

Article

Investigating the Evolution of Coal Pore Structure Triggered by Fault Activation

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Abstract

To investigate the quantitative relationship and dynamic response evolution between fault activation and coal pore morphology, this study employs coal samples from faults with varying throws to simulate the fault throw activation process. Taking the 120910 working face of the Longfeng Coal Mine in Guizhou as the study area, six groups of coal samples with gradient throws were collected. High-pressure mercury intrusion porosimetry (MIP), low-temperature nitrogen adsorption (LTNA), and fractal theory were integrated to systematically reveal the evolutionary characteristics of coal pores driven by fault activation. The results indicate a three-stage dynamic evolution characterized by distinct critical thresholds. (1) In the initial fracture development stage corresponding to fault throws not exceeding 1.2 m, fault activation promotes the propagation and coalescence of primary fractures, manifested as slight increases in specific surface area and pore volume. (2) As the throw increases to 1.2–1.6 m, corresponding to the strong compaction stage, intense compression triggers extensive collapse of pore throats ranging from 2 to 50 nm, resulting in a sharp 57.8% decline in specific surface area and the poorest pore connectivity; (3) When the throw exceeds 1.6 m and the process enters the secondary fracturing stage, the coal undergoes brittle failure, generating abundant ultrafine pores. This drives an exponential rebound in specific surface area and increases the micropore volume to 0.0069 m³/g, indicative of significant pore refinement. Collectively, this evolutionary process exhibits a three-stage dynamic pattern of “fracture development-strong compaction-secondary fracturing” with well-defined critical points. This study elucidates the pore structure evolution characteristics of coal during fault activation, providing guidance for safe gas drainage and coal and gas outburst prediction.

Keywords: fault activation; high-pressure mercury intrusion porosimetry; low-temperature nitrogen adsorption; pore structure



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1. Introduction

During underground mining, the phenomenon wherein originally stable faults undergo renewed dislocation and slip due to engineering disturbances is termed fault activation. This process involves rapid stress adjustment and release in the hanging wall and

footwall rock masses, potentially leading to large-scale structural instability and consequently inducing dynamic disasters such as rockbursts and mine pressure bumps [1–3]. Furthermore, as crucial geological weak planes and fluid migration pathways, fault activation can induce abrupt permeability changes within the fault zone and its influence range [4], thereby altering gas occurrence and migration conditions, and predisposing the area to fluid-related disasters like coal and gas outbursts [5]. Coal and gas outburst is a complex dynamic process involving multi-field coupling of in situ stress, gas pressure, and the physico-mechanical properties of coal [6]. Subjected to long-term tectonic stress, stress concentration zones and coal structure fragmentation zones often form near faults, leading to localized gas enrichment and the creation of gas anomaly areas. Under superimposed mining-induced stress, the stress equilibrium in these zones is easily disrupted, promoting rapid desorption and seepage of adsorbed gas, significantly increasing outburst risk. Therefore, an in-depth investigation into the impact of fault activation on coal microstructure modification serves as the scientific basis for understanding the mechanism of fault-controlled gas outbursts and developing targeted prevention technologies.

To deeply understand the influence of faults on coal microstructure, previous studies have conducted systematic research from multiple perspectives, including macroscopic stress monitoring, three-dimensional complexity evaluation, pore structure, and gas adsorption characteristics. Wang et al. [7] found through field measurements that faults Fd28 and N13 were significantly activated when a fully mechanized caving face passed through a fault group, with vertical stress peaks reaching 9.07 MPa and dislocation amounts of 9 mm and 39 mm, respectively; the activation effect was most significant 20–30 m from the fault. Yan et al. [8] further proposed a 3D complexity evaluation method for faults in working faces, indicating that complexity increases significantly when mining approaches faults, with microseismic events concentrated in high-complexity zones, revealing the correlation between fault instability and stress evolution. Shen et al. [9] studied the pore structure and gas adsorption/desorption characteristics of tectonic coal in minor fault zones, finding that mesopores and macropores are significantly modified near the fault, and the maximum adsorption capacity, desorption rate, and expansion energy of gas increase as distance to the fault decreases, with the hanging wall influence range exceeding that of the footwall. Sun et al. [10] investigated the evolution of coal permeability and gas outburst mechanisms adjacent to concealed faults. Their experimental results indicated that the permeability of coal specimens sampled 20 m and 50 m from the concealed fault was 3.2, 8.3, and 2 times higher than that of intact raw coal under the initial loading stage, minimum permeability stage, and post-failure stage, respectively. They further revealed that the well-developed fracture networks within the fault influence zone facilitate local gas accumulation and raise the risk of coal and gas outbursts. Liu et al. [5] compared the pore structures of coal samples near minor faults with those without faults, noting enhanced mesopore connectivity and significantly increased micropore quantity in coal near faults, accompanied by increased order in the macromolecular structure. Li et al. [11] combined AFM and SEM to characterize nanoscale pore structure and mechanical properties, providing methodological support for understanding fault-induced coal modification at the microscale. Wang et al. [12] compared the pore fractal characteristics of tectonic and intact coal using LTNA, indicating simpler pore structures and enhanced gas adsorption capacity in tectonic coal. Liu et al. [13] and He et al. [14] emphasized the controlling role of geological structures on coal and gas outbursts, suggesting enhanced prediction within 30 m ahead of structural zones and the necessity of outburst prevention measures within 10 m. Zhu and Xu [15] elucidated the theoretical basis of tectonic stress field evolution as the dominant factor in coal and gas outbursts.

In summary, existing research focuses on static pore differences at fixed distances from faults. Few studies have explored how coal pores evolve dynamically and stage-wise

with varying fault vertical displacement. Fault throw acts as a quantitative metric for fault vertical offset. Larger throw delivers stronger tectonic shear and compression to coal seams, which further activates coal's internal structures. On this basis, this work collects coal specimens with gradient fault throws ranging from 0 m to 3.2 m dislocation. Each throw gradient represents coal subjected to distinct tectonic damage. This continuous sampling scheme fully captures pore structural responses across the entire fault activation process. By integrating MIP, LTNA, and fractal theory, we systematically reveal the three-stage dynamic evolution law of coal pores driven by fault activation: “fracture development–strong compaction–secondary fracturing.” From an engineering perspective, the staged pore evolution law established in this work provides clear, targeted guidance for on-site gas drainage and coal and gas outburst prevention in fault-disturbed mining panels.

2. Experimental Materials and Methods

2.1. Sample Collection and Preparation

Faults are typical brittle fracture structures within crustal rock masses. When tectonically induced in situ stress exceeds the ultimate strength of rock strata, fractures develop in the crust. If the fractured rock blocks undergo relative displacement along the fracture surface, such brittle geological structures are defined as faults. To quantitatively characterize fault geometric features and support the subsequent experimental analysis of fault activation, the basic geometric components of faults are presented in Figure 1, including the three-dimensional stereogram (Figure 1a), a schematic of fault plane contact lines (Figure 1b), and a cross-section showing displacement parameters (Figure 1c).

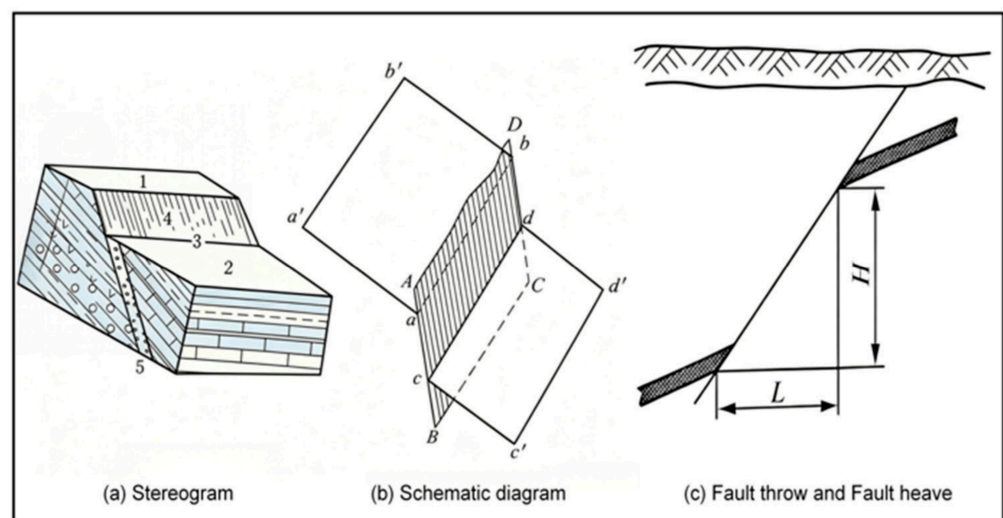


Figure 1. Schematic illustration of fault geometric parameters, fault throw and fault heave. (a) Stereogram of fault structure; (b) schematic diagram of fault plane and contact lines; (c) cross-section displaying fault displacement parameters. Legend: 1—Footwall; 2—Hanging wall; 3—Fault trace; 4—Fault plane; 5—Fault fracture zone; ABCD denotes the fault plane; AD represents the fault trace; ab = footwall contact line; cd = hanging wall contact line; H = Fault throw; L = Fault heave.

In a fault cross-section, the identical stratum boundary intersects the fault trace at two separate points on the hanging wall and footwall. The vertical elevation difference H between these two intersection points is defined as fault throw, the core index adopted in this study to quantify vertical fault dislocation. The horizontal distance L between the two points is defined as fault heave. Variations in fault throw govern the intensity of tectonic compression and shear damage acting on coal seams, which further alters coal microscopic pore architecture and gas adsorption–seepage performance. For this reason,

six groups of coal samples with gradient fault throws ranging from 0 m to 3.2 m were collected to clarify the staged evolutionary law of coal pore structures under different fault activation intensities.

The coal samples investigated in this study were taken from Lindong Longfeng Coal Mine, Xinhua Township, Jinsha County, which is characterized by complex geological structures. A total of 107 faults have been identified within the mining area; only one fault has a throw of 8.1 m, while all remaining faults have throws less than 5 m and are classified as minor faults. Sampling was carried out at the 120910 working face, covering five groups of tectonically deformed coal formed under different fault throws and one group of intact raw coal. The geographical location of the mine and detailed sampling layout are displayed in Figure 2. The samples are labeled YM, DC1, DC2, DC3, DC4, and DC5, corresponding to fault throws of 0 m, 0.7 m, 1.2 m, 1.6 m, 1.9 m, and 3.2 m, respectively. All fresh coal specimens were immediately wrapped with plastic film after collection to avoid oxidation and surface contamination before laboratory testing. The full sample crushing, sieving, and testing workflow is illustrated in Figure 3.

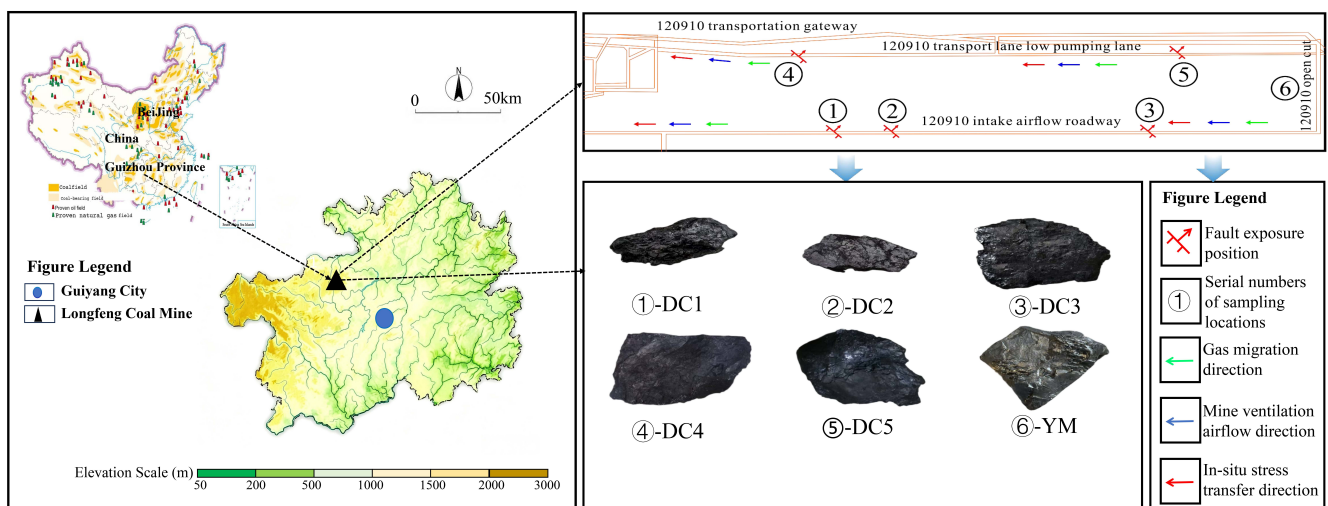


Figure 2. Study area and sampling location diagram.

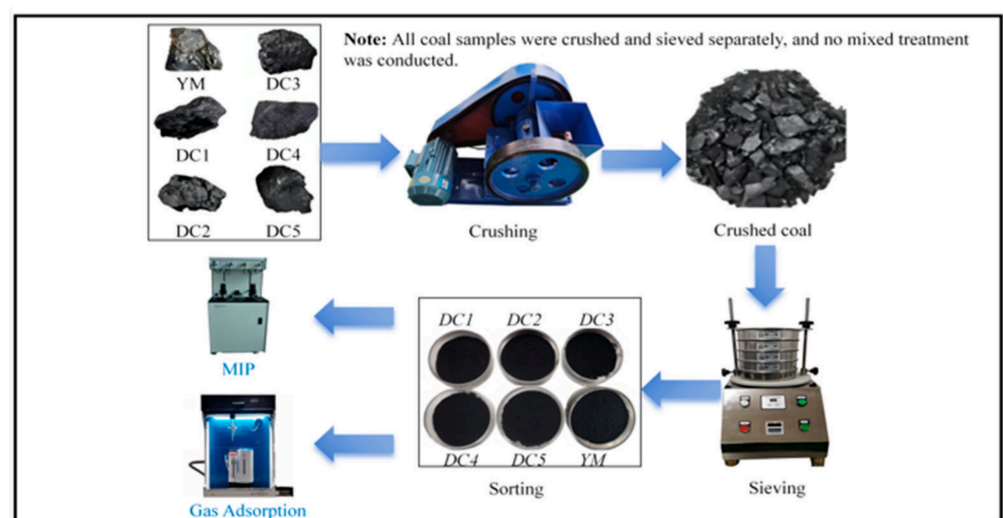


Figure 3. Preparation and experimental methods of different coal samples.

2.2. MIP

An AUTOPORE IV 9500 automatic mercury porosimeter (Micromeritics Instrument Corporation, Norcross, GA, USA) was used in this experiment. Each block sample was tested in triplicate. The mercury intrusion method applies external pressure to force liquid mercury into the coal pores against surface tension. By analyzing the relationship between mercury intrusion volume and applied pressure, pore characteristic parameters such as pore diameter, pore volume, and specific surface area were obtained. Testing smaller pore sizes requires higher mercury pressures, which can deform and damage the coal pore structure. Therefore, the effective detection range of MIP is typically limited to macropores with diameters > 50 nm, posing significant limitations for characterizing mesopores (2–50 nm) and micropores (< 2 nm) that determine gas adsorption capacity [16–18]. According to previous research, tectonic action primarily affects the proportion of micropores in coal samples [19–21]. To compensate for the limitations of MIP in characterizing micropores and mesopores, this study employed LTNA to identify and analyze the fine pores in coal samples.

2.3. LTNA

An ASAP 2460 fully automatic specific surface area and porosimetry analyzer (Micromeritics Instrument Corporation, Norcross, GA, USA) was used to conduct low-temperature nitrogen adsorption–desorption experiments under a liquid nitrogen constant temperature of 77.3 K, using high-purity nitrogen as the adsorbate. Prior to the experiment, accurately weighed coal samples (0.14–0.17 g) were placed in sample tubes and subjected to vacuum degassing pretreatment at 120 °C for 6 h, maintaining a system dynamic vacuum below 1×10^{-3} Pa. This ensured thorough removal of physically adsorbed moisture and gaseous impurities, providing a clean and stable surface for subsequent adsorption tests. After pretreatment, the sample tubes were transferred to the analysis station to acquire complete adsorption–desorption isotherms over a relative pressure range (P/P_0) of 0.001 to 0.995 in a liquid nitrogen bath. This wide-range scanning was designed to accurately capture the entire process from micropore filling to mesopore capillary condensation. Based on the obtained isotherms, the Brunauer–Emmett–Teller (BET) model was used to calculate total specific surface area; the Barrett–Joyner–Halenda (BJH) model was applied to the adsorption branch data to obtain pore volume and pore size distribution in the 2–300 nm range; the t-Plot method was employed to analyze low relative pressure data for quantitative assessment of micropore (< 2 nm) volume and specific surface area contribution.

3. Experimental Results and Analysis

3.1. Quantitative Characterization of Pores by MIP

The mercury intrusion–extrusion curves for raw coal and tectonic coal are shown in Figure 4. Obvious deviations appear between parallel MIP curves of the same coal specimen. This stems from the inherent particle-scale heterogeneity of tectonically deformed coal. After crushing and sieving, random particle loading in each test causes fluctuations in mercury intrusion volume. Even so, the average pore parameters of triplicate tests display regular variations with fault throw. Analysis reveals that the overall morphological characteristics of the intrusion–extrusion curves for all samples are similar. In the low-pressure section, mercury intrusion volume increases with rising pressure; when pressure reaches approximately 100 MPa, the growth rate significantly decelerates. The corresponding pore size in the low-pressure section is predominantly > 1.0 μm , indicating the presence of abundant micron-scale pores in the coal samples. When pressure is between 100 and 500 MPa, the mercury intrusion curve tends to flatten, suggesting limited pore development within this pressure range. For pressures exceeding 500 MPa, mercury intrusion

volume begins to increase markedly again, indicating the existence of numerous nanoscale pores. Additionally, DC1 shows a wider and slightly backward-shifted hysteresis loop compared with intact coal YM. More mercury is trapped after depressurization, widening the intrusion-extrusion gap and shifting the hysteresis range backward. DC2 and DC3 present nearly invisible hysteresis bands. Mercury can flow out almost completely during pressure release, resulting in negligible volume differences. DC4 has no obvious hysteresis at low and medium pressures, while DC5 forms a wide hysteresis band in the high-pressure zone. High MIP pressure corresponds to nanoscale ultrafine pores. Massive ultrafine pores are newly generated under strong fragmentation, trapping abundant mercury and creating prominent high-pressure hysteresis.

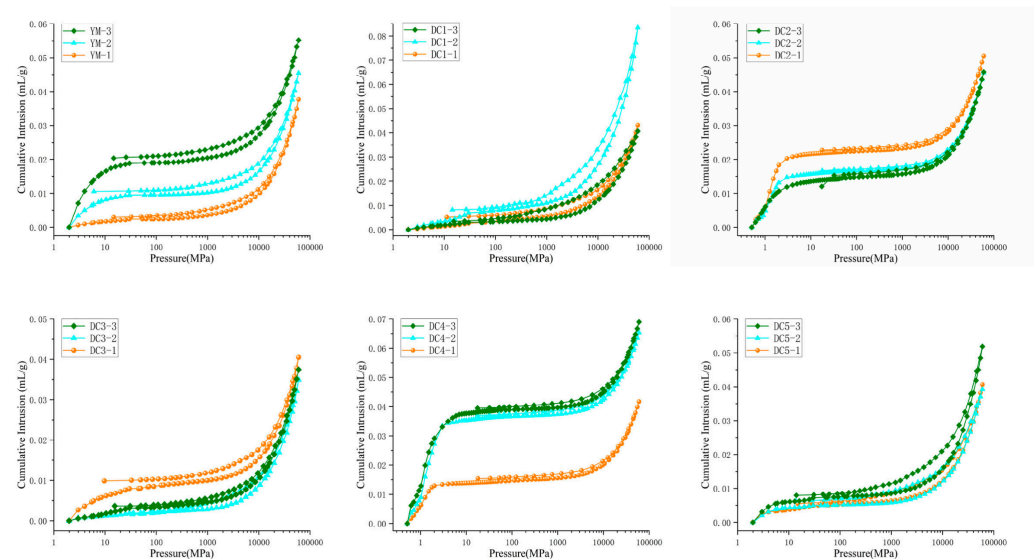


Figure 4. Mercury intrusion–extrusion curves of coal samples.

MIP can quantitatively measure fundamental parameters of coal macropore systems, including total pore volume, specific surface area, average pore diameter, and porosity. Parallel test data and average values of all samples are summarized in Table 1. Undisturbed raw coal YM has the highest average porosity of 6.630% among all groups. However, its average total pore volume is only 0.0461 mL/g and its average specific surface area is 21.906 m²/g. These two values are relatively low compared with tectonic coal samples, with an average pore diameter of 8.4 nm. This phenomenon indicates that raw coal only contains sparse isolated natural macropore fractures. Poor interpore connectivity leads to low macropore volume and specific surface area captured by MIP. DC1 has an average total pore volume of 0.0558 mL/g and an average specific surface area of 22.452 m²/g. Both values exceed those of intact coal YM. One replicate of DC1 shows an abnormally high specific surface area of 45.057 m²/g, resulting in obvious data divergence. This can be attributed to intensified tectonic fracturing that amplifies particle-scale heterogeneity of coal. For DC2, the average total pore volume is 0.0473 mL/g and the average specific surface area drops to 17.943 m²/g, while the average pore diameter rises to 10.6 nm. Sustained tectonic shear connects tiny fractures into larger macropores. Larger pore size reduces the specific surface area per unit volume. Even so, its overall macropore storage capacity is still higher than that of raw coal. DC3 reaches the minimum values across all samples. Its average total pore volume falls to 0.0376 mL/g and average porosity is only 5.6504%, with the average pore diameter shrunk to 7.4 nm. Intense tectonic compression triggers brittle collapse of expanded macropores and fractures formed in the previous stage. Severe compaction closes most pore throats and sharply reduces macropore storage space, which synchronously lowers total pore volume and porosity. DC4 possesses the maximum macropore volume

among all test groups. Its average total pore volume, specific surface area, and porosity are 0.0587 mL/g, 24.579 m²/g, and 6.2180%, respectively. These quantitative data demonstrate that severe tectonic fragmentation produces newly formed macropore fractures and promotes macropore development. Compared with DC3 in the strong compaction stage, DC5's average total pore volume increases by 16.8% and average porosity rises by 10.3%. Under large fault vertical displacement, part of the compacted macropores reopen. Meanwhile, pore collapse and reconstruction occur, generating numerous interconnected microcracks inside the coal matrix.

Table 1. Pore parameters of coal samples.

Sample ID	Data Analysis			
	Total Pore Volume/mL·g ^{−1}	Specific Surface Area/m ² ·g ^{−1}	Average Pore Size/nm	Porosity/%
YM	0.0377	21.780	6.9	5.4750
	0.0455	22.380	8.1	6.5141
	0.0552	21.558	10.2	7.9010
	0.0461	21.906	8.4	6.6300
Average	0.0088	0.43	1.67	1.22
DC1	0.0432	22.807	7.6	6.4619
	0.0835	45.057	7.7	6.6527
	0.0407	22.097	7.4	6.1177
	0.0558	22.452	7.6	6.4108
Average	0.024	0.50	0.15	0.27
DC2	0.0505	16.986	11.9	7.0207
	0.0456	17.830	10.2	6.3610
	0.0458	19.013	9.6	6.3938
	0.0473	17.943	10.6	6.5918
Average	0.0028	1.02	1.19	0.37
DC3	0.0405	19.506	8.3	6.3737
	0.0349	20.779	6.7	5.2090
	0.0374	20.869	7.2	5.3686
	0.0376	20.385	7.4	5.6504
Average	0.0028	0.76	0.82	0.63
DC4	0.0417	23.619	7.4	6.0603
	0.0654	24.556	7.4	6.2687
	0.0690	25.563	7.4	6.3246
	0.0587	24.579	7.4	6.2180
Average	0.015	0.97	0.00	0.14
DC5	0.0407	22.150	7.3	6.0921
	0.0519	28.101	7.4	6.8765
	0.0392	20.891	7.5	5.7416
	0.0439	23.714	7.4	6.2367
Average	0.0069	3.85	0.10	0.58

The pore fractal dimension was calculated from high-pressure mercury intrusion experimental data. The fitted curves are displayed in Figures 5–7, and the corresponding calculation results are listed in Table 2.

$$\log \frac{dv}{dp} = (D - 4) \cdot \log P + C \quad (1)$$

$$D = K + 4 \quad (2)$$

where V is the mercury intrusion volume (mL/g); P is the mercury intrusion pressure (MPa); D is the fractal dimension; and C is a constant [22].

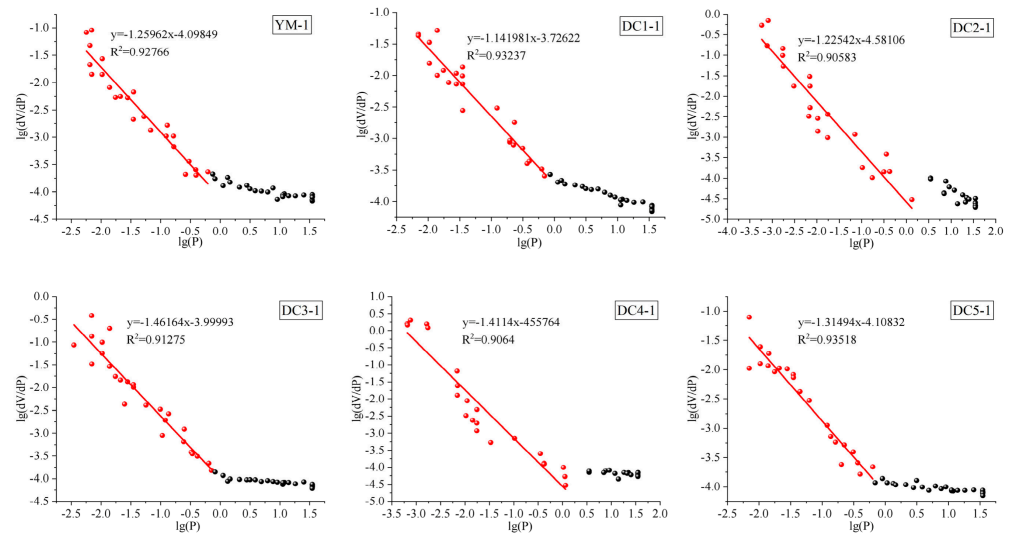


Figure 5. Plots of $\lg(dV/dP)$ and $\lg P$ reconstructed based on MIP (data from the first experiment).

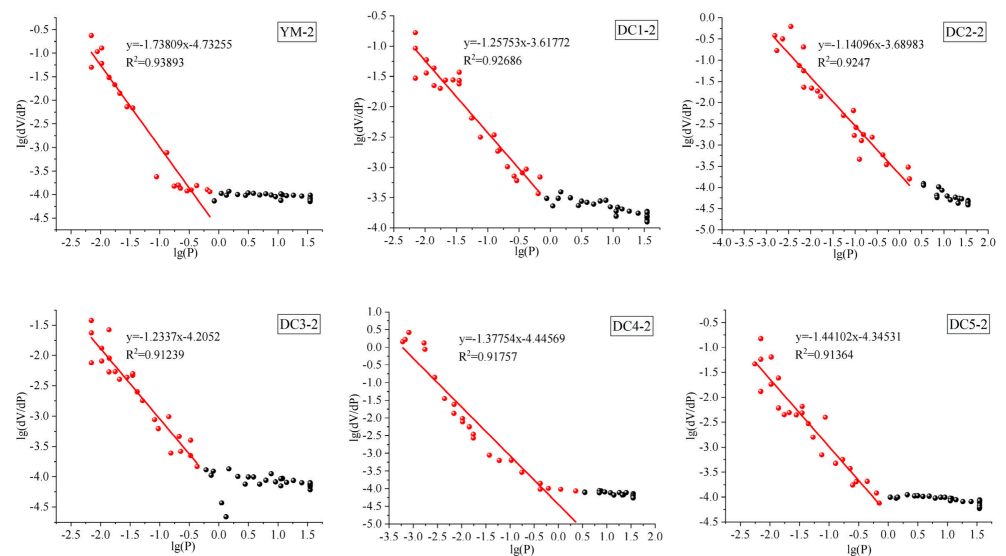


Figure 6. Plots of $\lg(dV/dP)$ and $\lg P$ reconstructed based on MIP (data from the second experiment).

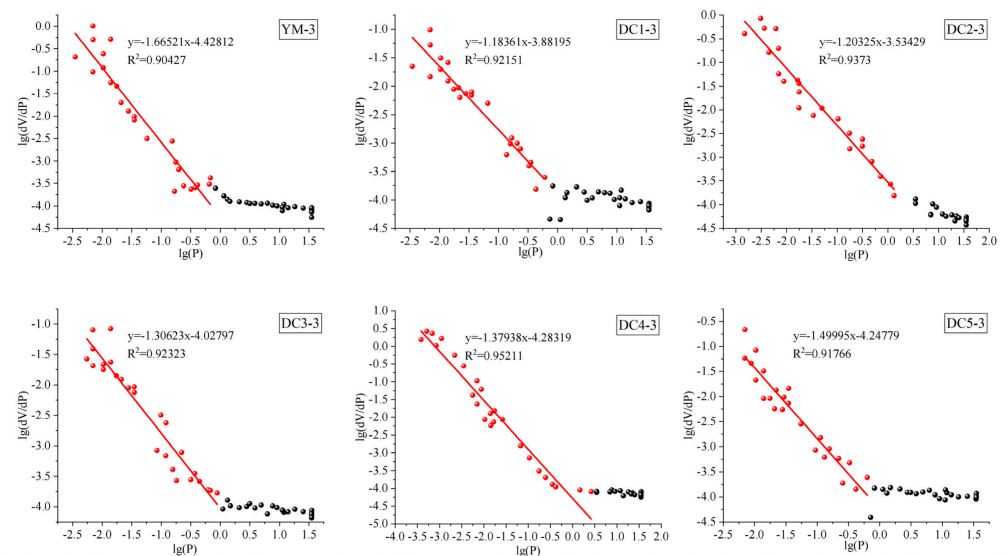


Figure 7. Plots of $\lg(dV/dP)$ and $\lg P$ reconstructed based on MIP (data from the third experiment).

Table 2. Fractal dimension based on Plots of $\text{Lg}(dV/dP)$ and LgP reconstructed.

Sample No	Fractal Fitting Equation	R ²	Fitting Slope	D	Average (D)
YM-1	$y = -1.25962x - 4.09849$	0.92766	−1.25962	2.74038	2.44569
YM-2	$y = -1.73809x - 4.73255$	0.93893	−1.73809	2.26191	
YM-3	$y = -1.66521x - 4.42812$	0.90427	−1.66521	2.33479	
DC1-1	$y = -1.14198x - 3.72622$	0.93237	−1.14198	2.858019	2.80563
DC1-2	$y = -1.25753x - 3.61772$	0.92686	−1.25753	2.74247	
DC1-3	$y = -1.18361x - 3.88195$	0.92151	−1.18361	2.81639	
DC2-1	$y = -1.22542x - 3.72622$	0.93237	−1.22542	2.87746	2.84442
DC2-2	$y = -1.14096x - 3.68983$	0.92470	−1.14096	2.85904	
DC2-3	$y = -1.20325x - 3.53429$	0.93730	−1.20325	2.79675	
DC3-1	$y = -1.46164x - 3.9999$	0.91275	−1.46164	2.53836	2.66625
DC3-2	$y = -1.23370x - 4.2052$	0.91239	−1.23370	2.76630	
DC3-3	$y = -1.30626x - 4.02797$	0.92323	−1.30626	2.69377	
DC4-1	$y = -1.41140x - 4.55764$	0.90640	−1.41140	2.58860	2.61056
DC4-2	$y = -1.37754x - 4.44569$	0.91757	−1.37754	2.62246	
DC4-3	$y = -1.37938x - 4.28319$	0.95211	−1.37938	2.62062	
DC5-1	$y = -1.31494x - 4.10832$	0.93518	−1.31494	2.68506	2.58136
DC5-2	$y = -1.44102x - 4.34531$	0.91364	−1.44102	2.55898	
DC5-3	$y = -1.49995x - 4.24779$	0.91766	−1.49995	2.50005	

MIP is suitable for macropores larger than 50 nm; fractal discussion is not provided for pore structures smaller than 50 nm. The results show that the average fractal dimension D of YM is 2.44569, significantly lower than that of fault coal samples, indicating a relatively simple pore structure. The fractal dimension of fault coal samples initially increases and then decreases with increasing fault throw. Fault activation destroys the pore structure of coal, forming a more complex pore network and increasing the fractal dimension. As the degree of fault activation intensifies, coal fragmentation increases, forming larger pores or cracks, making the overall pore structure tend towards uniformity and leading to a decrease in fractal dimension.

3.2. Quantitative Characterization of Pores by LTNA

The LTNA experiment focused on the precise characterization of small and medium pores (2–50 nm range, covering part of mesopores and micropores), compensating for the limitations of MIP in this pore size range. Through systematic analysis of the adsorption–desorption isotherms of six groups of coal samples, calculation of specific surface area using the BET model, analysis of pore volume and pore size distribution using the BJH model, and extraction of micropore structural parameters using the t-Plot method, quantitative parameters for small and medium pores were obtained for each coal sample (Table 3).

Table 3. Quantitative parameters of small and medium pores from LTNA.

Sample ID	YM	DC1	DC2	DC3	DC4	DC5
BET surface area (m ² /g)	3.8945	3.8402	4.0892	1.7250	12.9555	36.3590
t-Plot Micropore Area (m ² /g)	0.1117	0.2041	2.5497	0.5588	5.1223	16.5010
t-Plot micropore volume: (cm ³ /g)	−0.00015	0.000069	0.0010	0.00011	0.0021	0.0069
Adsorption average pore diameter (nm)	12.4107	16.7844	8.8276	14.1953	5.1678	4.4930
Desorption average pore diameter (nm)	8.8917	13.6744	5.6675	9.4978	4.2489	3.8160

From the overall trend, as the fault throw increases, the coal pore structure presents obvious staged evolutionary characteristics controlled by fault tectonism. For intact raw coal YM, the BET specific surface area is only $3.8945 \text{ m}^2/\text{g}$, and the t-Plot micropore specific surface area is merely $0.1117 \text{ m}^2/\text{g}$. The corresponding t-Plot micropore volume yields a negative fitted value, a mathematical artifact originating from the linear fitting algorithm for samples with extremely low micropore content; this non-physical value will not be discussed in subsequent evolutionary analysis. For DC1, weak tectonic shear imposes a mild disturbance on the coal matrix. Its BET specific surface area slightly reduces to $3.8402 \text{ m}^2/\text{g}$, whereas t-Plot micropore area and micropore marginally climb to $0.2041 \text{ m}^2/\text{g}$ and $0.000069 \text{ cm}^3/\text{g}$. The slight loss of total BET surface is balanced by mesopore shrinkage, marking the initial formation of nanoscale micropores under low tectonic disturbance. DC2 presents evident growth of fine pore parameters. Its BET specific surface moderately increases to $4.0892 \text{ m}^2/\text{g}$, accompanied by a sharp jump in t-Plot micropore area and volume up to $2.5497 \text{ m}^2/\text{g}$ and $0.0010 \text{ cm}^3/\text{g}$. Such obvious growth verifies extensive expansion of nanoscale micropores induced by accumulated shear strain inside coal. DC3 shows sharp attenuation of all fine pore parameters. The BET specific surface area plummets to $1.7250 \text{ m}^2/\text{g}$, and t-Plot micropore volume shrinks to merely $0.00011 \text{ cm}^3/\text{g}$. Strong extrusion crushes and blocks most micro-mesopore throats, causing widespread collapse of fine pore spaces. The massive disappearance of tiny pores leaves abundant medium-sized voids, which explains the rebound of DC3's average adsorption pore diameter. Obvious recovery of micropore indicators is observed on DC4 and DC5. Excessive tectonic load breaks coal matrix via brittle fragmentation. Their BET specific surface areas rise exponentially to $12.9555 \text{ m}^2/\text{g}$ and $36.3590 \text{ m}^2/\text{g}$, while t-Plot micropore volumes continuously grow to $0.0021 \text{ cm}^3/\text{g}$ and $0.0069 \text{ cm}^3/\text{g}$. The sustained growth of micropore parameters confirms the generation of numerous ultrafine pores on newly formed fracture surfaces after coal brittle failure. The evolutionary rule of adsorption and desorption average pore diameters further verifies the above tectonic force-controlled pore evolution pattern. The adsorption average pore diameter of YM is 12.4107 nm ; shear splitting refines pores down to 8.8276 nm at DC2; severe compaction closes fine throats and lifts the average pore size to 14.1953 nm at DC3; and subsequent brittle fragmentation continuously refines the pore network to 5.1678 nm (DC4) and 4.4930 nm (DC5). Apart from the strong compaction stage, intensified fault activation generally promotes the refinement of coal pore systems.

The adsorption–desorption isotherms of all coal samples (Figure 8) exhibit typical Type IV isotherms accompanied by H3-type hysteresis loops, indicating that the pore structure is dominated by slit-shaped pores formed by platelet stacking. As the throw increases, the hysteresis loop morphology changes significantly. At DC3, the hysteresis loop narrows, indicating reduced pore connectivity, whereas at DC4 and DC5, the hysteresis loop widens again, reflecting restored and enhanced pore connectivity. In summary, the LTNA experiment effectively reveals the dynamic evolution process of small and medium pore structures in coal during fault activation—from micropore development, compaction closure, to secondary fracturing refinement—providing direct experimental evidence for understanding the modification of coal's nanoscale pore structure by fault activation.

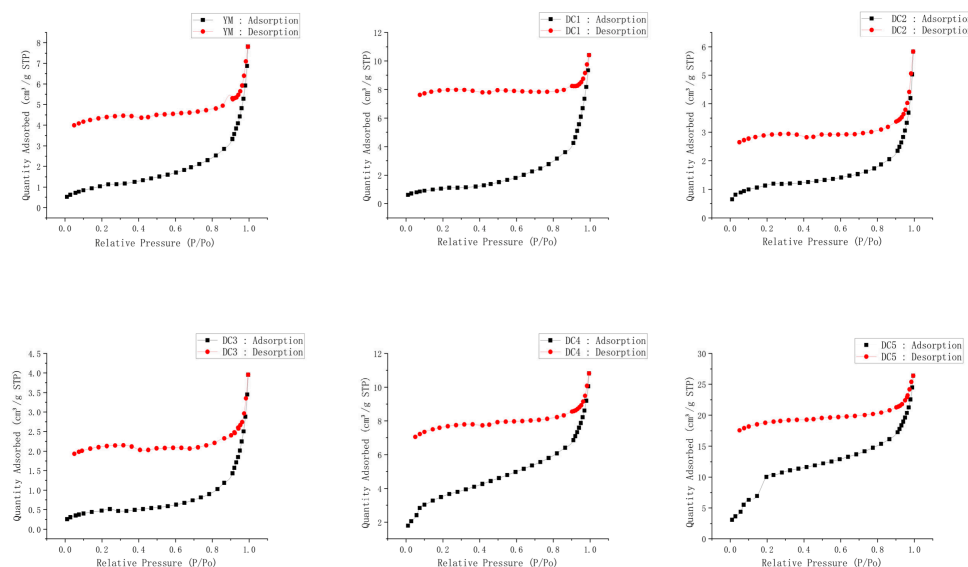


Figure 8. Adsorption–desorption isotherms of coal samples based on the BET method.

Various approaches are available to calculate the fractal dimension of solids from gas adsorption–desorption isotherms. The FHH model is the most widely adopted method due to its universal adaptability and simple computation [23]. Avnir et al. [24] integrated fractal dimension into adsorption potential theory for studies on gas adsorption over rough porous media, namely the well-known FHH equation:

$$\ln(Q) = C + (D - 3) \cdot \ln\left(\ln \frac{P_0}{P}\right) \quad (3)$$

where Q is the gas adsorption amount corresponding to the equilibrium pressure P , cm^3/g ; P is the equilibrium pressure, MPa; P_0 is the saturated vapor pressure of the adsorbed gas, MPa; C is a constant; D is the fractal dimension of the porous material, and the value of D is between 2 and 3.

In accordance with the classical application rules of the FHH model proposed in the above literature, only adsorption branch data (red dots in Figure 9) are adopted for linear fitting in this study, while desorption branch data (black dots) are merely retained in the figure for comparative reference without fitting analysis.

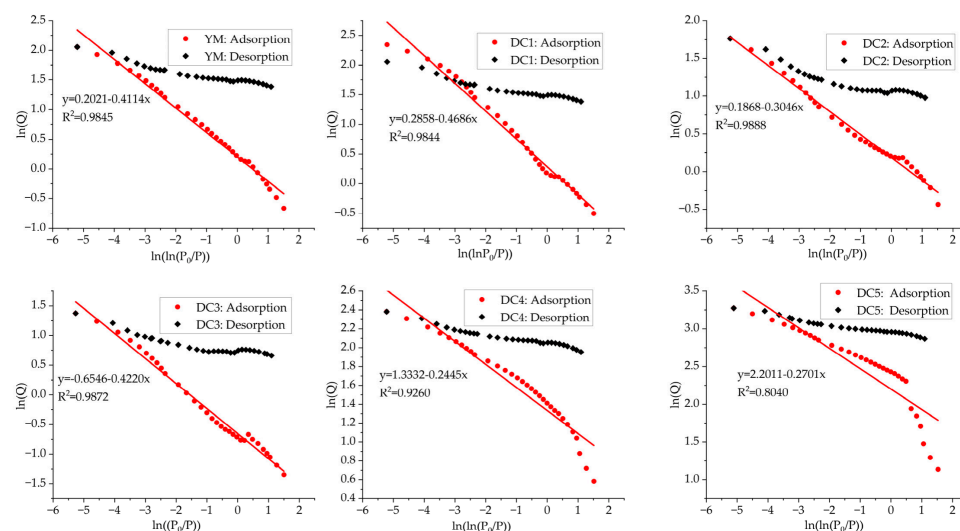


Figure 9. Plots of $\ln Q$ and $\ln(\ln(P_0/P))$ reconstructed based on LTNA.

Fractal dimensions of micro-mesopores were calculated via the FHH model based on LTNA data, as summarized in Table 4 and plotted in Figure 9. The fractal dimensions of YM, DC1, DC2, DC3, DC4, and DC5 are 2.5886, 2.5314, 2.6954, 2.5780, 2.7555, and 2.7299, respectively. All D values range between 2 and 3, which satisfies the physical definition of pore fractal dimension and verifies that coal pores under different fault dislocation intensities exhibit fractal geometric properties. The fractal dimension reflects the complexity of pore surface morphology; DC1 has the lowest value corresponding to relatively regular micro-mesopores, while DC4 shows the highest fractal dimension, representing the most disordered fine pore network.

Table 4. Fractal dimension based on the FHH model.

Sample No	Fractal Fitting Equation	R ²	Fitting Slope	D
YM	$y = 0.2021 - 0.4114x$	0.9845	−0.4114	2.5886
DC1	$y = 0.2858 - 0.4686x$	0.9844	−0.4686	2.5314
DC2	$y = 0.1868 - 0.3046x$	0.9888	−0.3046	2.6954
DC3	$y = -0.6546 - 0.4220x$	0.9872	−0.4220	2.5780
DC4	$y = 1.3332 - 0.2445x$	0.9260	−0.2445	2.7555
DC5	$y = 2.2011 - 0.2701x$	0.8040	−0.2701	2.7299

Notably, fractal dimension peaks derived from MIP and LTNA measurements do not coincide. The MIP method quantifies macropores, with DC2 presenting the highest fractal dimension. The LTNA-based FHH model characterizes micro-mesopores, and its maximum fractal value appears at DC4. This mismatch in peak positions arises from the two techniques' different detectable pore size ranges, instead of conflicting evolutionary trends of coal pore structures. DC2 corresponds to samples under moderate fault throw. Mild persistent shear distorts and elongates primary large fractures without intensive coal matrix compaction. This process generates highly irregular macropore channels, which explains the maximum macropore fractal complexity captured by MIP. At this stage, most micro-mesopore throats remain partially open. The disorder of fine pore networks stays moderate, so the FHH fractal dimension does not reach its peak. DC4 experiences larger fault displacement. Long-term compressive stress exceeds the coal matrix's bearing capacity and induces extensive brittle fracturing. Massive disordered nanoscale micro-mesopores form on fresh fracture surfaces. The complexity of fine pore systems rises sharply, yielding the highest LTNA fractal dimension. Meanwhile, persistent compaction homogenizes the tortuous macropore structures developed at the DC2 stage. Consequently, MIP fractal dimensions gradually decline from DC2 to DC4 and DC5.

4. Discussion

Based on quantitative test data from MIP and LTNA, it was found that coal pore structure parameters exhibit a non-monotonic evolutionary trend of “increase—sharp decline—exponential recovery” with increasing fault throw, with significant abrupt changes occurring at throws of 1.2 m and 1.6 m. Such non-monotonic abrupt changes in pore structure parameters cannot be reasonably explained by a single mechanical mechanism. Therefore, based on critical phenomena, the evolutionary process is divided into three stages: “fracture development—strong compaction—secondary fracturing.” This division represents a reasonable induction of the pore structure changes in coal driven by fault activation.

4.1. Evolutionary Characteristics of the Fracture Development Stage

At this stage, coal suffers low-magnitude tectonic shear, corresponding to the initial stage of fault activation. From MIP macropore data in Table 1, DC1 has higher total pore volume and porosity than intact raw coal YM. Its wider backward hysteresis loop in Figure 4 indicates a larger intrusion–extrusion volume difference. This quantitative feature proves that primary macropores are stretched and interconnected under weak tectonic disturbance. LTNA results reflect mild variations in fine pore parameters. The BET specific surface area and t-Plot micropore volume of DC1 only rise slightly (Table 2). Combined with the moderate macropore fractal dimension of DC1 in Table 3, it can be inferred that most tectonic strain acts on the expansion of >50 nm macropores, while sub-50 nm micropore structures receive limited structural damage. Existing compression tests of tectonic coal confirm that micropore frameworks maintain certain structural stability under low tectonic loading, which accounts for the slow growth of micropore-related indicators [25]. The widening macropore channels provide preliminary migration pathways for gas. Judging from the small gap between adsorption and desorption pore sizes in LTNA isotherms, the connectivity of fluid channels is moderately improved at this stage. However, the quantity of adsorption-dominated ultrafine micropores remains low. The dual control of an unbroken coal matrix and insufficient micropore development leads to weak gas enrichment capacity, resulting in relatively low coal and gas outburst risk in low-throw fault zones.

4.2. Evolutionary Characteristics of the Strong Compaction Stage

Coal with 1.2–1.6 m fault throw is subjected to intense compressive tectonic deformation. MIP data show that DC3 has the minimum total pore volume and porosity, accompanied by a nearly closed mercury hysteresis loop with a tiny intrusion–extrusion volume difference. Combined with the drastically reduced LTNA micropore parameters of DC3 and the maximum macropore fractal dimension of DC2, the synchronous shrinkage of macro-, meso-, and micropores under compression can be identified. Previous comparative tests on tectonically damaged coal prove that continuous compression reduces the coal firmness coefficient and triggers coordinated plastic collapse of multi-scale pore throats. Meanwhile, highly twisted macropore channels raise fractal complexity, while massive isolated ink-bottle pores narrow hysteresis bands and weaken pore connectivity. Hysteresis width and mercury extrusion efficiency are reliable quantitative indicators to evaluate fluid transport capacity, and the coexistence of high fractal dimension and poor connectivity is a typical feature of highly compacted coal [26]. From gas disaster perspectives, poorly interconnected pores trap adsorbed gas within isolated voids, readily forming localized high-pressure gas reservoirs and markedly elevating coal and gas outburst hazards in zones with 1.2–1.6 m fault displacement.

4.3. Evolutionary Characteristics of the Secondary Fracturing Stage

Coal with fault throw exceeding 1.6 m undergoes brittle fracturing after long-term compaction. Unlike the unidirectional pore shrinkage in the compaction stage, pore structures show obvious recovery when tectonic deformation reaches a critical intensity. MIP data demonstrate stable macropore volume and pore size for DC4 and DC5, indicating a dynamic balance between compaction and bearing support within the dense coal matrix. LTNA results exhibit exponential growth of BET surface area and t-Plot micropore volume, accompanied by widened adsorption–desorption hysteresis loops. This reflects the regeneration of massive ultrafine pores and restored pore connectivity superior to that of the initial fracture stage. Cumulated strain energy is released when tectonic stress surpasses coal compressive strength, triggering matrix fragmentation and generating numerous fresh

adsorption surfaces. The coexistence of well-developed micropores and interconnected fractures simultaneously strengthens methane adsorption and gas migration capacity. Rapid gas desorption and outflow can be easily triggered, making coal with fault throw above 1.6 m the highest-risk zone for coal and gas outbursts.

5. Conclusions

This study, focusing on the 120910 working face of Guizhou Longfeng Coal Mine, collected six groups of tectonic coal samples with gradient throws to simulate the fault activation process. By integrating MIP, LTNA, and fractal theory, the dynamic evolution process of coal pore structure driven by fault activation was systematically revealed. Through quantitative characterization of pore size distribution, pore volume, specific surface area, and fractal features of coal samples at different activation stages, the main conclusions are as follows:

- (1) The coal pore structure driven by fault activation exhibits a three-stage evolutionary characteristic: “fracture development—strong compaction—secondary fracturing,” with mechanical transition critical points existing at different fault throw intervals. At the fracture development stage, primary pores expand and interconnect, accompanied by widened mercury hysteresis loops and improved inter-pore connectivity. Under strong compaction, multi-scale pore throats shrink synchronously, hysteresis bands narrow sharply, and pore connectivity reaches the minimum value. At the secondary fracturing stage, large quantities of ultrafine micro-mesopores regenerate, and hysteresis loops widen again to recover fluid transport capacity.
- (2) The staged evolution of pore structure controls the adsorption-seepage capacity of coal, resulting in differentiated modes of gas outburst risk. The fracture development stage favors the construction of seepage pathways, with relatively low outburst risk. The strong compaction stage exhibits poor pore connectivity, facilitating the formation of enclosed high-pressure zones and significantly increasing outburst potential. The secondary fracturing stage shows synchronous enhancement of both adsorption and seepage capacity, posing the highest outburst risk.
- (3) Fractal analysis based on MIP and LTNA captures scale-dependent pore complexity differences. MIP fractal dimensions for macropores peak at DC2, whereas FHH fractal dimensions of micro-mesopores reach the maximum at DC4. This inconsistency of fractal peak samples originates from the different pore size detection ranges of the two testing methods rather than contradictory pore evolution trends. Macropore complexity rises first and then declines with fault throw, while micro-mesopore disorder continuously grows after the compaction stage, which jointly confirms the three-stage pore evolution law controlled by fault activation.

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