In Situ Stress Distribution and Variation Monitored by Microseismic Tracking on a Fractured Horizontal Well: A Case Study from the Qinshui Basin

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ABSTRACT: In situ stress is an important parameter regulating the production of coalbed methane (CBM), and the monitoring of rock deformation can provide a description of the state of stress. Microseismic monitoring in a multistage fractured horizontal CBM well was conducted as a case study with a completion depth of 1445.36 m. The results show that there is a good correlation among the seismicity parameters, $b$-value, stress drop, fracture length, fracture density, and orientation. In the stress concentration region, the fracture is longer with a smaller density, where the $b$-value is lower. On the contrary, in the stress relaxation zone, the fracture is shorter with a complex shape, where the $b$-value is higher. Stress drop is relatively higher where fractures are concentrated, which indicate the areas with successful reservoir stimulation. The reliability of the above results was verified by the normal fault occurring between stages 7 and 8. In the area affected by the hanging wall of the normal fault (stage 6 and 7), the $b$-value is 0.38–0.39, while in the area affected by the footwall (stage 8 and 9), the $b$-value is 0.64–0.66. This phenomenon reflects an obvious stress concentration in the hanging wall of normal fault, which is consistent with the conventional understanding. The microseismic source parameters have great potential in evaluating reservoir stress. With further exploration of source parameters, microseismic will provide more support for CBM development.

1. INTRODUCTION

Reservoir characterization is important in coalbed methane (CBM) development as well as other unconventional natural gas reservoirs. It is widely recognized that coal reservoir permeability is one of the most important parameters in determining the reservoir quality and the efficiency of gas production for a given CBM formation. Coal can be characterized as a weak rock with cleat aperture, and the natural heterogeneity and spatial distribution significantly affect the permeability. The in situ stress is a sensitive index affecting the degree of cleat opening and reservoir permeability, and the permeability decreases with the increase of effective stress. Thus, studies related to the distribution of in situ stress and its evolution are crucial for quantifying coal permeability and its evolution. The in situ stress is greatly influenced by two factors, gravitational and tectonic forces. Vertical stress (gravitational force) is mainly influenced by the overlying rock mass and can be estimated by the weight of the overlying strata. Horizontal stress is attributed to two components, namely, the Poisson’s effect-induced horizontal stress and the tectonic-induced stress defined by tectonic movement and geological structures. As we all know, the tectonic stress is complex and challenging to quantify and model using a mathematical function.

Various techniques have been developed to probe and measure the in situ stress of a subsurface formation. These techniques can be divided into two main categories: (1) stress-relaxing techniques that work by inducing strains, deformations, or crack opening pressures and then inversely quantifying the virgin stress condition; (2) techniques that measure rock behavior without any major rock condition alterations during measurements. The comprehensive analysis of stress measurement techniques indicates that the deformation and destruction of a rock will affect the reservoir in situ stress. In other words, monitoring of the deformation and destruction of rocks can be used to indirectly infer reservoir in situ stress alterations, based on which some key...
reservoir features such as permeability can be evaluated. Microseismic monitoring is an effective method in studying \textit{in situ} stress. The seismic spectrum potentially contains information on the properties of the triggering sources and can provide insights into the spatial and temporal variations. The source dimension ($r$), the stress drop ($\Delta \sigma$), and the seismic moment ($M_0$) have been generally estimated in previous studies.\textsuperscript{23} In addition, the $b$-value, estimated by the relationship between the seismic frequency and the seismic magnitude, is an additional valuable parameter for the evaluation of reservoir stress profiles.\textsuperscript{24−26} However, the understanding of microseismic in studying the reservoir stress is not enough. Especially in the coal reservoir with strong heterogeneity, the synergistic relationship between seismic source parameters and reservoir fractures remains to be further studied.

This study reports on the comprehensive microseismic monitoring conducted at a CBM multistage fracturing horizontal well in the Da’ning area, Qinshui Basin, China. The microseismic dataset is unique for a CBM horizontal well with multistage fracturing completion. Based on the dataset, the $b$-value was extracted, and the stress drop was evaluated for the coal formation. The results have been validated by the regional geological structure and will promote the application of microseismic in the efficient development of CBM.

### 2. GEOLOGICAL SETTING AND THE MULTIFRACTURING PROJECT

The Qinshui Basin is a large bilateral symmetric synclinorium basin. Structures within the basin are relatively simple with a few internal secondary folds.\textsuperscript{27} The entire basin is surrounded by several uplifts, such as the Taihang Mountain in the east, the Lvliang Mountain in the west, the Wutai Mountain in the north, and the Huo and Zhongtiao mountains in the southwest.\textsuperscript{27−30} The study was conducted in the Da’ning coal mine with an area of $\sim$38 km$^2$. The CBM resources of the mine are estimated to be 5.7 billion m$^3$. The study site is located in the southern Qinshui Basin to the west of the southern tip of the Taihang anticline and northeast of the Zhongtiaolong fault zone.

The research area is in the east wing of the Shitou fault, which is a NE plunging syncline with open boundaries in the north and south. Less frequent tectonic deformations have resulted in wide strata with a gentle dip ranging between 3 and 10° and an average of 6° (Figure 1). The main coal-bearing strata are the Permian Shanxi formation and the Carboniferous Taiyuan formation. The target coal seams for CBM development are coal seam #3 in the lower part of the Shanxi formation and coal seam #15 in the upper part of the Taiyuan formation. Coal seam #3 is a CBM reservoir with relatively low permeability and pressure. The gas content on air-drying basis is 8−15 m$^3$/t with a virgin reservoir permeability of 0.03−0.8 mD. The gradient of the reservoir pressure has been tested at 0.4−0.6 MPa/100 m. The mechanical parameters of coal seam and surrounding rock are listed in Table 1.

#### Table 1. Statistical Table of Mechanical Parameters of Coal and Surrounding Rock

| parameter | Young’s modulus $E_0$ (GPa) | Poisson’s ratio $v$ | tensile strength $\sigma_t$ (MPa) |
|-----------|-------------------------------|--------------------|----------------------------------|
| roof      | 18−27, 21 (4)                 | 0.24−0.28, 0.25 (4) | 1.6−3.8, 3.0 (4)                 |
| coal seam | 1.96−3.52, 2.74 (2)            | 0.33−0.37, 0.35 (2) | 0.14−0.64, 0.39 (2)              |
| floor     | 16−26, 19 (4)                 | 0.2−0.26, 0.23 (4)  | 1.8−3.2, 2.3 (4)                 |

*The four values are minimum−maximum, average (sample size).*

The horizontal CBM well (LDP-02) was drilled in February 2015 at the center of the study area with a segment of 920 m and a completion depth of 1445.36 m, as shown in Figure 1. A normal fault with the displacement about 4.5 m was exposed during the drilling process at the depth of 736 m between stages 7 and 8 (Figure 2).

The multistage fracturing stimulation was designed and conducted in October 2015. The adjacent fracture stage was separated by a drillable bridge plug, and the casing was
perforated using a larger caliber projectile designed for CBM development. The lateral well stimulation included 10 stages with a total of 38 clusters, as illustrated in Figure 2. The average interval of the fracturing stage was ~90 m. During the stimulation, the maximum, minimum, and average cluster spacings were 23, 11, and 15 m, respectively.

The fracturing process of each stage involved the initial nitrogen gas injection of 16,000 m$^3$ with an injection rate of 250 N m$^3$/min, followed by the injection of ~800 m$^3$ of fresh water and 40 m$^3$ of proppant with a pump stop at the midpoint and a pumping rate of about 10 m$^3$/min.

3. MICROSEISMIC MONITORING
The current study used monitoring data from 32 stationary monitoring sites. The OMNI2400 monitoring system manufactured by Geospace Technologies (USA) with a sensitivity of 52 V s/m and a stationary frequency ranging from 3 to 200 Hz was used for microseismic monitoring. A sampling frequency of 1000 Hz was used, and the lower detecting limit for earthquake intensity was magnitude −3.0.

The monitoring array is illustrated in Figure 3. For station deployment in the longitudinal direction of the horizontal well, the monitoring coverage exceeded the length of the horizontal segment by a factor of 1.3, and the stations were distributed evenly. Along the normal direction of the horizontal wellbore, the stations were deployed in double rows with a radius of 200 m, as shown in Figure 3. To obtain a complete dataset, all 10 stimulation stages were continuously monitored, and the data were transmitted to the controller in real time for analyses.

4. RESULTS AND DISCUSSION
There were 1936 effective microseismic events recorded during the hydraulic fracturing of the 10 stages. As shown in Figure 4, the waveforms were clear, and the travelling time of seismic
activity could be accurately distinguished. A detailed velocity model with 10 layers was constructed from the sonic logs of the well. This model was used to estimate the arrival time at each point at 5 m intervals. This information was used to correct the seismic events of different phases and ray-path orientations by comparison. A database of event locations was then prepared for fracture imaging.

4.1. Spatial Distribution of the Microseismic Events. Hydraulic fracture effectiveness is one of the key parameters for CBM development because it offers a sustainable pathway for gas depletion and production. In evaluating the effectiveness, the induced fracture geometry relative to the reservoir architecture is critical as it determines the production potential of a stimulated CBM well.

Information on fracture attributes has traditionally been interpreted from well data. However, microseismic monitoring is an effective method for characterizing the spatial distributions of fractures for reservoirs undergoing active stimulation at a greater depth as well as for subsurface fluid migration. Typically, microseismicity is assumed to be the product of deformations directly associated with hydraulic fracturing. Therefore, the spatial distribution of the microseismic events can represent and revivify the growth of hydraulic-induced fracture networks.

The directly monitored microseismic data can serve as the base data for the interpretation of the number, direction, and morphology of microseismic events. Figure 5 shows the spatial distribution of the microseismic events for our project. The
In this study, the horizontal well depth (m) buried depth (m) microseismic event spatial distribution fracture length (m) south wing north wing

| stage | horizontal well depth (m) | buried depth (m) | microseismic event | spatial distribution | fracture length (m) |
|-------|---------------------------|------------------|-------------------|---------------------|--------------------|
| 1     | 1361.0–1414.0             | 491              | 120               | N75°E               | 93                 |
| 2     | 1314.0–1269.0             | 487.1            | 62                | N50°E               | 107                |
| 3     | 1160.0–1215.0             | 477              | 226               | N60°E               | 113                |
| 4     | 1073.0–1120.0             | 473.1            | 116               | N40°E               | 101                |
| 5     | 964.0–1015.0              | 471              | 106               | N40°E               | 102                |
| 6     | 883.0–918.0               | 465              | 206               | N60°E               | 106                |
| 7     | 784.0–811.0               | 465              | 122               | N65°E               | 72                 |
| 8     | 672.0–705.0               | 438.4            | 331               | N60°E               | 82                 |
| 9     | 573.0–619.0               | 434.6            | 170               | N65°E               | 70                 |
| 10    | 484.0–524.0               | 430.2            | 477               | N70°E               | 77                 |

Table 2. Statistical Table of the Basic Fracture Parameters

4.2. b-Value. The method used to estimate the b-value is from classical earthquake seismology. This method relies on the fact that the frequencies and magnitudes of the events in any earthquake sequence are not random; rather, they follow a power-law relationship. The frequency—magnitude relationship of any earthquake sequence can be written as follows

\[
\log N = a - bM
\]

where \( N \) represents the cumulative number of earthquakes or events with magnitudes \( \geq M \), whereas \( a \) and \( b \) are constants.

Recent studies have shown that the b-values of microseismic variations change with changes in crustal stress. The b-values decrease with increasing stress and can abruptly increase with a sudden stress drop during a slip event.\(^{24,26,34–41}\) The b-value can be used to isolate fault activation from microseismicity associated with a hydraulic fracture. Previous studies have shown that the b-value in a fault-affected zone is smaller than the values normally associated with hydraulic fracturing. In addition, variation in the b-value is closely related to the properties of the rock medium, such as brittleness, elasticity, plasticity, and breakage.\(^{42}\) It should be noted that there are some uncertainties in the calculation of b-value, such as the error of earthquake magnitude measurement, the selection of the minimum integrity magnitude, and so on.

In this study, the b-values were divided into three sections on the plane. Stages 1–5 represent the western section, with an average value of 0.522. Stages 6 and 7 represent the central section, with an average value of 0.385, and stages 8–10 represent the eastern section, with an average value of 0.683 (Table 3).

The results show that the b-values of microseismic events induced during hydraulic fracturing in the study area did not follow the same magnitude scaling relationship as that of natural earthquakes and shale gas fracturing. The b-values were significantly lower than 1, indicating an abundance of relatively greater events. This may be related to the shallow burial depth of the coal seam, the lower elastic model, and the higher Poisson’s ratio. Furthermore, it might also be due to the low bulk modulus that allows the coal reservoir to store a lot of fracturing fluid compressive energy. The specific reason for these observations needs to be further studied based on the physical significance of the b-value.

In addition, the well completion report of this project showed that a normal fault with a drop of \( \sim 3.5 \) m was encountered at a depth of 736 m, which is roughly located at the junction of stage 7 and stage 8 (Figure 6). The monitoring results showed that the b-values during stages 6 and 7 were significantly lower than those of the other fractured stages, which indicate a higher stress in the coal reservoir.

Many studies have demonstrated that the stress states of the two plates of a normal fault are different, with a clear concentration of stress in the upper plate of the fault. In addition, the degree of stress concentration is related to the fault tendency and reservoir strike.\(^{45–46}\) The changes of b-value on both sides of the fault in this study indicate that the b-value can be feasibly and reliably used to evaluate the in situ stress and also confirm the reliability of the monitoring results. The b-value can transform the scattered microseismic events into a continuous distribution of reservoir stress, which is of great significance to evaluate the reservoir reconstruction effect.

4.3. Stress Drop. The stress drop of an earthquake represents a change in stress on the dislocation surface immediately after the earthquake, which can be used to evaluate the focal mechanism and the behavior of energy
release in underground blocks and the behavior of a stress drop resulting from a rock fracture during abrupt changes in stress.

The stress drop represents the difference between initial stress $\sigma_0$ before an earthquake and the final stress $\sigma_1$ after the earthquake.

$$\Delta \sigma = \sigma_0 - \sigma_1$$

(2)

The stress drop is a parameter closely related to earthquake occurrence, source medium, and tectonic stress, which reflects the magnitude and release of tectonic stress during an earthquake. On the contrary, the stress drop depends on the acquisition of microseismic source parameters, and there are some uncertainties in the calculation of single seismic events.

The disk fault model proposed by Brune (1970) is generally used to calculate the stress drop during microseismic monitoring. In this model, the seismic fault plane is equivalent to a disk with a radius of $r$. Shear stress was assumed to act on the entire fault plane concurrently. The equation for the stress drop can be written as

$$\Delta \sigma = \frac{7M_0}{16\pi r^3}$$

(3)

where $\Delta \sigma$ is the stress drop (MPa), $M_0$ is the seismic moment (m), and $r$ is the source size (m).

In the Brune model, the source size is the radius of the disk $r$

$$r = \frac{t_2-t_1}{3\pi} - 4\sqrt{2}V_P$$

(4)

where $t_2 - t_1$ is the half period (s) and $V_P$ is the velocity of the P-wave (m/s).
The seismic moment is a direct measure of the amount of energy released during an earthquake and can be written as

\[ M_0 = \frac{4\pi R G V_0 D}{3} \]  

(5)

where the hypocentral distance \( R \) is the direct distance from the earthquake source to the seismic monitor (m), \( G \) is the shear modulus of the target reservoir (MPa), and \( D \) is a conversion parameter for ground motion speed (m/s), simply written as

\[ D = \frac{V_0}{2\pi f E_0} \]  

(6)

where \( V_0 \) is the maximum voltage amplitude (V), \( E_0 \) is the sensitivity conversion of the seismometer (V/m), and \( f \) is the maximum corner frequency (Hz).

The stress drop values of microseismic events were calculated using the above method, and the data were distributed between 1 and 200 kPa. The number of microseismic events with a stress drop of 1–10, 10–50, and 50–100 kPa accounted for 9.9, 52.3, and 22.6% of all microseismic events, respectively. The number of microseismic events with a stress drop exceeding 100 kPa was extremely high, accounting for 15.2% of all events.

A contour map was plotted to present the stress drop distribution in the affected fracturing area. The black circles in Figure 7 define areas with higher stress drop, and the distribution characteristics of the stress drop represent the fracturing area of influence. The spatial distribution of the stress drop clearly shows the following: (1) zones with higher stress drop present a shape similar to the fracture orientation and length. In the western region, the number of fractures is smaller, but the extension distance is longer. In the eastern region, the fractures are more complex, and the propagation is shorter. (2) In the central region, there is an obvious low stress drop area. (3) The distribution of the stress drop on the plane was consistent with the fractures, indicating that increasing the range of influence of artificial fractures is an effective approach for reducing reservoir stress. Therefore, increasing the density and complexity of fractures can effectively increase the stimulation effect of a reservoir.

5. CONCLUSIONS

(1) The present study analyzed the state of stress of a coal reservoir based on microseismic monitoring. The results showed good agreement between the \( b \)-values, stress drop, and fracture morphology. Importantly, the reliability of these results was verified through geological phenomena. Therefore, evaluating the stress state of a CBM reservoir by microseismic monitoring is feasible.

(2) The stress drop and \( b \)-value are key parameters that directly reflect the changes in stress and energy release during fracturing. The combination of \( b \)-value and stress drop can be used to not only evaluate the state of stress but also reflect the effect of reservoir stimulation.

(3) Although the present study achieved some progress in the microseismic evaluation of the reservoir stress state, many factors in the calculation of stress drop and \( b \)-value remain uncertain contributing to uncertainties in the state of reservoir stress.

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Notes
The authors declare no competing financial interest.

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