The effects of key rock layer fracturing on gas extraction during coal mining over a large height

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Abstract
To prevent outbursts and extract the gas, it is necessary to investigate the structure of the key layer and the evolution of cracks during coal mining over a large height. A physical similarity model with a geometric similarity ratio of 1:100 and a strike length of 2 m was established on the basis of prevailing geological and mining conditions. Stress sensors and microseismic equipment were adopted to monitor the collapse characteristics of different key layers through variations in stress and energy. The research results showed that: The displacement of the overlying strata exhibited group motion characteristics marked by the key layer and there was zone of rapidly increasing stress in the goaf behind the working face before and after the fracture of the key layer. Through the analysis of microseismic events, fissure density, and fractal dimension, we found that: before and after the primary key layer fractured, the energy loss in the microseismic event accounted for 27% of the total, the fissure density also changed abruptly from 8 cracks/m to 10 cracks/m and the slope of the fractal dimension curves changed from 0.00243 to $9.94801 \times 10^{-4}$. Then a gas drainage model suitable for this condition was constructed. When the primary key layer had not fractured, the cracks below fully developed to form a gas migration channel and a gas enrichment area, and gas boreholes could be arranged therein. After the primary key layer had been fractured, the rate of crack development decreased, the permeability would increase, and the gas concentration would increase. The boreholes could still be arranged in the gas migration channel. This study elucidated the control role of the primary key layer from multiple angles and provided experimental guidance for gas drainage over large-mining heights and during complex key layer mining.

KEYWORDS
complex key layer, crack evolution, gas migration channel, high-level borehole, microseismic events
1 | INTRODUCTION

With the gradual depletion of coal resources in eastern China, coal mining has been expanded in central and western regions, and thick coal seams are widely present therein. At present, the maximum mining height reaches 8.8 m, and the geological conditions of large-mining height and a complex key layer are often associated with gas, and the incidence of gas outbursts and explosions increases with the continual increase in mining intensity. To prevent outbursts and extract this gas, some new gas drainage techniques, models, and mathematical models have been proposed to improve the efficiency of gas drainage; however, the most critical technique for gas drainage is to find gas enrichment areas through the analysis of the evolution of cracking in the overburden. It is essential to investigate the structure of the key layer and the evolution of cracks on the fully mechanized top coal caving face with a large-mining height based on complex key layer theory.

At present, the research methods used to assess fracture evolution include physical similarity simulation experiments in the laboratory, numerical simulation methods, and on-site monitoring of gas-bearing coal specimens. On-site monitoring often relies on microseismic monitoring systems, drilling holes, and other means with which to achieve the goal of mine safety; research into gas-bearing coal samples and has also involved use of acoustic emission and Hopkinson pressure bar experimental systems; floor stress; and displacement are also used as laboratory-test-based monitoring methods. To quantify cracking, some studies into crack density and fractal dimensions have been conducted. Scholars have successively proposed O-shaped circle theory, double-circle theory, the theory of the elliptic paraboloid zone, etc.

Based on the fracture on key layers, some scholars have used elastic plate theory, thin-plate theory, and a Winkler foundation to theoretically investigate the mechanical model of the key layer fracture, established the stiffness and strength conditions of the key layer, the complex key layer model, and the mechanical model of rotational motion about a cantilever beam. With the widespread application of numerical simulation methods, new information about the key layer has been proposed, some scholars have validated the correctness of the six-movement types of the first subordinate key layer, constructed a mechanical model of the arch structure in the unconsolidated layers, analyzed the working resistance based on the type of movement of the first sub-key layer in a fully mechanized face with a large-mining height and found the primary key layer failed by rotational instability. These studies and theories provided an important basis for research into the evolution of cracks in the key layer, but there are still relatively few studies on the quantitative study of energy and stress before and after the fracture of the key layer and the change in location of the gas enrichment area, so we conduct this research.

In summary, the previous studies on the crack evolution and key layer were based on numerical simulations and similarity experiments, related theories, and engineering models, but a microseismic monitoring system is rarely applied in similar simulation experiments and there were few quantitative studies on the role of key layer fracture in crack evolution. Therefore, the present research has guiding significance for the high-efficiency mine gas drainage. A physical similarity simulation experiment was undertaken based on microseismic monitoring to quantify the energy, stress, and fractal dimension changes before and after the breaking of the complex key layer during mining. This study provided an on-site gas drainage model based on before and after the fracture of the key layer. The model provides important theoretical guidance for on-site gas drainage and offers advice to those seeking to increase the efficiency of gas control.

2 | EXPERIMENTAL WORK

2.1 | Engineering background

The test mine (Wangjialing Coal Mine) is located in Shaanxi Province, China. The length of the working face is 1231 m, the width is 260 m, the average thickness of the coal seam is 6.2 m, and the average burial depth is 309 m. Fully mechanized top coal caving mining with a higher mining height was adopted here. Figure 1 shows the location of Wangjialing coal mine.

The rock in the Wangjialing coal mining area was mainly formed during the Carboniferous and Permian periods. Table 1 displays the roof and floor lithology.

2.2 | Model building

The experiment was carried out using a two-dimensional plane simulation test bench. The simulation test was mining along the direction of the working face (Figure 2). A simulation model (2.0 × 0.2 × 1.2 m) was established on the basis of the geological conditions in a mine in Shanxi Province. The geometric similarity ratio (model:prototype) was 1:100. Considered the 2 # coal seam with its 309-m burial depth, the height was simulated at 120 m, and the remaining unpaved parts were simulated with a counterweight to load. The main materials used in the model were sand, starch, plaster, water, and pulverized coal. In this experiment, the composition and strength of similar materials differed slightly from the actual materials. This could better simulate the actual strata. Forty stress sensors were installed at the
bottom of the model to monitor real-time stress data during mining; five microseismic sensors (numbered 3, 6, 9, 11, and 13) were adopted to monitor and analyze the fracture of various strata. A cut was made at 10 cm (corresponding to the prototype distance of 10 m) from the right-hand border of the model, and mining was started, until the end at 10 cm (corresponding to the prototype distance of 10 m, and all the following dimensions are prototype values) from the left of the model. To imitate the complete mining process as undertaken in-situ, the mining speed was alternately set to 2 and 3 m/d when stoping the working face.

To reduce boundary effects generated by the model during the test, coal pillars with a length of 10 m were reserved on both sides of the working face, and uniform loads were
TABLE 2 The ratios of test materials

| No. | Thickness (cm) | Layer          | Number of Ratio | Sand (kg) | Plaster (kg) | Starch (kg) | Coal (kg) |
|-----|----------------|----------------|-----------------|-----------|--------------|-------------|-----------|
| 20  | 11             | Mudstone       | 837             | 5.7       | 0.21         | 0.5         |
| 19  | 8              | Middle sandstone | 737            | 5.61      | 0.24         | 0.56        |
| 18  | 8              | Siltstone      | 728             | 5.61      | 0.16         | 0.64        |
| 17  | 3              | Mudstone       | 837             | 5.7       | 0.21         | 0.5         |
| 16  | 1              | Siltstone      | 728             | 5.61      | 0.16         | 0.64        |
| 15  | 6              | Middle sandstone | 737            | 5.61      | 0.24         | 0.56        |
| 14  | 5              | Siltstone      | 728             | 5.61      | 0.16         | 0.64        |
| 13  | 3              | Fine sandstone | 746             | 5.61      | 0.32         | 0.48        |
| 12  | 2              | Middle sandstone | 737            | 5.61      | 0.24         | 0.56        |
| 11  | 5              | Fine sandstone | 746             | 5.61      | 0.32         | 0.48        |
| 10  | 13             | Siltstone      | 728             | 5.61      | 0.16         | 0.64        |

9  5  Mudstone  837  5.7  0.21  0.5
8  10 Fine sandstone  746  5.61  0.32  0.48
7  13 Middle sandstone  737  5.61  0.24  0.56
6  4 Fine sandstone  746  5.61  0.32  0.48
5  1 No. 2 coal  928  2.31  0.13  0.51  3.46
4  8 Siltstone  728  5.61  0.16  0.64  0.48
3  6 Fine sandstone  746  5.61  0.32  0.48
2  2 Middle sandstone  737  5.61  0.24  0.56
1  6 No. 2 coal  928  2.31  0.13  0.51  3.46

3  | Results

3.1 | Crack evolution

In order to ascertain the evolution of the cracks before and after the fracture of the key layer, MATLAB™ software was used to conduct gray-scale binarization on photographs of the experimental process.

After the first weighting of the basic roof, when it was advanced to 81 m, the first periodic weighting occurred (sub-key layer fractured and collapsed), and the step length was 26 m. When it was advanced to 104 m, the second periodic weighting occurred at a step length of 23 m; when it was advanced to 132 m, the third periodic weighting occurred at a step length of 28 m; when it was advanced to 156 m, the fourth periodic weighting occurred (the primary key layer fractured and collapsed) at a step length of 24 m, and mining continued to the end at 170 m. Figure 4 demonstrates that, before the primary key layer had fractured and collapsed, the widths among the crack area behind the working face (crack area I, below *ibid.*) and the crack area by the side of the open-off cut (crack area II, below *ibid.*) were unchanged, nevertheless the width of crack area I was significantly smaller than crack area II after
the primary key layer fractured. The reason for this is that the primary key layer played a major role in bearing its overlying strata.

3.2 Stress on the coal seam floor

During the normal advance of the working face, the overburden in the goaf will collapse, delaminate, bend, and sink in sequence from bottom to top, which will lead to changes in the stress and displacement within a certain distance from the working face. The stress distribution characteristics are illustrated in Figure 5.

It can be seen from Figure 5 that, after the working face was mined, stress-concentration areas were formed on both sides of the goaf. The stress-concentration coefficient of the goaf changed within the range from 0.15 to 0.45, with the increase of stress-concentration coefficient.
the stress peak appeared ahead of the working face by 20-24 m.

3.3 Displacement of overlying strata

Figure 6 shows the subsidence at various measuring points after the mining face was finished. As shown, the displacement of the overlying strata shows obvious group motion characteristics as denoted by key layers, and each group of layers underwent coordinated motion. The experimental results showed that, movement along survey lines 2, 3, and 4 was controlled by the sub-key layer and the maximum displacement of the three survey lines was 4.6, 4.0, 3.8 m; that along survey lines 5-9 was controlled by the primary key layer and the maximum displacement of the three survey lines was 2.9, 2.7, 2.1, 1.7, and 0.4 m. Figure 6 illustrates that the displacement of each stratum is non-linear and the movement pattern is asymmetric; the strength and stratified thickness of the strata and the development of the layers and joints are different, and the movement and fracture step of each stratum are also different. There is a step-change in the displacement from the sub-key layer control group to the primary key layer control group. The reason for this is that both the sub-layers and the primary key layer play a major bearing role in the overlying strata, but the primary key layer plays a more prominent role, the sub-key layer exerts less control over the overlying strata than the primary key layer. The control of the overlying strata is expressed in the displacement curve as the step-change in the aforementioned sets of curves.

3.4 Three heights and three-zone distribution

The plots of the collapse height, cavity height, and the furthest distance from the separated crack to the floor during each weighting are demonstrated in Figure 7. The slope of the collapse height and the furthest distance from the separated crack to the coal floor plots, in the critical stage before the fracture of the key layer increased, indicating that sufficient crack evolution occurred in the overlying strata above the coal seam before the key layer fractured and collapsed, which caused the bearing capacity of the key layer to reach its limit whereupon it finally fractured and collapsed. The slope of the cavity height curve was larger in the critical stage before the fracture of the key layer, suggesting that, as the key layer fractured and collapsed, the cavity height decreased and became more compact.

As mining progressed, the crack area underwent several stages of generation, expansion, and closure. This process affected the desorption, flow, and storage of gas in the goaf,
and with the formation of a stable three-zone distribution, the position of the gas flow active area in the crack area could be determined, which provided a theoretical basis for gas control in the working face. Figure 8 shows the stable three-zone distribution.

4 | DISCUSSION

4.1 | Stress analysis of the key layer

4.1.1 | Vertical stress under the control of the key layer

Key-layer theory indicates that the key layer is generally a thick, hard rock layer, and its zone of influence includes the key layer itself and the loaded rock layer. Its state of motion directly determines the structural characteristics of the overburden layer and the stress distribution in the stope, therefore, the study of the evolution of vertical stress should be based on the state of movement of the key layer, and the relationship between the movement of the thick, hard rock and the load transfer should be further investigated.

The coal and rock masses that are unaffected by mining are subjected to the uniformly distributed load from the overlying rock, and the loads from the key layer and the overlying rock are evenly transmitted to the bottom coal seam. As shown in Figure 9, as the width of the goaf increases, the rock above the coal seam fractures layer-by-layer from bottom to top, and the fractured rock expands upwards at a certain angle (the angle between the line of the fracture point of the stope boundary rock and the horizontal direction is defined as the overburden fracture angle \( \alpha \)), the broken rock strata gradually touches the gangue, compacts, and stabilizes in the goaf (the angle between the line through a point touching the gangue and the horizontal direction is the overburden contact gangue angle \( \beta \)). Regardless of the influences of other factors such as structure, the average static vertical stress \( \delta_0 \) on the working face before mining is as follows\(^39\):

\[
\delta_0 = \frac{\gamma_1 h_1 + \gamma_2 h_2 + \gamma_3 h_3}{\gamma H} = \sum_{i=1}^{n} \gamma_i h_i = \gamma_1 h_1 + \gamma_2 h_2 + \gamma_3 h_3 = \gamma H
\]  

(3)

where \( \delta_0 \) is average static vertical stress on the working face; \( h_1, h_2, \) and \( h_3 \) are the heights of thick, hard rock from the ground surface, the thickness of hard rock layer, and the height of coal seam to the thick hard rock; \( \gamma_1, \gamma_2, \) and \( \gamma_3 \) are the average bulk densities of rock formations 1, 2, and 3, respectively.

The average static vertical stress of the working face is mainly composed of two parts superimposed according to the different sources of load: the self-weight stress caused by the mining overburden \( \sigma_0 \) and the increment \( \Delta \sigma \) formed by the transfer of the overburden:

\[
\sigma = \sigma_0 + \Delta \sigma
\]  

(4)

The average stress increment \( \Delta \sigma \) under different mining conditions after the formation of the goaf comes from the transfer load of the overlying rock in the goaf. The magnitude of \( \Delta \sigma \) under two different conditions of insufficient mining and full mining can be estimated:

\[
\Delta \sigma' = \frac{C(\gamma_1 h_1 + \gamma_2 h_2)}{2L} + \frac{\gamma_1 h_1^2 (\cot \beta - \cot \alpha)}{4L}
\]  

(5)
where $\Delta \sigma', \Delta \sigma''$ are respectively the average stress increment produced by the overburden load of the goaf on the working face under insufficient and full mining conditions, $C$ is the limit breaking distance, $D$ is the length of the cracked rock in the key layer, and $L$ is the length of the working face.

Thus, the average static vertical stress of the working face under continuous mining conditions is as follows:

$$
\Delta \sigma'' = \frac{D(y_1 h_1 + y_2 h_2)}{2L} + \frac{\gamma_3 h_3^2 (\cot \beta - \cot \alpha)}{4L} (6)
$$

According to Equation (7), the average static vertical stress on the face is related to mining depth where Equation (7a–c) give the vertical stress when the working face is not mined, the roof of the hard, thick rock layer is suspended, and the hard, thick rock layer is broken.

According to the analysis of Equation (7), the average static vertical stress of the working face is a piecewise function related to the mining depth $H$, the working face length $L$, the mechanical parameters of the key layer and its movement characteristics. Under continuous mining conditions, $\sigma$ increases with the increase of the width of the goaf. The value of $\sigma$ decreases for the first time after the suspended roof size of the key layer reaches the limiting value. The second sudden change (a decrease) occurs when the key layer is broken for the first time, before it finally stabilizes. In this experiment, stress sensors were used to collect vertical stress data.

Before the first fracture of the key layer, the size of the exposed span first increases with the increase of the length of the stoping. At this time, the average static vertical stress of the working face to be mined also shows a corresponding increasing trend. When a fracture occurs, the load on the rock is controlled by the key layer and undergoes its first sudden change; the average static vertical stress transmitted to the working face to be mined will also undergo a sudden change. Theoretically, the suspended roof load transitions to one of hinging, half of the suspended roof structure load before the initial failure of the key layer suddenly changes to half of the hinged structure load after the initial failure. Based on this analysis, in the case of continuous mining, $\sigma$ first increases as the length of the mined-out section increases. After the suspended roof to the key layer reaches its limiting value, $\sigma$ changes for the first time (decreases), and when the key layer is broken in the first cycle the second sudden change (also a decrease) occurs, and finally stabilizes.

### 4.1.2 Stress analysis of physical simulation

After processing the data captured before and after the key layer fractured, as shown in Figure 10A,B, the changes in the stress-concentration coefficient curve before and after the primary layer fractured can be seen. There was a coefficient about zero in an area about 10-15 m behind the working face. The reason for this is that the key layer played a major bearing role in the overlying strata and a cantilever roof was formed behind the working face, after the key layer had fractured, the stress-concentration coefficient in the goaf increased, and the change in the stress-concentration coefficient in the stress-concentration area in front of the working face is such that the slope of the curve before fracture was much larger than that after fracturing (Figure 10A where $K_{ab} = 0.047, K_{cd} = 0.015$, and in Figure 10B where $K_{AB} = 0.172, K_{CD} = 0.074$). The peak stress-concentration coefficient changed from 1.54 to 1.77 around sub-key layer fractured, and the peak

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**FIGURE 10** Changes in floor stress
stress-concentration coefficient changed from 2.33 to 2.73 around primary key layer fractured.

The reason for this is that the key layer was the main body bearing the weight of the overlying strata before fracture, the growth in stress concentration in the stress-concentration area was large, and the slope of the stress curve was large. After the key layer fractured, the overlying strata were decompressed, the support and control effects of the key layer on the overlying strata were weakened, and at this time, the increasing stress concentration in the stress-concentration area was small, and the slope of the stress curve was low, and there was a zone of sudden stress change in the goaf behind the working face before and after the fracture of the key layer.

In the cantilever stage of the primary key layer, the gas migration channel under the key layer has been fully developed, that is, the stress-concentration coefficient of the goaf became smaller. With the advancement of the working face, the stress-concentration coefficient of the goaf increased after the fracture of the key layer, and the rate of development of the gas-migration channel also decreased.

### 4.2 Energy analysis of the key layer

The SOS microseismic monitoring system adopts 0.1-600 Hz vibration velocity type mine vibration measuring probe with an embedded signal transmission module. The instrument itself has strong anti-interference performance, stable and reliable operation, and can realize automatic filtering, filtering and noise removal of interference signals. The specific layout of microseismic monitoring system was shown in Figure 11, 5 microseismic sensors (number 13#, 3#, 6#, 11#, 9#) were installed in the model.

#### 4.2.1 Distribution of microseismic events during mining

Due to the long experiment time, the amount of data is too large. Therefore, when analyzing microseismic data, selected a specific time period (1 hour before and 1 hour after the periodic weighting) for analysis. The data in this time period was representative and could support the results of the experiment. According to microseismic data recorded in a laboratory, there was one significant microseismic event energy peak during simulated mining corresponding to the fracture of primary key layer.

The data collected between two periodic weighting events were acquired and plotted on the same axes. The overlay of the major fracture events on the working face is shown in Figure 12. Based on the development height of the microseismic events during the mining of this working face, it can be seen that the microseismic events in this similarity experiment were mainly concentrated in the range of 7 m ahead of the open-off cut and 10 m ahead of the working face, and the heights thereof were 6-110 m above the coal seam. The roof fractured periodically as the working face was advanced, and the energy reached a maximum when the primary key layer fractured.

#### 4.2.2 Microseismic characteristics of key-layer fracture

To ascertain the relationship between the evolution of the key layer and the magnitude of the microseismic event energy and whether the key layer played a major role in supporting the overlying strata, the microseismic event characteristics of the sub-key layer and the primary key layer at fracture and collapse were explored.

When the working face was advanced to 81 m, the roof fractured suddenly (sub-key layer fractured). As shown in Figure 13, a large-scale weighting event occurred there, which exerted a significant influence on the working face. The total energy of the microseismic event was 8200 J (occurring 203 times), and the energy of each single microseismic event was mainly concentrated between 0 and 100 J. After the sub-key layer had fractured, the overburden strata suddenly lost stability and subsided as the roof collapsed, which affected the working face and a large-scale weighting event occurred.

As shown in Figure 14, the collapsed height of the overlying strata after primary key layer fractured was 91 m, and
microseismic events were concentrated behind the working face and 55.7 m above the coal seam. When the primary key layer fractured, the overlying strata about 25.5 m away that it controlled, fractured suddenly, which had a strong impact on the goaf. The microseismic event with the highest frequency and highest energy occurred during the fracture of the primary key layer. The total energy of the microseismic event was 12 875 J (occurring 476 times), and the energy of each single microseismic event was mainly concentrated between 0 and 100 J. During this stage of the failure, the range of impact of mining disturbance was shown to be large, there were many fissures in the overlying strata, and the fissures were inter-linked.

As shown in Figure 13, before the fracture of the primary key layer, the microseismic events were concentrated below the key layer, and the crack area formed a gas migration channel: because the key layer hindered the upwards movement of gas, a gas enrichment area was formed in the cavity. The boreholes arranged in the crack area behind the working face and the gas enrichment area were designed to drain gas.

As shown in Figure 14, when the primary key layer fractured, the microseismic events were mainly concentrated around the key layer and the overlying rock layer. At this time, the cracks forming the gas migration channel were fully developed. With the fracturing of the primary key layer, the permeability increased suddenly, and the gas concentration in the gas migration channel also increased suddenly. Boreholes from the gas migration channel of the crack area behind the working face can be arranged for gas drainage.

We analyzed the proportion of energy induced by the major collapse events during mining through Figure 15: the energy loss in the microseismic event in the primary key layer accounted for 27% of the total, the sub-key layer accounted for 17%, various other weighting events accounted for 41% of the compression, and the first weighting accounted for 15%. The fracture of the key layer accounted for the largest proportion and had a decisive control effect on microseismic events and energy release.

4.3 Analysis of fissure density and fractal dimension in the key layer

To quantify the development of mining fractures, the fissure density (that is, the number of fractures per unit thickness,
cracks/m) was used to represent the crack development process. Based on the experimental data, we plotted the development as a function of fissure density before, and after, the sub-key layer and the primary key layer fractured (Figure 16). When the working face was advanced to 81 m, the fissure density of crack area II reached a maximum of 7 cracks/m before the sub-key layer fractured, and the fissure density of crack area I was approximately 7 cracks/m. There was no obvious change in the fissure density in crack area II, but the fissure density in crack area I underwent a step-change (marked by the green box in Figure 16), where the fissure density changed from 7 to 8 cracks/m after sub-key layer fractured. Before and after the primary key layer fractured, the fissure density also changed abruptly from 8 to 10 cracks/m.

The reason for the step-change is that the key layer played the main bearing role in supporting the overlying strata. Before the key layer fractured, the key layer controlled the displacement and movement of the overlying strata, and the fissure density in II was smaller. When the key layer fractured, the control effect of the key layer on its overlying strata was reduced. At this time, the fissure density in crack area I increased, and the step-change in the primary key layer was more significant, implying that both the sub-layer and the primary key layer played a role of bearing and controlling the overlying strata; however, the primary key layer played the dominant role.

Overlying rock fractures exhibit fractal characteristics. Using fractal dimension calculation software written for MATLAB based on box-counting dimension theory, the test model is divided into multiple regions to calculate its fractal dimension D, namely:

\[ D = \lim_{r \to 0} \frac{\log N(r)}{-\log r} \]  

where \( r \) is the length of the boxes to cover the crack area (mm); \( N(r) \) is the number of boxes containing the crack (piece); \( D \) is the calculated fractal dimension (dimensionless).

We divided the stoping process into four areas (I-IV) according to the cycle stress step in Figure 17 and analyzed the fractal dimension of each area. With the stoping of the working face, the fractal dimension tends to increase.

The key layer fracture occurred in zone IV. Before the key layer broke, the key layer supported the overlying rock layer. The key layer was suspended, and the cavity remained unclosed. The rock layer under the key layer would not be compacted by the upper rock layer and the cracks in the lower part of the layer had fully developed, but there were no visible cracks in the upper part. Before the fracture of the key layer, the fractal dimensions of area III (the slope of the fractal dimension curve is 0.00243) and area IV (the slope of the fractal dimension curve is 9.94801 \times 10^{-4}) were both increasing but the rate of change in the slope of the fractal dimension curve before the key layer fractured was greater than after it had fractured, which further demonstrates the controlling effect of key layers on their overlying strata.

From the analysis of the fissure density and fractal dimension, it can be found that cracks under the key layer were fully developed when the primary key layer had not collapsed and the roof remained suspended, and the cracks developed slowly after the primary key layer was broken, which was consistent with the results of microseismic...
event monitoring. According to this conclusion, we could arrange the boreholes in suitable locations for efficient gas drainage.

4.4 Construction of gas drainage model

By analysis the stress, placement, fissure density, fractal dimension, and energy in the key layer, we find that the key layer plays a decisive role in controlling the overlying strata. As shown in Figure 18, if the key layer is not broken, the gas in the goaf will not diffuse to the top of the key layer and will form a gas enrichment area below the key layer. We could determine the location of this gas enrichment area through the identification of the key layers, and then use high-level boreholes for gas drainage to ensure safe production at the working face.

If the primary key layer is broken, the breaking of the key layer controls the migration of the accompanying rock formations, thereby controlling the change in stress-relief gas drainage, that is, the stress-relief gas drainage volume increases periodically with the periodic breaking of the primary key layer. Therefore, by observing the fracture step of the primary key layer or according to the distance between the extreme points of the stress-relief gas drainage curve, the prediction of the next peak position of the stress-relief gas drainage volume could be achieved to a certain extent.
When we used high-level drilling to extract gas, the final position of the borehole could be found in the cracked area on the side of the working face and the gas enrichment area under the key layer.

5  |  Field applications

5.1  |  Layout of high-level drilling

The fracture of the key layer will cause the simultaneous fracture of all or part of the overlying strata, causing a large range of strata movement, a sudden increase in permeability, and a sudden increase in stress-relief gas drainage. Determining the collapse position of the key layer can provide a key reference for the layout of high-level drilling and safe mining. Figure 19 shows the layout and parameters pertaining to high-level drilling.

5.2  |  Gas extraction efficiency of high-level drilling

The gas flow and concentration in high-level drilling operations were monitored in real-time. Pure gas drainage volumetric flow rates and mixed flow rate were calculated (Figure 20A): the pure gas drainage value was 0.05-0.38 m³/min, and the mixed flow was 8.82-25.76 m³/min.

By monitoring the gas concentration in the upper corner and the return air-flow, it was found that the average gas concentration in the upper corner was 0.46% and the average gas concentration in the return air-flow was 0.34%, which met the specification for safe mining. This shows that the high-level drilling was safe and effective.

6  |  CONCLUSION

In this study, physical similarity simulation experiments based on microseismic monitoring were used to quantify the energy, stress, and displacement changes before and after the breaking of the complex key layer on large-mining-height coal. The work provides advice for those seeking to increase the efficiency of gas control. The following conclusions were drawn:

Stress sensors and microseismic equipment were adopted to monitor the collapse characteristics of different key layers through variations of stress and energy. The research results showed that: the displacement of the overlying strata showed group motion characteristics marked by the key layer and there was a zone of rapidly increasing stress in the goaf behind the working face before and after the fracture of the key layer. Through the analysis of microseismic events, fissure density, and fractal dimension, we found that: before and after the primary key layer fractured, the energy loss in the microseismic event accounted for 27% of the total, the fissure density also changed abruptly from 8 to 10 cracks/m and the slope of the fractal dimension curve changed from 0.00243 to 9.94801 × 10⁻⁴. Then a gas drainage model suitable for this condition was constructed.
When the primary key layer had not fractured, the cracks below fully developed to form a gas migration channel and a gas enrichment area, and gas boreholes could be arranged in the area. After the primary key layer fractured, the rate of crack development would decrease, the permeability would increase, and the gas concentration would increase. The boreholes could still be arranged in the gas migration channel.

The role of key layers in the evolution of cracks was assessed from multiple aspects. According to the test results, two drilling fields were arranged for gas drainage. After high-level drilling, the average gas concentration in the upper corner was reduced to less than 0.46%, and the average gas concentration in the return air roadway was reduced to 0.34%. Observing the fracture step of the upper key layer can ensure safe and efficient stoping.

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CONFLICTS OF INTEREST
The authors declare no conflict of interest.

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