

Article

Effect of Primary Fracture Orientation on CO₂ Fracturing in Coal Seam Stress Relief

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Abstract

CO₂ fracturing (CO₂-Frac) is a novel technology for coal mine gas control, which is distinct from CO₂ Enhanced Coalbed Methane, and has been applied to alleviate in situ stress concentration and to eliminate coal and gas outbursts in coal mines. However, the reasons for the greatly varying effects of CO₂-Frac application among different regions remains largely unknown, and the influence of geological structures, particularly pre-existing fracture orientations, remains poorly understood. The equipment system of phase fracturing and permeability improvement of low-permeability coalbed methane and the gas phase fracturing and permeability improvement technology are studied and analyzed, and the engineering application is carried out in the head face of Xinyuan Coal Mine. This study conducted three CO₂-Frac experiments in the Xinyuan coal mine in which borehole orientations were varied, with the primary fracture strike of coal seam #3 in the Shanxi Formation ranging from N3°E to N15°E. The characteristics of reservoir stress redistribution after CO₂-Frac and its mechanism controlled by the orientation of primary fractures were explored based on the analysis of microseismic focal mechanisms. The results showed that (1) Both the fracturing section and the buffer section determined the stress relief effect of CO₂-Frac. While the different experiments showed largely similar stress relief effects of the fracturing section, the effects of the buffer section greatly differed. (2) The microseismic events generated by the CO₂-Frac in the borehole with an N–S orientation showed a more concentrated spatial distribution, with higher proportions of tensile and dip-slip events. (3) The range of the stress relief in the buffer section of the borehole with an N–S orientation exceeded those of the other sections. Further geological analysis revealed that higher stress relief was achieved in both boreholes with a N–S orientation and a smaller angle between the borehole direction and the primary fracture orientation (angle BF). An improved numerical calculation model that integrated fracture mechanics and gas reservoir engineering was used in this study; the result showed that an improved CO₂-Frac effect was achieved under a BF angle of 0–21°, in good agreement with the field experiment results. The results of this study can help improve the effectiveness of CO₂-Frac and reduce the occurrence of coal and gas outbursts.

Keywords: CO₂ fracturing; microseismic; stress drop; stress relief; primary fracture orientation

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1. Introduction

CO₂ fracturing (CO₂-Frac) is a novel method for mitigating coal mine gas outburst disasters, which is distinct from CO₂ Enhanced Coalbed Methane (CO₂-ECBM), acid-washing, and water flooding. CO₂-Frac applies high-pressure CO₂ gas on the coal seam

to form fractures and to re-stretch the primary cleat in a specific station [1]. The main applications of CO₂-Frac in regulating coal mine gas relate to increasing the permeability of the coal reservoir and the efficiency of gas extraction, relieving the stress on the coal seam, and reducing or eliminating the risk of coal and gas outbursts [2]. While CO₂-ECBM generally uses low pressure CO₂ injection into coal seams, utilizing the competitive adsorption mechanism between CO₂ and CH₄ to displace methane production [3,4], and acid-washing and water flooding are both methods for improving oil recovery in petroleum extraction [5,6]. Although CO₂-Frac has been widely applied in China, the effectiveness of this method varies among different regions. Therefore, there is an important need to develop a method for effectively evaluating the effect of CO₂-Frac and to identify approaches for optimizing its effect.

The mechanism under which CO₂-Frac induces damage to the coal seam can be divided into two stages: (1) the stress wave resulting from the CO₂ jet damages the coal; (2) the high pressure of the CO₂ gas re-opens the primary cleat. The primary cleat in the coal does not regulate the new fracture system formed by the stress wave since the pressure of the CO₂ jet is generally 80–200 MPa, which far exceeds the compressive strength of the coal [7,8]. However, the subsequent process results in a rapid decrease in borehole pressure, with its effect on the re-opening of the cleat closely related to in situ stress, fracture density, and fracture orientation [9,10]. Since it is not possible to change in situ stress and the density of the cleat, adjusting the drilling direction according to the extension direction of the primary cleat has become an effective method of optimizing the effect of CO₂-Frac [11]. Unfortunately, there remains little published research on optimizing the effect of CO₂-Frac, particularly on the optimal angle interval between the fracture orientation and borehole direction. The large quantity of gas blown into the fracture after CO₂-Frac increases the pore pressure and reduces effective stress, thereby providing mechanical conditions conducive to the extension of tensile fractures [12]. A tensile fracture generally indicates a zone undergoing relaxation stress [13], which is beneficial to eliminating the risk of coal and gas outbursts [14,15]. Therefore, the ratio of tensile fractures to the distribution of stress in the affected zone is a key index for evaluating the effect of CO₂-Frac. Given the effectiveness of the microseismic method for evaluating reservoir fractures and in situ stress, this method has become increasingly important within the development of unconventional oil and gas [16,17]. An analysis of the focal mechanism can allow the inversion of the mechanical properties and stress drop of each fracture [18–20], which is important for evaluating the reduction in stress around the fracture [21]. Microseismic monitoring has been widely proven as a feasible and reliable method for evaluating the effect of CO₂-Frac [22,23], and the research results have been publicly reported in terms of crack growth, stress state description, and evolution [24,25].

The aim of the present study was to identify the mechanisms under which the effect of CO₂-Frac application varies among different conditions by conducting field experiments in the Xinyuan coal mine, northern Qinshui Basin, China. The results of the present study can guide the optimization of CO₂-Frac in coal and gas outburst control, and the methods used in the present study can also be applied to studies relating to gas fracturing, including power ultrasounds, controllable shock waves, and explosive blasting.

2. Experiments and Results

2.1. Geologic Setting

This study was conducted in the Xinyuan coal mine, Yangquan City, Shanxi Province, China (Figure 1a). The study area falls along the northern edge of the Qinshui Basin, bounded by the Taihang Mountain uplift to the east and the Fenhe graben to the west, respectively (Figure 1b) [26]. The present study focused on the coal seam in the lower part of

the Permian Shanxi Formation at a burial depth of 500–650 m and with an average thickness of 2.80 m (Figure 1c). The coal in the study area is classified as anthracite with a firmness coefficient of about 0.5. The roof and floor of the mine are composed of carbonaceous mudstone with a mechanical strength far exceeding that of the coal seam. A group of conjugate cleats has developed in the coal seam. The strike orientation of the face cleat is NE3–15° (Figure 1d), which dips to the west at an angle generally exceeding 60° [27]. The strong deformation has contributed to a relatively small extension distance of the cleat in the coal seam. The cleat is mostly closed, without a clear opening.

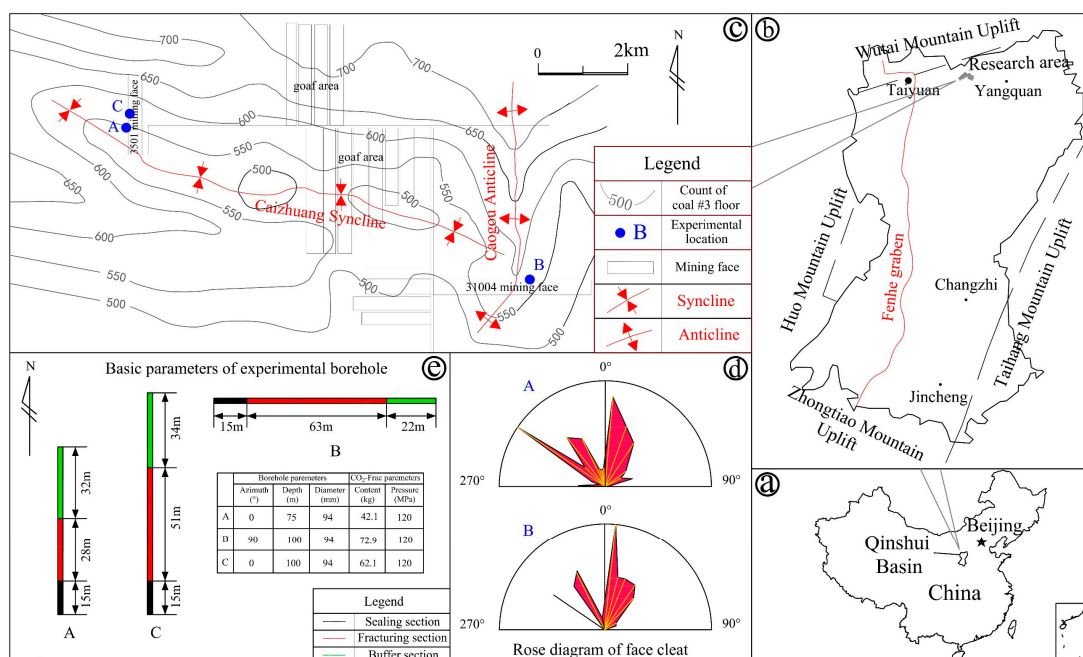


Figure 1. Schematic diagram of the basic parameters of the experimental area. (a) Location of the study area; (b) Location of the test site; (c) Contours of the No. 3 coal seam floor near the study area; (d) Rose diagram of face cleat; (e) Basic parameters of experimental borehole.

2.2. CO₂ Fracturing

CO₂-Frac is a gas blasting technology applied for directional multi-fracturing of low-permeability reservoirs and has played an important role in gas control of coal mines in recent years [1]. Figure 2 shows a schematic diagram of the CO₂-Frac system. The explosion resulting from the application of CO₂-Frac produces a stress wave and high-pressure expanding gas. This in turn generates a pulverized zone and a fracture zone, which increases the permeability of the coal seam and forms a stress relief zone. The connectivity of the new cracks and primary fractures within the stress relief zone acts to homogenize and release in situ stress and gas pressure, thereby greatly increasing the permeability of the coal seam.

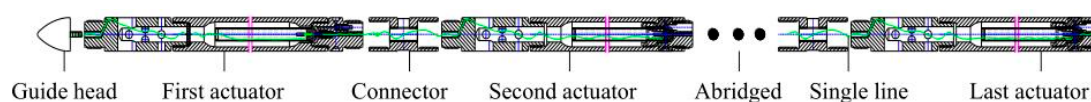


Figure 2. Schematic diagram of the CO₂-Frac device.

The present study conducted three groups of parallel tests (Figure 1e): group A with a borehole depth of 75 m, direction of N0°, and 20 filled actuators; group B and group C with borehole directions of E0° and N0°, and filled actuators of 33 and 27, respectively, and both with a borehole depth of 100 m. A fracturing pressure of 120 MPa was applied to all

three groups, and the mass of liquid carbon dioxide used by a single actuator was ~2.2 kg (Figure 2).

2.3. Microseismic Monitoring

Microseismic monitoring is a geophysical technique involving the observation and analysis of microseismic events and is used to monitor the influence of production activities [28]. Highly sensitive microseismic monitoring stations were established at different locations around the fracturing zone. The stations continuously recorded the microseismic data generated by the coal seam fracturing or fracture extension. The orientation, scale, mechanical properties, and stress drop of fractures were determined after deep processing and inversion.

Surface microseismic monitoring generally involves both permanent and temporary monitoring. Permanent monitoring is typically conducted over the long term to assess the risk to the safety of high-stress coal mining and underground gas storage. In contrast, temporary monitoring can persist over a few hours to several days, with the collected data used to manage temporary production activities. Between these two categories of monitoring, temporary monitoring is more widely used and is more mature. Consequently, the present study applied temporary microseismic monitoring to investigate the effect of CO₂-Frac by calculating the radius of influence of CO₂-Frac, inverting the resulting fracture development and stress relief, and providing reliable parameters for safe tunneling of the roadway and efficient gas extraction.

The present study established a temporary monitoring system consisting of 12 stations operated under the three-component acquisition mode. A global positioning system (GPS) was set at the front of each station to ensure a sampling rate of 1000 reads per second. The present study applied geophone sampling bits and effective bits of 32 and 22, respectively, with this system able to record a minimum earthquake magnitude of up to -3 .

The present study adopted a rectangular arrangement of monitoring stations, with the long axis parallel to the drilling direction. As shown in Figure 3, in the extension direction of the testing borehole, the stations covered 1.2–1.5 times its length; and in the radial direction, the stations covered 30–40 m on both sides.

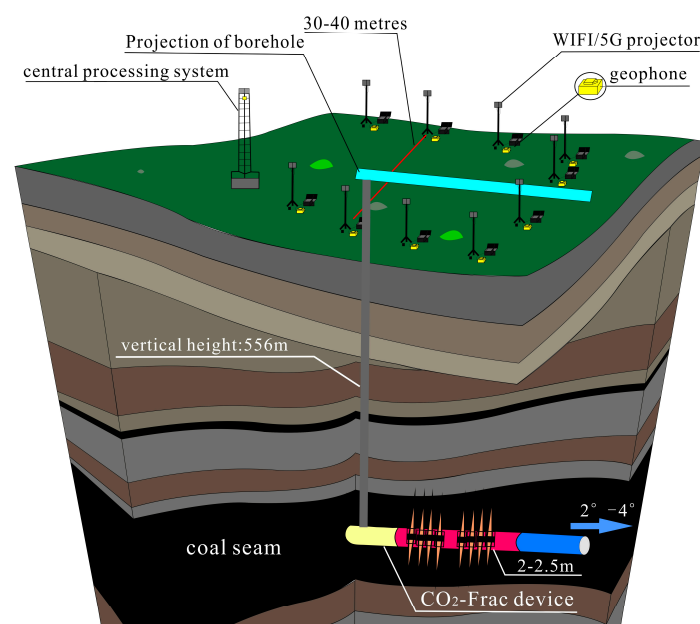


Figure 3. Schematic diagram of the layout of the microseismic monitoring ground stations implemented in the present study.

3. Methods

Microseismic monitoring associated with stress changes in and around the reservoir can be used to probe the reservoir dynamics in response to external and internal perturbations. A microseismic event analysis can be used to locate the fracturing and determine the orientation, height, length, complexity, and temporal growth of the induced fracture by using the recovered focal mechanism [29,30].

The focal mechanism of an earthquake describes the deformation in the source region that generates the seismic waves. In the case of a fault-related event, it refers to the orientation of the fault plane that slips with the slip vector, also known as a fault-plane solution. The focal mechanism is derived from a solution of the moment tensor for the earthquake, which is estimated by an analysis of observed seismic waveforms [19]. Based on the microseismic focal mechanism, a series of source parameters including stress drop, seismic moment, and magnitude can be analyzed. To achieve the main aim of quantifying the effect of primary fracture orientation on stress relief, we employed microseismic monitoring. The spatial distribution of events delineates the fracture network, while the calculated stress drop serves as a direct metric for quantifying the intensity of stress relief in different experimental groups.

3.1. Stress Drop

Microseismic events are driven by stress in the crust of the Earth. These microseismic events can result in changes to the stress field as they release and redistribute stresses accumulated during the inter-seismic period [24]. Changes in microseismic-induced stress can be observed through the inversion of the focal mechanisms of sets of microseismic events to obtain the stress orientation, with the stress drop acting as the correlation parameter [31–35].

Stress drop $\Delta\sigma$ during an inter-seismic period is quasi-static and directly related to microseismic events, the focal medium, and in situ stress. The Brune model has been generally used to characterize the stress drop of microseismic events, typically expressed as [36]:

$$\Delta\sigma = \frac{7}{16} \cdot \frac{M_0}{R^3}, \quad (1)$$

where M_0 is the seismic moment (N·m) and R is the scale of the fracture (m).

Although the Brune model assumes a circular fault plane, it provides a robust first-order approximation for estimating stress drops associated with the complex fracture network generated by CO₂ fracturing, as commonly applied in microseismic analysis [37,38]. The calculated stress-drop values are thus used for comparative analysis between experiments rather than as absolute measures.

3.2. Description of the Distribution of Stress Drop

Fracturing-related stress drop is reflected in stress disturbance around fractures, with its distribution regulated by the scale, properties, and focal mechanics of fractures. The calculated stress field induced by artificial fractures is important for describing the fracturing effect. Many previous studies have shown that stress drop has an ellipse-shaped range of influence with the fracture plane acting as its major axis and the ratio of the major axis to the minor axis of 1.3–1.6 [39–43].

Based on the above theory, the present study plotted cloud maps of stress drop for the three conducted experiments. The present study used the locations of the microseismic events, fracture scale, strike direction, and stress drop generated by the CO₂-Frac to describe the stress drop. The discretization network model and interpolation method were used to map the distribution of stress drop, with an average ellipse axis ratio of 1.4.

4. Results and Discussions

The present study conducted three groups of microseismic monitoring tests. As shown in Figure 4, the experiments provided clear waveforms in which the traveling time of the seismic activity could be accurately distinguished.

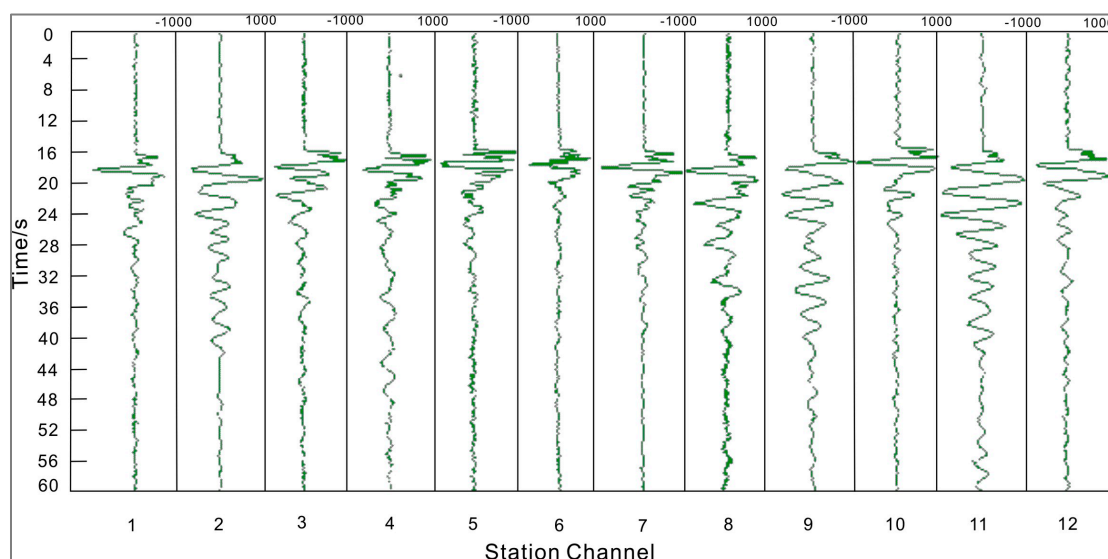


Figure 4. Seismic waveforms produced by CO₂-Frac.

4.1. Spatiotemporal Distribution of Microseismic Events

The sonic logs of the adjacent well were used to construct a detailed velocity model with 12 layers. A database of event locations was then prepared for fracture imaging. Figure 5 shows the distributions of the microseismic events at 1 min, 3 min, 5 min, and 10 min after the CO₂-Frac in each group.

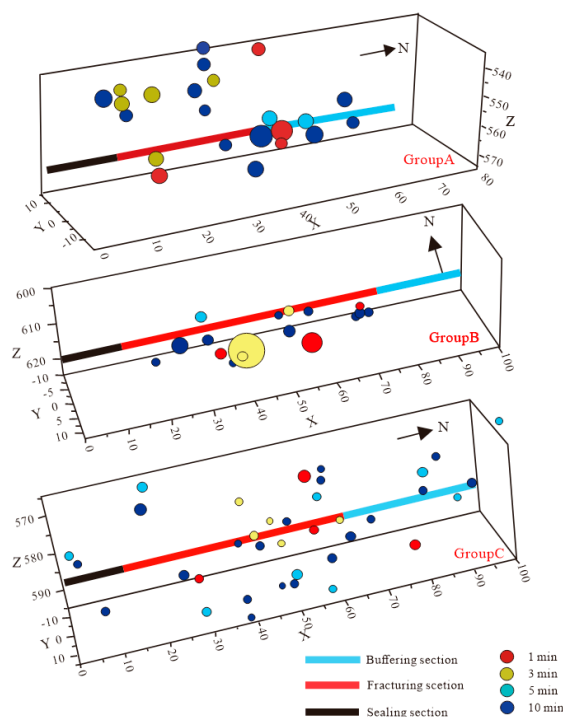


Figure 5. Distributions of microseismic events from 1 to 10 min after CO₂-Frac.

The microseismic events in group A were generally distributed along the N–S direction with a length of ~80 m and a sweep area in the E–W direction of ~17 m; those in group B showed a mostly concentrated distributed along the N–S direction with a length of ~60 m and an affected area in the E–W direction of ~18 m; those in group C were distributed along the N–S direction, as in group A, with an affected length and width of 110 m and 15 m, respectively. The microseismic events were uniformly distributed in strips.

The seismic source parameters, including the fracture scale, source property, seismic moment, and stress drop, provide important information for characterizing the attributes and effects of fractures. The 77 groups of effective microseismic events obtained in the three experiments were successively extracted. These events consisted of 25, 20, and 32 groups of tensile, dip–slip, and strike–slip fractures, respectively. The scale and corresponding stress drop of the fractures ranged between 10.81 and 48.63 m and 0.24 and 1469.57 kPa, respectively. Table 1 and Figure 6 show a statistical summary of parameters and the distribution of fractures, respectively.

Table 1. A statistical summary of the source properties of microseismic events.

Test Serial	Seismic Dots	Focal Mechanism			Fracture Scale (m)	Stress Drop (kPa)
		Tensile	Dip–Slip	Strike–Slip		
Group A	23	4	4	15	16.21–34.22	0.24–569.81
Group B	16	5	2	9	10.81–48.63	1.53–1469.57
Group C	38	16	14	8	10.81–18.01	24.62–992.72

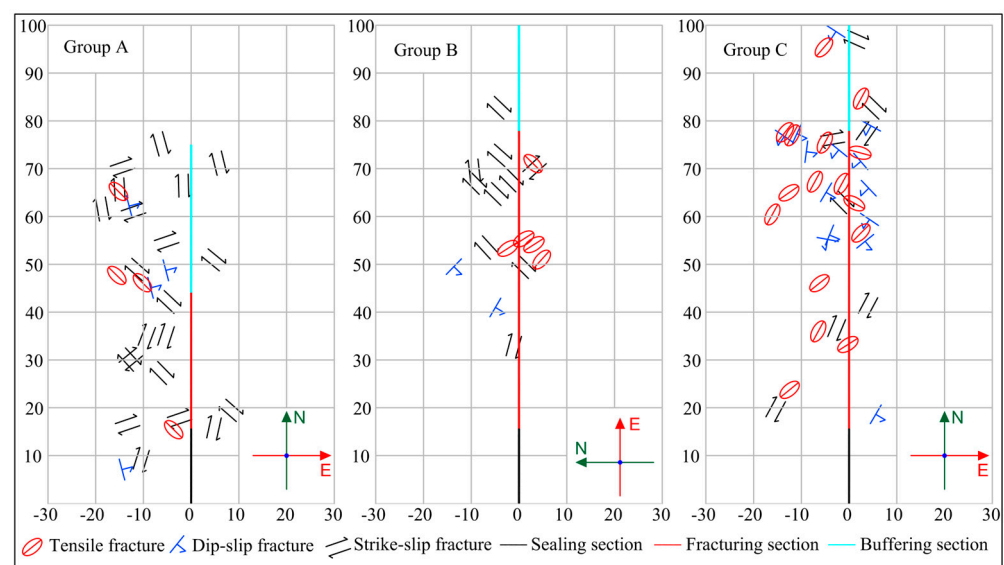


Figure 6. Distribution of different types of microseismic sources.

4.2. Shape of the Stress Relief Zone Formed by CO₂-Frac

The CO₂-Frac created a complex fracture network in the coal seam [44]. This network consisted of three different types of fractures: radial fractures, reopened fractures, and invisible micro-fractures. The fracture network formed by the fractures, characterized by variable properties and scales, coupled with the range of disturbance of in situ stress in the reservoir, constituted the stress relief zone.

The shape of the stress relief zone was generally ellipsoid with a volume of [25],

$$V = 4\pi abc/3, \quad (2)$$

where a and b are the radii of the ellipsoid, representing the maximum scales of the stress disturbance in the horizontal and vertical directions in the coal reservoir, respectively, and the latter generally equivalent to the thickness of the coal seam; c represents the radius of the pole of the ellipsoid, which represents the range of the stress disturbance in the axial direction of the borehole.

The radius of the stress relief zone (a) in the horizontal direction was determined by the fracture scale generated by the CO₂-Frac. The fracture scale can be calculated as the scale of the microseismic source.

In the Brune model, the disk radius r represents the size of the source [45]:

$$r = \frac{t_2 - t_1}{3\pi} \cdot 4\sqrt{2}V_p \quad (3)$$

where r is the source size (m), t_1 is the take-off moment of the arrival signal, t_2 is the peak moment of the arrival signal and $t_2 - t_1$ is the half period of microseismic event arrival signal (s), and V_p is the P-wave velocity (m/s).

The P-wave velocity (V_p) was determined by the structure of the formation in the study area, and the half period of the initial motion of the microseismic wave ($t_2 - t_1$) was related to the source frequency of the CO₂-Frac. The frequency had negative and positive relationships with the half period and fracture scale, respectively.

The polar radius of the stress relief zone was calculated as:

$$c = c_1 + c_2, \quad (4)$$

where c_1 is the fracturing section of the borehole, representing the radial fracture section generated by the CO₂-Frac shock wave, and c_2 is the pressure buffer section in front of the fracturing section; i.e., the reopened fracture section formed by the high-pressure gas in the buffer section in front of the borehole.

A single borehole used 10–40 actuators in which adjacent tubes were connected by a specialized wireline. Each actuator conducted one blast that produced a single set of fractures in the coal. Therefore, 20 actuators produced 20 blasts and produced 20 sets of radial fractures in the coal. The length of each actuator was 2–2.5 m. The number of actuators used in one operation was proportional to the length of borehole section being fractured. Therefore, c_1 was mainly determined by the number of actuators used in a single borehole.

The fracturing effect was optimized by reserving a 20–50 m pressure buffer section in front of the fracturing borehole. The mechanism contributing to primary fractures in the coal reservoir differed from that producing radial fractures in the fracturing section, with the former reopened by the high-pressure gas produced by the CO₂-Frac in the buffer section. The re-opening of the fractures generally produced slight dislocation on the fracture surfaces, thereby releasing stress. This release of stress in the buffer section (c_2) directly determined the polar radius of the ellipsoid (c), thereby affecting the shape of the stress relief zone.

Within extremely heterogeneous coal seams, the direction of extension of the fractures induced by CO₂-Frac and its angle of intersection with the primary fractures in the coal seam have considerable influences on the fracturing effect. In general, the direction of the borehole is perpendicular to the coal wall, and the direction of the CO₂-Frac is conveniently determined by the drilling direction of the borehole.

In contrast, the results of the experiments conducted in present study showed that a small angle between the drilling direction and the direction of the primary fracture produced a longer stress disturbance in the buffer section (Figure 7).

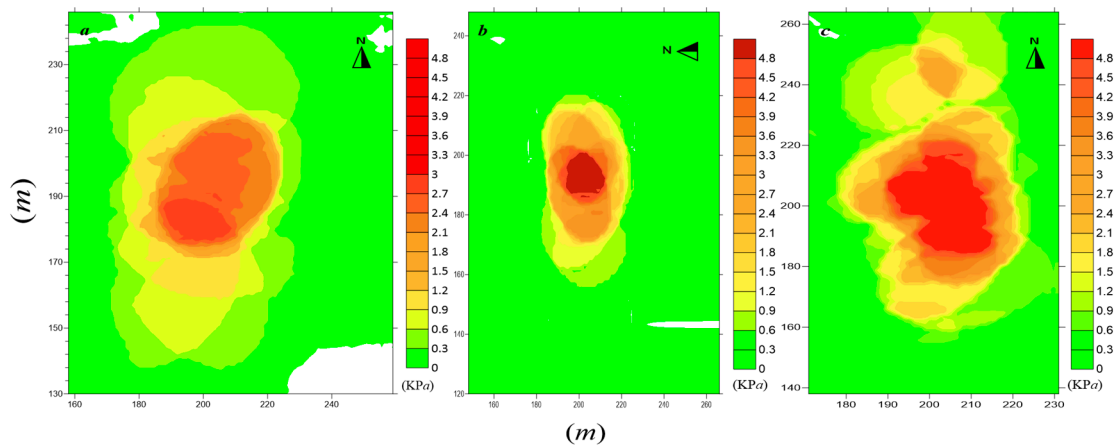


Figure 7. Stress-drop cloud maps for the three experiments conducted in the present study for (a) Group A, (b) Group B, and (c), Group C.

CO₂-Frac fracturing is analogous to intensive perforation operations, and its improvement in the formation skin factor can be referred to as the impact of perforation operations on the skin factor [46]. proposed that the total skin factor of perforation S_{pf} can be decomposed into the combined skin factor S_p and the skin factor of perforation compaction damage S_c . And the perforation geometry skin factor S_p is divided into radial flow seepage skin factor S_h , vertical skin factor S_v , and wellbore skin factor S_{wb} .

$$\begin{aligned} S_p &= S_h + S_v + S_{wb} \\ S_h &= \ln(r_w/r_{we}) \\ r_{we} &= \alpha(r_w/l_p) \end{aligned} \quad (5)$$

In the formula, r_w is the wellbore radius, m; r_{we} is the effective wellbore radius, m; and l_p is the penetration depth of the borehole, m. Due to the large number of fractures formed by CO₂-Frac and their transverse intersections, α is generally taken as 10–30.

The wellbore skin factor is $S_{wb} = C_1 \exp(C_2 r_{wd})$; among which r_{wd} is the dimensionless wellbore radius, $r_{wd} = \frac{r_w}{r_w + l_p}$. For CO₂-Frac, C_1 is generally taken as 0.001–0.1, and C_2 is generally taken as 2–5.

Due to the relatively small thickness of the coal seam in the CO₂-Frac operation area, the variation in the vertical skin factor S_v can be ignored. And then the reservoir skin factor at different positions from the wellbore after CO₂-Frac fracturing was calculated.

From Table 2 and Figure 8, it can be seen that within a range of 20 m, the skin factor is negative, and the permeability is greatly improved. The settlement results of the skin factor and the stress-drop distribution cloud map have a high degree of agreement, which confirms the transformation effect of CO₂-Frac from another perspective.

Table 2. Comparison of crack location and skin coefficient relationship.

l_p	α	r_w	r_{we}	r_{wd}	C_1	C_2	S_h	S_{wb}	S_p
0.1	25	0.06	15	0.375	0.0005	3	−5.5215	0.0015	−5.5199
0.2	25	0.06	7.5	0.230769	0.0005	3	−4.8283	0.0010	−4.8273
0.5	25	0.06	3	0.107143	0.0005	3	−3.9120	0.0007	−3.9113
1	25	0.06	1.5	0.056604	0.0005	3	−3.2189	0.0006	−3.2183
2	25	0.06	0.75	0.029126	0.0005	3	−2.5257	0.0005	−2.5252
5	25	0.06	0.3	0.011858	0.0005	3	−1.6094	0.0005	−1.6089
10	25	0.06	0.1	0.005964	0.0005	3	−0.9163	0.0005	−0.9158
20	25	0.06	0.075	0.002991	0.0005	3	−0.2231	0.0005	−0.2226
30	25	0.06	0.05	0.001996	0.0005	3	0.1823	0.0005	0.1828

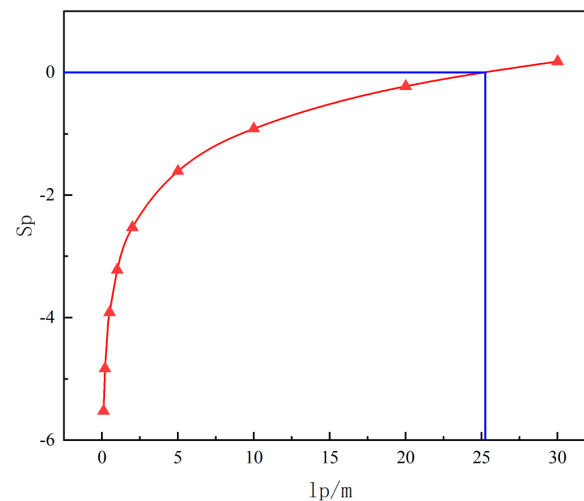


Figure 8. Map of crack location and skin coefficient relationship.

4.3. Effect of the Orientation of Primary Fractures on Stress Relief and Its Rationality

Irwin divides simple cracks into three types [47]. Crack-type I, also known as tensile crack, is formed by a stress perpendicular to the crack surface; and crack-types II and III are formed under the action of shear stress, where crack-type II is the shear crack in plane, and crack-type III is the shear crack out of plane or anti-plane. All of the complex cracks can be composed of these simple cracks, which are called composite cracks. There are many mathematical methods to analyze the stress field and displacement field at the crack tip. Here, we use the complex variable function method to analyze the distribution of stress around CO₂-Frac cracks.

The I-type represents the case where the displacement of the crack surface is perpendicular to the crack surface under the tensile stress perpendicular to the crack surface, so it is also called the open type. The II-type and III-type cracks represent the case where the crack surfaces slip past each other under the action of shear stress, which is called shear-type cracks. The II-type crack is called in-plane shear crack; type-III crack is called an out-of-plane shear crack or anti-plane crack. More complex cracks can be composed of these simple cracks, which are called composite cracks. There are many mathematical methods to analyze the stress field and displacement field at the crack tip. Here we use the complex variable function method.

The reopened fractures formed by the high-pressure gas were of typical composite crack-types I – II according to fracture mechanics, with the stress component in the polar coordinates of the crack front expressed as [48],

$$\sigma_{\theta\theta} = \frac{1}{2\sqrt{2\pi r}} \cos \frac{\theta}{2} [K_I(1 + \cos \theta) - 3K_{II} \sin \theta] + o(r^{-\frac{1}{2}}). \quad (6)$$

where K_I is the stress intensity factor of crack-type I, K_{II} is the stress intensity factor of crack-type II, r is the distance between point (x, y) and $(0,0)$, θ is the angle between the crack and the maximum horizontal principal stress, and $\sigma_{\theta\theta}$ is the stress component.

As shown in Figure 9, the maximum circumferential tensile stress criterion stipulates that a crack following the corresponding direction of θ should obey

$$\frac{\partial \sigma_{\theta\theta}}{\partial \theta} = 0, \frac{\partial^2 \sigma_{\theta\theta}}{\partial \theta^2} < 0. \quad (7)$$

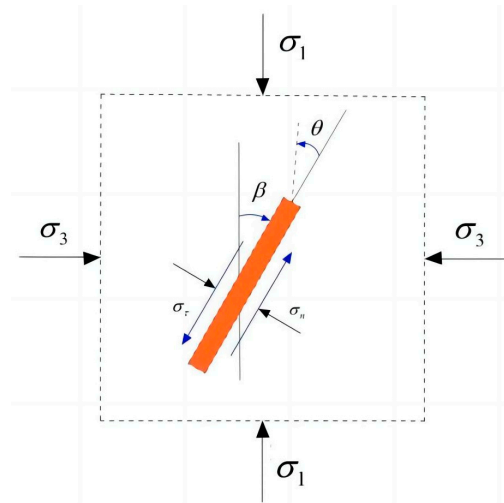


Figure 9. Stress components in polar coordinates of the fracture front.

Under non-zero K_I and K_{II} , Equations (1) and (2) can be simultaneously used to obtain the expression of θ :

$$\theta = 2 \arctan \frac{1 - \sqrt{1 + 8(K_{II}/K_I)^2}}{4(K_{II}/K_I)} \quad (8)$$

Under in situ stress, $\frac{K_{II}}{K_I} > 0$, from which we can calculate $|\theta| < 70^\circ 32'$. Figure 10 shows the function curve of θ .

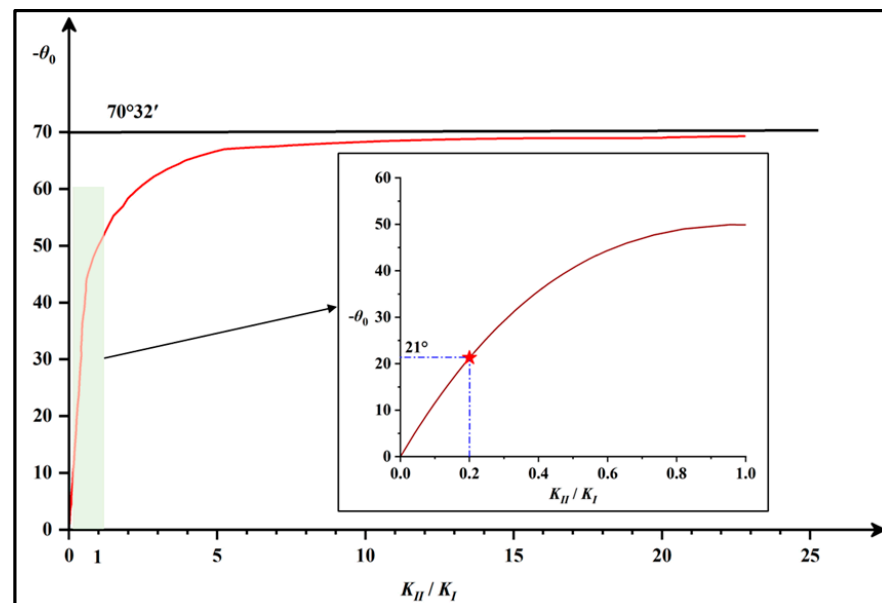


Figure 10. The relationship between the fracture angle (θ) and ratio (K_{II}/K_I) (Adapted from [48]).

For the crack shown in Figure 10, under far-field stress, the expression of the stress intensity factor is:

$$f(K) = \frac{K_{II}}{K_I} = \frac{\sigma_\tau \sqrt{\pi a}}{\sigma_n \sqrt{\pi a}} = \frac{M \cos \beta + \sin \beta}{M \sin \beta - \cos \beta + \frac{P_0}{M}} \quad (9)$$

where $M = \frac{\sigma_1}{\sigma_3}$ is the coefficient of the lateral pressure in the formation, σ_1 and σ_3 are the maximum and minimum stresses in the horizontal direction, respectively, P_0 is the pore

pressure after gas fracturing, and β is the included angle between the crack strike and the maximum stress in the horizontal direction, which is equal to σ in Figure 9.

The extreme value of $\frac{K_{II}}{K_I}$ can be obtained based on the analytical solution of $f'(K) = 0$. The present study calculated the trend in variation of $\frac{K_{II}}{K_I}$ under different lateral pressure coefficients and pore pressures using the trial solution method (Figure 11a,b).

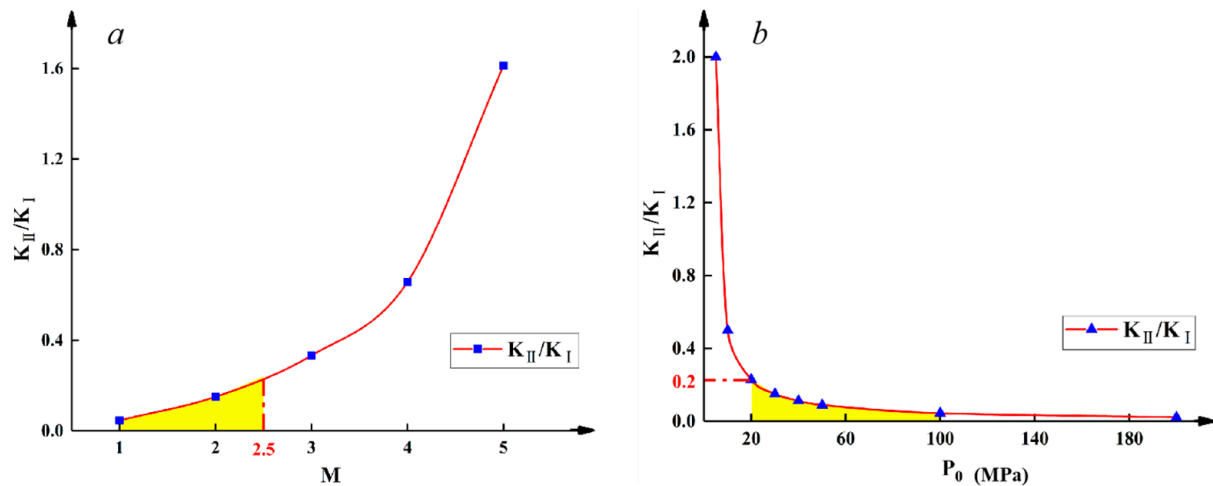


Figure 11. The trends in variation under different (a) lateral pressure coefficients and, (b) pore pressures.

In the coal mining area, the coefficient of the lateral pressure and pore pressure after CO₂-Frac were generally 1–2.5 and 20–100 MPa, respectively. As represented by the yellow area in Figure 10, under these conditions, the range of the change in $\frac{K_{II}}{K_I}$ was 0–0.2. θ was calculated to be 0–21° by substituting the range of variation of $\frac{K_{II}}{K_I}$ into Equation (8) [49–54].

The field experiments show that the smaller the angle between the direction of the fracturing borehole and the maximum horizontal principal stress, the better the pressure relief effect. The results of theoretical calculations further validate and quantify this conclusion, suggesting that the pressure relief effect of CO₂-Frac is optimal when the angle range is 0–21°.

The results of the present study can provide theoretical guidance for the optimization of CO₂-Frac [55]. Optimized stress release was achieved by adopting a direction of the fracturing borehole parallel to the cleat to form increasingly tensile fractures through the application of a large quantity of CO₂ gas.

5. Conclusions

In this study, microseismic monitoring was conducted for three CO₂-Frac boreholes in Xinyuan coalmine, China. The results provide a differential distribution of stress drop in the testing borehole, which can increase the understanding of the effect of primary fracture orientation on CO₂-Frac. Based on the results of this study, the following conclusions can be drawn.

- (1) Stress drop and the range of the buffer section varied greatly, with the degree of stress release an important index influencing the effect of CO₂-Frac.
- (2) The fractures in the buffer section extended from the fracturing section, with their length affected by the angle between the orientation of the borehole and the direction of the primary fracture. Furthermore, the effect of stress release in the buffer section decreased as the angle increased.
- (3) Fracture mechanics modeling confirms that the optimal stress relief is achieved when the angle BF is within 0–21°, which aligns well with the field observations. It should

be noted that this optimal range is derived from the specific conditions of this study and may vary with in situ stress regimes and coal properties.

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