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Mining seismicity, gas outburst and the significance of their relationship in the study of physics of earthquake source*

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Abstract

This paper presents an overview of mining seismicity, gas outburst and their origin. The internal relation of mining seismicity and gas outburst in the dynamic process is studied on the basis of the fact that these disasters sometimes occur simultaneously. The examples show a close relationship between mining seismicity and gas outburst in high gassy coal mines. It is proposed that strong mine shocks plus the response of low value and delay time are early warning signals. The mechanism of the relationship between mining seismicity and gas outburst is analyzed by using the location of mining shocks, focus mechanism, cause of mining shocks and conditions of gas outburst. The trigger action of gas fluid on mining shocks, especially the effect of the anomalous property of supercritical fluid on the preparation and occurrence of mining shocks is discussed. According to the similarity between mining-induced earthquakes and tectonic earthquakes in terms of mechanism, the significance of the above results in the study of physics of earthquake source is also discussed.

Key words: **physics of earthquake source**; **safety of mines**; **mining seismicity**; **gas outburst**
CLC number: P315.72^{+}8 **Document code**: A

Introduction

There are five kinds of coal-mine disasters in China: gas-related disaster, mining-induced earthquake, flooding accident, surface collapse and spontaneous combustion of coal stockpile. Basically, the five kinds of disasters are the result of interaction between mining and tectonic action and the expression of runaway dynamic process. The basic way for studying disaster mechanism is to study the dynamic mechanism of these disasters and the internal relation in the dynamic process. On the other hand, the study of dynamic mechanism of mine disasters is an important part

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of moderate-scale seismic field experiment. The present paper focuses on mining seismicity, gas outburst and their relationship.

1 Mining-induced seismicity

1.1 General knowledge of mining-induced seismicity

Earthquakes induced by mining are often called mine tremors, “coal burst”, “rock burst” or “pressure bump”. For a mining-induced earthquake, radiant elastic waves are produced in the process of rock-coal rupture. Small event can cause large damage in the working face because of the shallow source and high frequency of radiated waves. The magnitudes and quantities of mining events are becoming larger as the average depth and extent of mining increase. Global statistics show that mines with a mining depth of 500 m are imperiled by M_L>3.0 seismic events.

Mining seismic events are usually divided into two types (Gibowicz and Kijko, 1994). The first type refers to those near the working face. These tremors are associated with the fractures at the working face and, though with small magnitudes, they have a strong impact on the working face. In China, the former Soviet Union and east European countries, this type of mining seismicity is referred to as pressure bump; in other countries, they are called the first type of mining seismicity. The second type of mining seismicity often occurs relatively far away from the working face, and is related to large geological discontinuity (fault). These events are generally characterized by large magnitude and therefore can be felt more violently. The two types of mine tremors can be further divided into six models (Horner and Hasegawa, 1978). However, the division of mining-induced seismicity is rather subjective. There are no clear-cut lines between all mine tremors that are directly connected with mining operations.

From common knowledge mining-induced seismicity is simply considered as cavity collapse. In fact, cavity collapse is only a small part of seismicity induced by mining, related with gravity action. Most of mining-induced seismicity belongs to superficial tectonic movement triggered by new stress concentration with mining operations, among which the focal mechanism of shear-rupture is dominative. Seismicity induced by mining (rock burst) close to the working face causes not only roof fall but also sheeting, heaving, coal outburst and gas outburst. Mining-induced seismicity is defined as a mining dynamic phenomenon associated with not only regional stress field but also tectonic movement under certain geological and tectonic condition, affected by the extent and means of mining (WU and TAN, 1994).

1.2 Location of mining seismic events

Accurate positioning is the primary step in the study of mining-induced seismicity. It is more difficult locating mining-induced seismic events than locating other kinds of earthquakes due to complicated velocity structure caused by mining operations and strong anisotropy. Several approaches for positioning, which are carried out step by step, are applied to increase the precision of location. First, preliminary location is carried out (intersection method is often used when the number of seismic stations is small, while P wave residual method is used when the number of seismic stations is equal to or larger than 4). Second, polarization analysis and relativity methods are used to revise the results of preliminary location. Finally, wave correlation analysis method is used to locate seismic events based on the results of the second step. The accuracy of location is expressed by travel time residual (ZHANG *et al*, 2005).

Figure 1 shows the epicentral distribution of seismic events recorded by a small-aperture seismic network at Laohutai coal mine, Fushun, Liaoning Province of China from June, 2003 to

June, 2004. The average residual of travel times is 0.001~0.002 s, which corresponds to 7~10 m provided that the average P wave velocity is 5.5×10^3 m/s. To illustrate the location of mining events in administrative urban areas, we use an administrative map for Figure 1. As only a rough description is made of the fault strikes, it appears that the mining seismic events in the western section mainly concentrate on the EW-trending Hunhe fault F_1. Therefore, one may rush to the conclusion that the Hunhe fault is activated by mining. However, if the epicenters and faults are projected onto the map of the first seam bottom contour of Laohutai coal mine (Figure 2), we may find that the illustration in Figure 1 is not accurate enough. In fact, most of the seismic events in Fushun are distributed near three synclinal axes: one at the juncture of Laohutai coal mine and Longfeng coal mine in the east, one at the juncture of Laohutai coal mine and Shengli coal mine in the west and another at the east-central region of Laohutai coal mine. The seismic events in the west of Laohutai coal mine are mostly located at a small fault F_{30} near the synclinal axis of F_1 (Figure 2). Few seismic events took place in the main fault F_1 (LI *et al*, 2004; 2005; 2006a, b). Thus, the conclusion from Figure 1 that Hunhe fault is activated by mining cannot be confirmed by Figure 2. This shows that accurate positioning and accurate description of geological structure in coal mines are crucial to the study of origin of mining seismicity. Inaccurate description often leads to irresponsible conclusions.

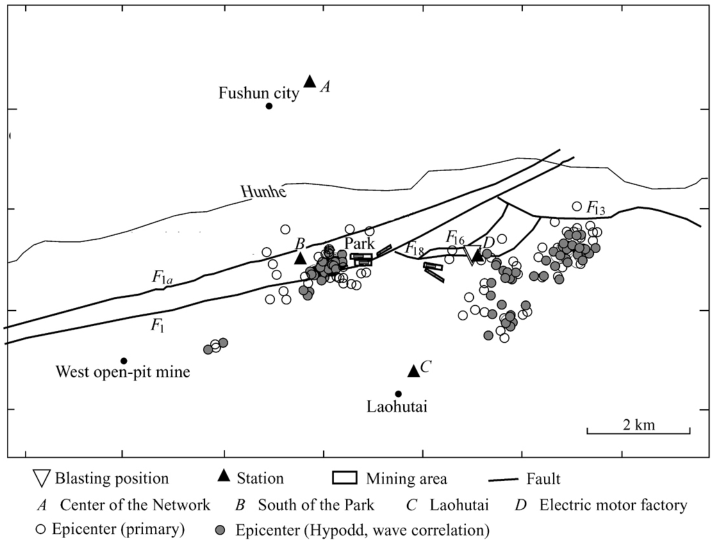

Figure 1 Distribution of epicenters of mining seismic events relocated by wave correlation analysis
The faults in the figure are referred to MAPSIS common software

1.3 Relation between distribution of mining-induced events and tectonics

According to mine records, the bumps and rock-coal bursts often happen near a synclinal axis, whereas the main fault in a mining region is not necessarily the prerequisite for mining-induced earthquakes. The results of high precision location of seismic events in Laohutai coal mine shows that the seismic events are mostly related with synclinal axes, especially with small faults near the synclinal axis. The synclinal axis demonstrated by the contour of the bottom of coal seam shows stress concentration in this region after tectonic deformation.

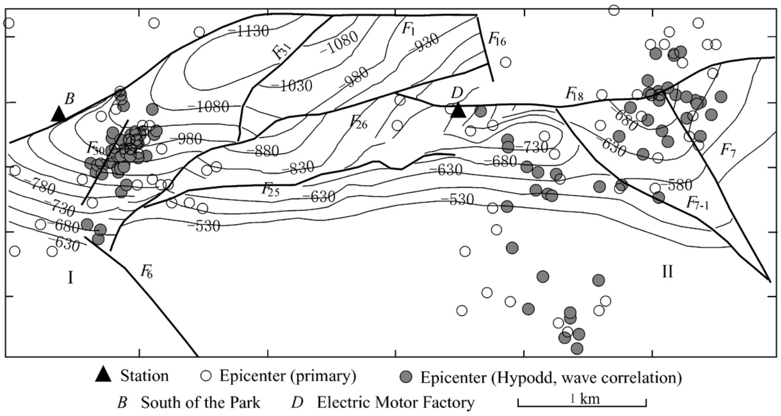

Figure 2 Relation between epicentral distribution and district map of the first seam bottom contour of Laohutai coal mine

I. Shengli Coal Mine; II. Longfeng Coal Mine. The faults in the figure are referred to MAPSIS common software

The seismic events recorded by a small-aperture seismic network in Baodian coal mine, Yanzhou, Shandong Province in China are found to be mainly distributed over two active zones, one near the fault at Yanzhou synclinal axis and the other near Damachang fault. What is noteworthy is the relation between mining-induced seismicity and small or micro structures. In the process of mining, some small faults, usually known as small structures and micro structures, were found in the working face. When the working face approaches the small fault, seismicity becomes obviously stronger, whereas after the working face passes across the small fault, seismicity becomes gradually weaker. The investigation results by JIANG *et al* (2006) show that the interaction between working face and micro structures in the course of mining operation causes micro shocks and rock burst, and then relatively far away seismic events are triggered after strain energy in micro structures has been released. It seems that working face brings small faults into existence and small faults trigger the activity of large faults. This is the progressive process of mining-induced earthquakes.

1.4 Relation between mining-induced seismicity and the progression of mining

It is well known that mining-induced seismicity increases generally with the mining depth. The evidence of relation between mining-induced seismicity and mining progression was found from observation and research in Baodian coal mine. The results indicate that the correlation of mining-induced seismicity with mining progression is shown in two different stages: clear and unclear. During the clear stage, the working faces are close to characteristic structures, especially to small faults. Two regular patterns of mining-induced seismicity are found in the clear stage:

1) Correlation of mining-induced seismicity with the fluctuating of excavation footage.

Calculation of differences of daily footage at the working face in Baodian coal mine shows that seismic events with magnitude above 3.0 always occur when the difference of daily footage fluctuates violently (Figure 3), especially on the days when the difference has a positive high value.

2) Correlation between time interval of mining-induced seismic events and cumulative value of excavation footage.

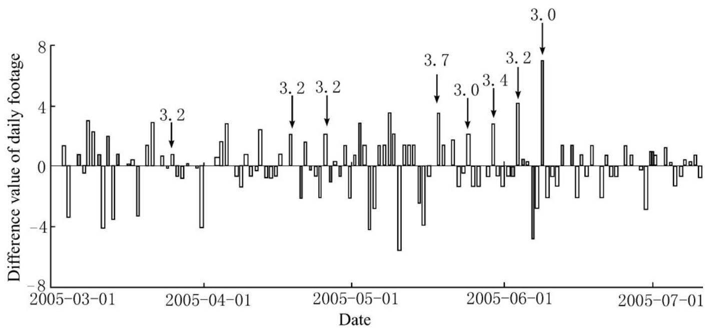

Figure 3 Correlation of the difference value of daily footage with $M\geq3.0$ seismic events in Baodian coal mine

Statistics of the cumulative value ΔL of the excavation footage between two large mining-induced seismic events show that ΔL is the integral multiple (mostly 1~4 times) of ΔL_0 (Figure 4):

$$\Delta L \approx n \cdot \Delta L_0, \quad n = 1, 2, 3, 4 \tag{1}$$

where ΔL_0 is associated with the quasi-cyclic character of impact pressure at the working face. The quasi-cyclic character is related to the state of hanging roof after excavation, so ΔL_0 also depends on the width of working face and the properties of roof, coal mass and surrounding rock. At this working face in Baodian coal mine from March to June 10, 2005, $\Delta L_0\approx23.5$ m (Figure 4), whereas, between June 1, and Jully 10, 2005, $\Delta L_0\approx18$ m. The quasi-cyclic character of mining-induced seismicity is also called commensurability.

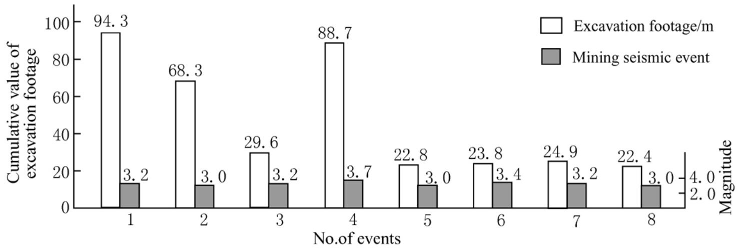

Figure 4 Correlation between time interval of large seismic events and the cumulative value of excavation footage at Yanzhou coal mine

The above regularity can only be found in the stage when there is a distinct relationship between seismic events and excavation footage. Otherwise, when the working face is far away from the characteristic structure (synclinal axis or active fault), or there is an isolated area, the regularity of mining-induced seismicity becomes unclear. However, the spatial distribution of mining-induced seismicity is still associated with the location of working face and characteristic structure.

2 Gas outburst

Gas disasters at the working face are mostly coal and gas outbursts, *i.e.*, dynamic disasters as a result of sudden movement of gas stored in coal seams and mingled with coal mass. The methane gas may suffocate the workers in the working face and explode in the heat of a fire. The three essential factors for gas explosion are methane density (5%~15%), oxygen density (≥9.47% when

N_2 is mixed with methane and air, and ≥12.32% when CO_2 is mixed with methane and air) and the source of fire (associated with the action of workers, underground temperature and pressure). The process less violent than gas outburst is called gas emission. Gas outburst is always accompanied by rock outburst. In some coal mines, the major component of gas outburst is carbon dioxide (CO_2).

The major component of gas is methane (CH_4), which is produced in the coal forming process. Under natural state of pressure in the coal seam, methane is absorbed by coal mass. In a place where the roof of a coal seam is poorly sealed, methane will gradually diffuse into the air. So methane density differs greatly in different coal mines. In the process of coal mining, methane will be gradually desorbed and diffuse into the roadways. Especially in the case of rock-coal rupture, high-pressure methane existing in coal mass will burst along with rock-coal outbursts, leading to disasters (CHENG *et al*, 2005). In developed countries, gas pre-drainage must be carried out before mining, and mining are not allowed in places with hidden gas trouble. In China, gas pre-drainage is at a very low rate, in most cases lower than 10%. Overexploitation is commonly seen in both highly and lowly gassy coal mines in China. This not only leads to imbalance of the physical state of stress and gas pressure, but also leads to the loss of gas energy (statistics show that the annual amount of lost methane from coal mines across China equals the total amount of imported gas).

The scale of gas outburst hazards may be raised with the increasing of mining depth. The increasing of gas hazards is caused by the raising of gas pressure in coal mass. In most other countries, the pressure 1.0 MPa is specified as the critical value of gas outburst risk. In China, the pressure 10.8 MPa is specified as the critical value (CHENG *et al*, 2005).

Study shows that media with high risk of gas outburst are characterized by (CHENG *et al*, 2005):

1) High gas pressure and gas content;
2) Insecure coal bed;
3) High porosity of coal bed, contributive to gas desorption;
4) Low gas permeability, which hinders gas movement and diffusion.

It is also found that the severer the coal seam breakage is, the more distinct the above four characters will become. In the prediction of gas outburst area, the more active the tectonic activity is, the high the coal metamorphic degree will become, resulting in severer coal bed deformation and breakage (CHENG *et al*, 2005).

3 Relation between mining seismicity and gas outburst

3.1 Similarity of postulates

From the above-mentioned data and analysis, we can see that there are many similarities between postulates of mining seismicity and gas outburst. Both require high stress concentration and severe structure breakage, and both are closely related to the process of mining. More and more observations prove that most large mine disasters in China are related to geological disasters in the whole mining area, usually accompanied by seismic events.

3.2 Evidence from Laohutai coal mine in Fushun

Based on seismic records from the regional seismic network and the small-aperture mobile network and gas density records of the coal mine, we have obtained evidence of the relationship between mining seismicity and gas outburst in Laohutai coal mine in Fushun (LI *et al*, 2004; 2005;

2006a, b).

Nearly ten abnormal curves of gas (methane) density in Laohutai coal mine in 2002~2003 are analyzed. The sampling interval is five minutes. Figure 5 shows the curve of gas density around the M_L3.2 seismic event on October 7, 2002. It can be seen that gas density declined first (low value response) immediately after the event and then rose rapidly one hour later. Then two hours after the event, the gas density rose to about 7.6%, much higher than the critical value for explosion. The high value of gas density continued for 8~16 hours before it returned to normal. According to the engineers working in the coal mine, similar phenomenon could be seen for 1~2 days after every M_L>2 seismic event in 2002.

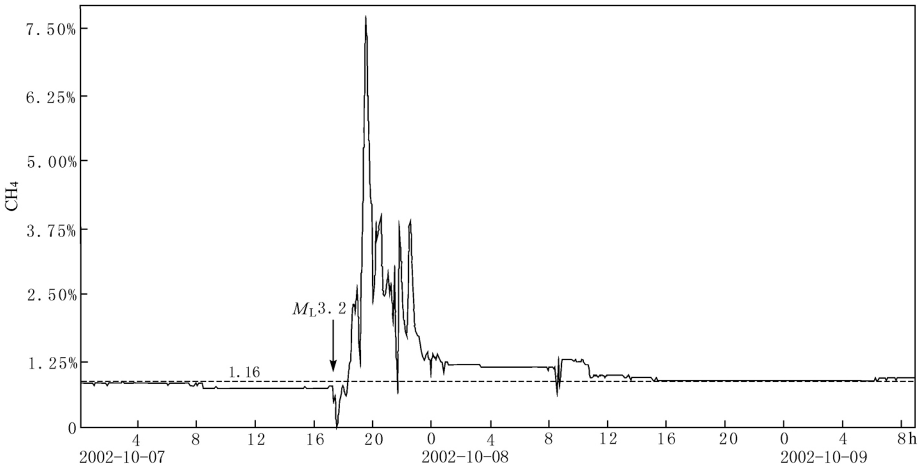

Figure 5 Curve of gas density record around the M_L3.2 seismic event on October 7, 2002 in Fushun

Figure 6 presents the locations of mining seismic events in the wake of gas outbursts. As seen in this Figure, most of the seismic events occurred in the periphery of the mining area, near the goaf section. The only one mining seismic event without gas outburst in the ten figures of gas density records is located at the east of the west open-pit mine (lower part of Figure 6, about 1.8 km away from the new mining area. This shows that the instantaneous increase in gas pressure from faraway seismic waves may unnecessarily cause immediate gas outburst, only local rupture can result in gas outburst. Most of the mining seismic events occurred near the former mining area and may cause new ruptures.

There are about nine events similar to those illustrated in Figure 5, which show that M_L1.5 mining seismic events occurred 0.5~1 hour before gas outburst. These events also show that gas density remained low for some time to various degrees just after the events and then rose up suddenly about 10~30 minutes later.

3.3 Evidence of Sunjiawan coal mine in Fuxin

According to the seismic records of the Earthquake Administration of Liaoning Province①, an M_L2.0 seismic event occurred 14 minutes before the gas explosion in Sunjiawan coal mine on February 14, 2005.

Figure 7 gives the N-S seismogram recorded by DD-1 analog micro-seismograph of Fuxin coal mine seismic station on February 14, 2005. This station is located 12.9 km southeast of Sun-

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① Earthquake Administration of Liaoning Province. 2002. Earthquake monthly report, February.

jiawan coal mine. In this map the waveform of the M_L2.0 event and the gas explosion can be seen and the arrival times of P wave are displayed respectively, which show that the seismic event occurred 14 minutes before the gas explosion.

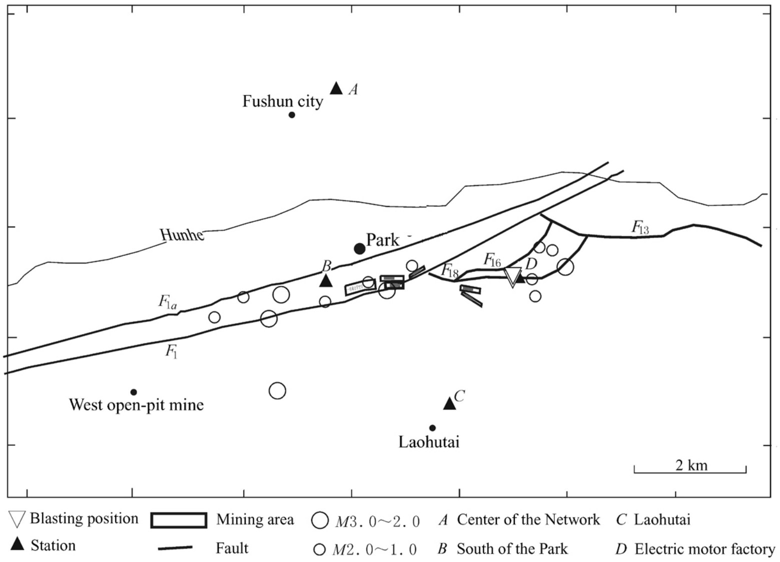


Figure 6 Locations of the mining seismic events in the wake of gas outbursts
The faults in the figure are referred to MAPSIS common software

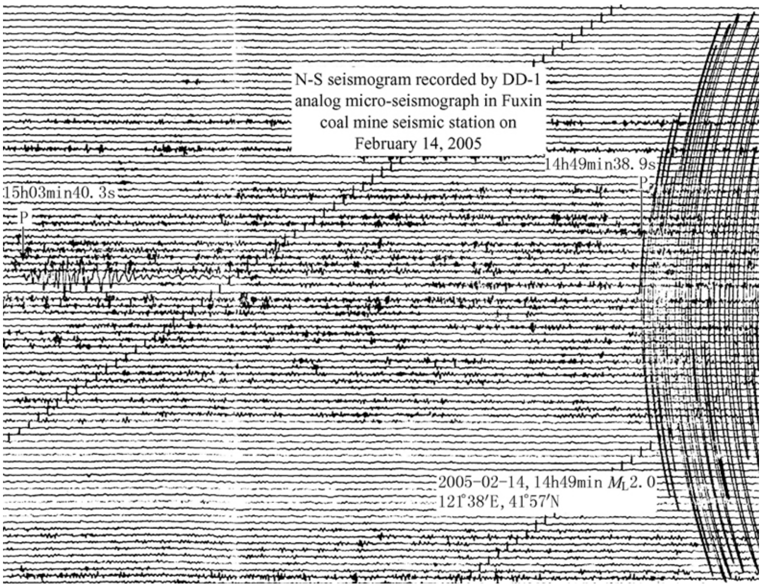


Figure 7 N-S seismogram recorded by DD-1 analog micro-seismograph in Fuxin coal mine seismic station on February 14, 2005

In this map, the amplitude of gas explosion is smaller than that of the M_L2.0 mining seismic event, because gas explosion occurred in the air and the radiated wave entered coal and rock body, featuring weak coupling.

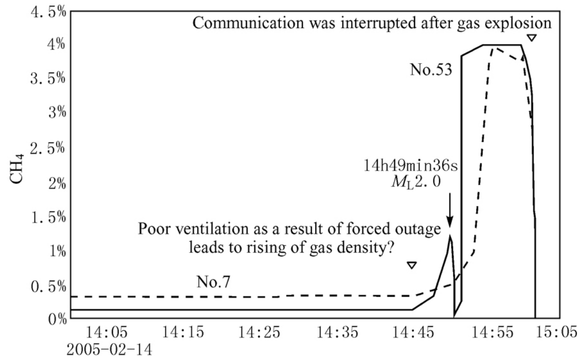


Figure 8 Gas density records at some vents in Sunjiawan coal mine, Fuxin, on February 14, 2005

Figure 8 displays gas density curves at No.7 and No.53 points of Sunjiawan coal mine on February 14, 2005. After the M_L2.0 event, gas density at No.53 point dropped promptly against the background of rising. About 3 minutes later, it rose abruptly again to 4%. At 15h03min, the communication of record was interrupted due to gas explosion following misoperation (false switching by electricians). Poor ventilation as a result of forced outage may partly account for the rising of gas density, but it cannot account for so rapid rising of gas density. Particularly, the low value response of gas density at No.53 point is similar to the condition at Fushun coal mine and is obviously the reflection of coseismic effect.

According to the in-situ investigation results by JIANG Xiu-qin *et al*, during the M_L2.0 mining seismic event, a strong shock was felt under the shaft and violent deformation phenomena like roof falling, sheeting and heaving appeared in the 3 316 mining area, which corresponds to the location of seismic center determined by seismic networks. From the above evidence, the seismic center is located near the 3 316 mining area, close to a synclinal axis.

1) More than ten pressure bumps had happened in Sunjiawan coal mine, followed by gas emission;

2) At 16 O'clock on February 19 after the accident, the maximal density of gas pouring out from the crack in the tunnel wall of outer wind way is 3.4%. Water bubbled up continually through the pond, indicating that a great deal of gas is still pouring out, in a place which roughly coincides with the location of seismic center of the M_L2.0 seismic event (LI *et al*, 2005, 2006a, b, 2007).

In general, the low value response of gas density after mining seismic events is similar to sea level response before earthquake-induced tsunami. The two phenomena may differ in terms of mechanism. The former belongs to a process of hydrodiffusion, while the latter features fluid gravity wave, yet both are essentially response of fluid to the rupture of solid. As rupture happens, the gas in the coal body must first fill the new gaps. In this way, the original exuding of gas is interrupted temporarily, resulting in temporary low gas density in the section of return airway. High pressure gas spillage cannot occur until the new gaps are completely filled. Therefore, we can come to the conclusion that this type of gas spillage reflects coseismic effect, and the existence of high pressure gas and coal-rock rupture are the basic reasons for gas spillage. The above results are of great significance in early warning concerning coal mine safety and in the study of physics of earthquake source.

3.4 Analysis of earthquake source mechanism

3.4.1 Analysis of mining seismic event in Fushun

The waveforms of seven large-magnitude mining seismic events were selected from the records of the small-aperture network and the regional network of Liaoning Province, and the focal mechanism solutions were obtained based on the vertical direction of P wave first motion.

Table 1 provides some basic parameters of the seven mining seismic events in Fushun (No.1~7).

Table 1 Basic parameters of the seven seismic events selected for focal mechanism solution

No	Date a-mo-d	Origin time h:min	Epicenter		Depth/km	M_L	Number of stations
			λ_E/°	φ_N/°			
1	2003-02-06	21:47	123.928	41.890		2.8	9
2	2003-02-21	02:54	123.932	41.892		3.0	2
3	2003-05-03	20:35	123.950	41.850	0.6	3.3	7
4	2003-08-27	14:45	123.924	41.845	0.7	3.1	9
5	2003-10-25	14:56	123.924	41.855		3.1	8
6	2004-03-10	10:46	123.925	41.845		2.6	3
7	2004-04-10	20:50	123.925	41.855		3.0	6
8	2005-02-14	14:39	121.633	41.950	0.5	2.0	9

Note: The events labeled No.1~7 are in Fushun and the event No.8 is in Sunjiawan, Funxin.

Table 2 presents focal mechanism solutions of the eight mining seismic events. Figure 9a and the row labeled 1, 2, 3, 5, 7 in Table 2 show the average focal mechanism solution of five events obtained by inversion with optimal data. It seems that this solution implies a normal fault.

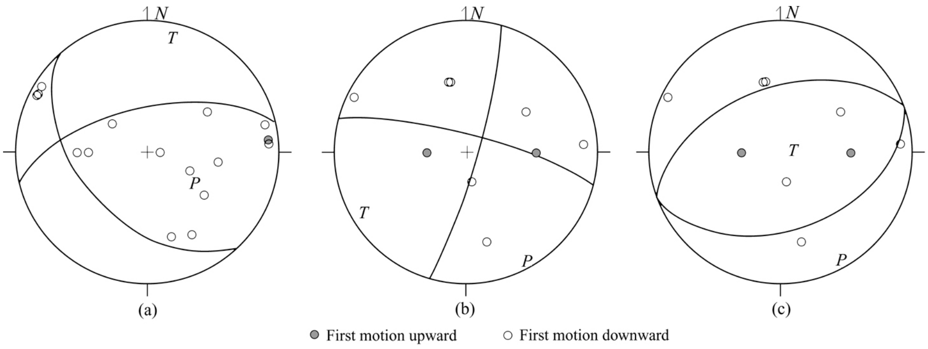
Figure 9b and the row labeled 4, 6$^{(1)}$ in Table 2 give the first possible average focal mechanism solution of No.1 and No.6 events, suggesting a strike-slip fault.

Due to the small number of seismic stations, the focal mechanism solution presented in this paper is not unique. Figure 9c and the row labeled 4, 6$^{(2)}$ in Table 2 shows the second possible average focal mechanism solution of No.4 and No.6 events, suggesting a thrust fault.

According to focal mechanism solutions (upper hemi-sphere projection of Wulff's net) of strong (major) seismic events in Liaoning Province between 1969~1999 (ZHANG and JIANG, 2001), the focal mechanism solutions of natural events in this area are quite consistent. In general, the predominant directions of stress axes are: ENE-WSW for *P* (principal compressive stress) axis, with a dip angle of 0~40°; NNW-SSE for *T* (principal tensile stress) axis, with a dip angle of 0~30°; a steep *N* (middle) axis, with a dip angle 40°~80°; the dip angle of the nodal plane is 60°~90°.

Table 2 Focal mechanism solutions of the eight mining seismic events

No.	Nodal plane I		Nodal plane II			*P* axis		*T* axis			*N* axis	
	Strike	Dip	Rake	Strike	Dip	Rake	*Az*	*Pl*	*Az*	*Pl*	*Az*	*Pl*
1, 2, 3, 5, 7	257	62	−120	137	46	−40	117	55	14	10	277	33
4, 6$^{(1)}$	16	82	11	284	79	172	150	2	240	14	50	76
4, 6$^{(2)}$	256	52	98	63	38	88	340	7	202	80	71	6
8	10	80	−90	190	10	−90	280	55	100	35	190	0



(a) (b) (c)

Figure 9 Focal mechanism of some mining seismic events in Fushun

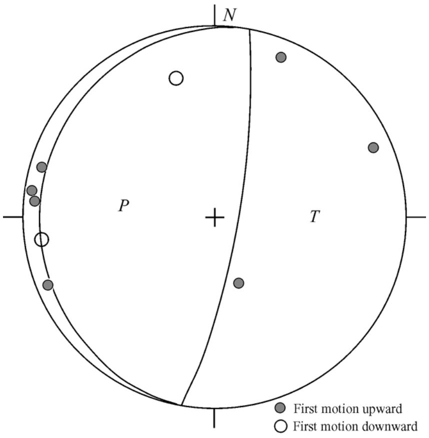


Figure 10 Focal mechanism solution of the M_L2.0 mining seismic event on February 14, 2005 in Sunjiawan coal mine, Fuxin

The results show that the average focal mechanism of the mining seismic events in Fushun is similar to that of the natural seismic events in Liaoning-Jilin area.

3.4.2 Focal mechanism of the mining seismic event before the accident on February 14, 2005 in Sunjiawan coal mine

The basic parameters of the M_L2.0 mining seismic event on February 14, 2005 in Sunjiawan coal mine, Fuxin, are shown in Table 1 (No. 8); the focal mechanism parameters of the event are shown in Table 2 (No.8) and Figure 10. The causative fault of the event is a normal fault with dip-slip as the principal feature. This kind of dip-slip is of tensile failure, and is conducive to gas outburst.

4 Mechanism analysis of the relationship between mining seismicity and gas outburst

4.1 Previous studies of the relationship between gas outburst and pressure bump

Earlier studies of the relationship between gas outburst and pressure bump (mining seismic event) can be traced back to the mid 1960's. Cook of South Africa and Huoduot of the former Soviet Union respectively put forward the energy theory of pressure bump and gas outburst. According to this theory, both pressure bump and gas outburst are caused by the rupture of coal and rock body (Buhoyino, 1985). In recent years, a series of results about the mechanism of mining seismic event and gas outburst have been obtained:

1) It has been confirmed that gas (methane) existing under the pressure at mining depth takes the form of chemical adsorption, physical adsorption (solid) and free state (YU *et al*, 1998; ZHANG *et al*, 1998; ZHANG *et al*, 2000). JING (2001) observed the relationship between the initial velocity of gas spillage and the central paramagnetic density using the spectrum of electronic paramagnetic resonance. He found that under normal condition, rising of the central paramagnetic density should agree with the steady increasing of the initial velocity of gas spillage in a borehole, but the relationship is broken when gas and coal outbursts occur. As fold increase in the initial velocity of gas spillage occurs, the spectrum line becomes narrow, indicating the central paramagnetic density is decreasing. This proves that there is another source of gas spillage at the time of coal and gas outburst, *i.e.*, the process of hydrocarbon transforming from solid and absorption state to gas state.

2) Most of the mining seismic events and gas outbursts occur at the position of stress concentration. In the process of mining and pressure relief, desorption and phase change of methane may lead to the rising of pore pressure, which is one of the important factors for triggering coal and gas outbursts (JIANG and YU, 1998).

3) The internal energy released by gas outburst from coal layer is one to three orders of magnitude larger than the elastic potential energy of the coal body (ZHENG, 1982).

These results show not only an intrinsic unity between gas outbursts and mining seismic events (pressure bump), but also a close relationship between them in the process and development.

In the following sections, we will demonstrate that there is no essential difference between formative factors of mining seismic event and pressure bump. Therefore, it is not difficult to use the above results for illustrating the relationship between mining seismicity and gas spillage (or outburst).

4.2 Failure criterion for coal and rock body

According to Mohr-Kulun criterion (Jaeger and Cook, 1979), the failure condition of rock material is

$$\tau^f = \tau_0 + f(\sigma_N - p_0) \tag{3}$$

where f is friction coefficient, σ_N the normal stress acting on the shear plane, p_0 pore pressure and τ^f shear strength of the material. Material failure occurs when the failure line is tangent to Mohr circle. $\sigma_N - p_0$ is effective normal stress. Both pressure bumps and mining seismic events are coal and rock ruptures under stress concentration, and can be judged by Mohr-Kulun criterion. For example, due to mass defect caused by coal mining, σ_N acting on the fault plane is decreased, bringing about shear failure of the fault, which is referred to as mining tremor (seismic event) in the goaf and pressure bump near the working face. These two events are only different in location, but are identical in essence.

4.3 Analysis by using defect theory

The velocity of stress adjustment is fast near coal faces of new mining sections. According to the defect theory, the time for the development of micro-fractures in these sections are short, so the density of micro-fractures is low and the magnitude of mining seismic events is small (though directly imperils the working face). In contrast, in worked-out sections and coal wedges, the time for stress adjustment is long and micro-fractures are comparatively fully developed. The time for stress adjustment is especially long in fault structures, so micro-fractures grow denser (sometimes forming fault gouge) and in a larger space. Thus, a larger quantity of strain energy is released and, accordingly, the magnitude of seismic events becomes larger. Here, it is necessary to illustrate theoretically why the density of micro-cracks is related to the time of development.

According to micro-examination and defect theory, rock failure does not happen abruptly from its original status; on the contrary, it must undergo a series of evolution processes such as initiation, growth and nucleation. Base on quasi-chemical equilibrium theory, the conversion process from order to disorder and the formation process of defect in crystal can be imitated as a quasi-chemical reaction (TANG, 1979). According to Arrhenius equation (TANG, 1979) and transition theory, the velocity constant of the basic process of the quasi-chemical reaction is

$$k_{V_N} = A\exp\left(-\frac{U_0}{kT}\right) \tag{4}$$

where U_0 is activation energy, T is absolute temperature, k is Boltzmann constant, γ is the characteristic parameter of the material and A is pre-exponential factor or frequency factor. When the specimen is subjected to the external force F, the atomic binding energy decreases to $U_0 - \gamma F$. At this moment, the growth velocity of defect or micro-crack is

$$k_{V_N} = A\exp\left(-\frac{U_0 - \gamma F}{kT}\right) \tag{5}$$

And then, life of the specimen is (Zhurkov, 1965)

$$t = t_0 \exp\left(\frac{U_0 - \gamma F}{kT}\right) \tag{6}$$

where t_0 is the period of self-excited vibration of atoms in the solid, $t_0 \approx 10^{-13}$ s. A series of experiments were carried out later with many kinds of material. The results show that this formula can satisfy all kinds of material, including rocks (Kuksenko *et al*, 1996).

The above-mentioned theory indicates that the development of micro-cracks is related to stress state and the course of time. In the medium with uneven stress distribution, the growth rate of micro-cracks varies in different positions, and an exponential relation is found between the magnitude of stress and the growth rate of micro-cracks. In the area of stress concentration, the growth rate of defect and micro-cracks is fast, bringing a process zone into existence.

Near the working face, the stress difference among different sections becomes rapidly larger because of the fast unloading rate, leading to premature coalesce, nucleation, instability and eventually shear failure in the local process region; meanwhile, the density of micro-cracks developing in other locations is not high enough, as a result, the scale of shearing instability is restricted, the scope of buckling deformation is small and the magnitude of mining-shocks is small as well (first kind of mining seismic events).

Most of the second kind of mining seismic events take place in large seismic structures (especially active faults), and a small number occur in the goaf area. In these regions, damage has developed for a long time and, therefore, micro-cracks grow widely and fully, and the degree of soundness becomes low while porosity becomes high. These are all favorable conditions not only for mining seismic events, but also for gas desorption and outbursts. The area of goaf is much larger than that of the new working faces (especially in old mines with tens or even hundreds of years' mining history), therefore, strong mining seismic events (the second kind) are more likely to take place in goaf areas. When the second kind of mining events are close to the working face or roadway, they may cause damage and casualties.

5 Relationship between mining-induced seismicity and fluid

What is significant about the relationship between mining seismicity and gas outburst is that it shows the origin of some mining-induced seismic events is related to fluid. This shows no difference from coal and gas outbursts observed at working faces. Available findings have shown the effect of fluid on mining seismicity as follows:

1) Pore pressure boost [the increase of p_0 in equation (3)] may trigger mining seismic events. In the process of pressure relief during mining, methane is desorbed and enters pores in a free state; as a result, pore pressure p_0 is boosted.

2) Stress corrosion lowers the intensity of coal body, *i.e.*, f and τ_0 in equation (3) diminish. HE *et al* (1996) studied the effect of stress corrosion of methane on coal body. They found that gas absorbed on coal can reduce the free energy of coal surface, and thus reducing the strength of coal.

Regarding the effect of fluid, special attention should be paid to supercritical fluid, as it has many anomalous properties and effects. These properties are closely related to the dynamic processes of rock failure, fault activity and geological movement.

Supercritical fluid is defined as non-coacervation high-density fluid with temperature and pressure above their respective critical values (Yasuhilo and Takeshi, 1993; XIE, 1997). For example, the critical temperature and pressure are respectively 374 °C and 22.06 MPa for water, −82.3 °C and 4.64 MPa for methane and 31 °C and 7.38 MPa for carbon dioxide. Supercritical fluid has a series of special properties:

1) Supercritical fluid has a density between those of gas and fluid, thus, many of its physical properties, such as diffusion coefficient and viscosity, are between those of gas and fluid.

2) As dissolvent, the most obvious property of supercritical fluid is that subtle change of pressure can lead to significant change in density. In general, solubility is related to density, so, boosting pressure can increase the density of supercritical fluid, and thus, increasing solubility.

3) The permeability of supercritical fluid is much greater than that under normal temperature and pressure, therefore, deep lying intercommunication cannot be weakened even when porosity is decreased (XIE, 1997).

Therefore, when the density of supercritical fluid is similar to that of liquid, its diffusivity is higher while its viscosity is lower as compared with liquid. Thus, supercritical fluid has many properties superior to those of ordinary liquid as a dissolvent.

These properties of supercritical fluid provide new approaches for us to study the relationship between mining seismicity and gas outburst. HE *et al* (1996) found that, when gas pressure is high and gas energy is higher than the bond energy of coal molecule (or atom), the gas molecule can then wedge into the interval of bigger molecules (with a diameter equivalent to that of gas) or aromatic layers of coal. After the gas molecule enters the micro-crevice, it stays there in the form of solid solution and cannot be desorbed easily. HE (1996) concluded that the coal body will dilate due to surface energy degradation after coal absorbs gas. The macro dilation of coal follows an exponential pattern as the gas pressure rises. Especially for the coal with initial value of d^{002} (interval between aromatic layers in the carbon unit, i.e. interval of plane net) greater than 4A°, the third type of deformation will appear. The most noticeable phenomenon is that, under gas pressure 2.2~6.1 MPa, the parameter d^{002} increases rapidly, and the most rapid increase appears at the pressure 4.5 MPa. We notice that this pressure is just the critical pressure of methane. As the experiment was carried out under room temperature, then methane is just supercritical fluid. Hence, the experiment of HE (1996) indicates that supercritical methane really has the property of increasing the solubility of the dissolvent (coal).

We notice that at the depth of 500 m, some mining operations have reached the depth where methane and carbon dioxide are in the supercritical state. For instance, the average gas pressure at the depth of 730 m is measured to be 4.5 MPa in Laohutai coal mine, Fushun (SUN, 2001). Therefore, apart from stress increase, the origin of some mining tremors might be related to the desorption of supercritical methane (or carbon dioxide) in the process of pressure relief during mining. The above theory can account for the common phenomenon in coal mines both home and abroad that the magnitude and frequency of mining tremors (or pressure bump) increase rapidly when mining reaches the depth of about 500 m.

6 Discussion and conclusions

The above analysis also brings new ideas for the study of origin of tectonic earthquakes.

Recently, a general condition has been proposed for fault fracture with super-S-wave velocity that the uncracked section at the front end of the fault must be in the critical state, i.e. the distribution of shear stress must reach shear-resistance level, and this section has become slip-weakening zone, also known as fully developed process region. In fact, shear fracture with super-S-wave velocity is the result of new ruptures in these sections triggered by P wave. That means the potential rupture sections should have the conditions for rapid energy boost. According to Mohr criterion, we propose a hypothesis that the rapid desorption of supercritical fluid in the activated sections caused rapid boost of pore pressure, which may satisfy the above conditions. In this way, the crux of the problem becomes whether or not the evidence of dynamic action of fluid can be found. Are there really dynamic actions of fluid in the seismic source? So far, some circumstantial evidences have been found by seismic observations, such as low-frequency microseism before large events, however, these evidences are not cogent enough and they can not be used as direct evidences. This is because fluid actions are mostly in the interconnected pores, while seismic records mainly reflect surface movement of solid framework. One of the important ways for study is to find evidences from moderate-scale experimental fields according to the principle of comparability.

The most significant development in the study of mining seismicity across the world is the verification of similarity between mechanisms of mining-induced seismicity and natural earthquakes. ① Both have components of double couple source; ② Both have similar seismic moment and stress drop (Gibowicz and Kijko, 1994), which satisfy scale invariance proposed by Kanamori (Kanamori and Anderson, 1975). The two similarities, plus the visibility of mining seismic sources, are important evidences for mines to become international moderate-scale experiment fields for studying natural earthquakes. We believe that the fluid behavior of methane (including carbon dioxide) in the cause of mining seismicity and water at a depth of more than ten kilometers in the crust are all at supercritical states, therefore they have similar desorption effects. In the occurrence of earthquakes, they both play the role of triggering rupture and releasing strain energy. If this assumption could be justified, the third similarity between mining seismicity and natural earthquakes, *i.e.*, similarity between physical mechanisms of fluid effect, could also be verified.

The conclusions from this study are based solely on the observation data on hand, further study depends on more observations in mines.

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