverized coals are compacted and form tectonic coals again. The microstructure of tectonic coals determines their differences from intact coals in terms of porous structure, mechanical properties, and gas occurrence/flowing features. When external dynamic factors are changed, tectonic coals are crucial to outburst control for its evolution of porous structure as well as the unique mechanical behaviors and gas flowing responses
- (3) The outburst process is generally divided into the preparation stage, triggering stage, development stage, and termination stage. The preparation stage of outburst includes the tectonic process and mining process. The former one refers to the restructuring process of the original coal-bearing strata by tectonic movement, while the mining process is the prerequisite of outburst and it refers to the disturbance of human mining activities to the initial coal seams
- (4) Ground stresses and gases of the original coal-bearing strata change with tectonic movement. However, it still lacks a systematic study on physical and chemical changes that coals have undergone during tectonic movement to form tectonic coals and relations among tectonic structural form, tectonic strength, and types of tectonic coals. The unique mechanical behavior and gas flowing of tectonic coals when external factors change are the key to study the occurrence mechanism and process of coal and gas outburst

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

The authors are grateful for the support from the National Natural Science Foundation of China (No. 52004008), the Natural Science Foundation of Anhui Province (Nos. 2008085QE260 and 2008085QE222), and the Independent Research Fund of the State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines (Anhui University of Science and Technology) (No. SKLMRDPC19ZZ07).

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