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Quantitative Analysis of Small Fault Sealing

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Abstract This article determines the proper parameters to evaluate fault sealing, models and calculates mathematically on a few small normal faults in Changping Mine Field, measures the fault sealing from a stress perspective, and, using the evaluation results, examines the primary factors influencing sealing. Analysis has revealed that the fault's lithology, attitude, and depth of burial all have a significant controlling influence on the fault's sealing conditions, gas pressure, fault stress distribution, and stress conditions. These factors also directly affect the fault's gas content and accumulation conditions.

Keywords Coal seam, Gas occurrence, Normal fault, Closure coefficient, Coal and gas outburst

1. Introduction

Although deep coal seam mining has not yet taken over as the primary mining technique, shallow coal seam resources are gradually running out. The discovery of geological formations is a significant difficulty in deep coal seam mining. The risk of deep geological structures grows exponentially with mining depth[1], and the expense of exploring coal seams and geological structures likewise rises. A novel strategy and methodology for the investigation and evaluation of deep coal-bearing faults is presented in this paper.

The formation and destruction of coalbed methane reservoirs are intimately associated with faults[1], which usually have a dual function of sealing and guiding. For this reason, the examination of fault opening and sealing is crucial to the assessment of coal seam gas. Currently, there exist numerous techniques to assess the sealing of fault zones, which can be broadly classified into four categories.[2]: (1) analyzing the lateral juxtaposition of lithology on both sides of the fault zone: Allen diagram method, Knipe diagram method, and sand mud docking probability method; (2) Analyze the ability of mudstone coating in fault zones[3, 4]: mudstone coating potential method[5], mudstone coating factor method, and fault mudstone ratio method; (3) Analyze the displacement pressure of fault rocks and surrounding rocks[6]; (4) Analyze the geological or fluid properties on both sides of the fault zone: oil gas water interface analysis method, oil gas water property analysis method[7], production dynamic analysis method, and structural stress analysis method.

Lv[8] et al. utilized section pressure computation and probability simulation of sand and mud docking between two fault plates to investigate the lateral and vertical sealing of faults, respectively. Tong[9] et al. established a quantitative mathematical model for fault opening and sealing, and analyzed the factors that affect fault opening and sealing based on the model, including the strike, dip angle, depth, etc. of tectonic stress faults. Wang[10] et al. developed a mathematical force analysis model for the faults, chosen sealing assessment coefficients, and assessed the faults quantitatively. It has been discovered that compressive and torsional faults have substantially superior sealing performance than tensile and torsional faults when viewed from a force standpoint.

2. Quantitative analysis of the opening and sealing of faults

2.1 Fault sealing principle

Faults can serve as channels for the migration and overflow of coal seam gas, and also serve as seals for gas accumulation. The sealing of faults is mainly influenced by various factors such as fluid pressure, section stress, and the properties of the surrounding rock in the section. The determination of whether a fault acts as a sealing effect or a migration channel mainly depends on the fault stress. Fault stress can be divided into compressive stress, shear stress, tensile stress, and their composite forces, compressive shear stress and tensile shear stress. Faults are subjected to different stresses, and their effects on gas vary. It is generally believed that faults with compressive stress, shear stress, and compressive shear stress have a sealing effect on gas. Among these, the sealing effect of tensile shear stress on faults is weaker than the other two stresses, while faults under tensile stress do not have a sealing effect on gas. Therefore, the stress state of the cross-section is the key factor determining the sealing effect of the fault on gas.

When the depth of a fault exceeds a certain value, the compressive stress caused by the overlying rock layer becomes the dominant factor in the stress state of the fault. The fault and its surrounding rock cannot experience tensile stress, even if the fault is located in an extensional basin. In the absence of tensile stress, the fault must rely on gas pressure to maintain its opening. When the fluid pressure of gas is greater than or equal to the positive pressure stress on the fault plane, the fault can open up and become a channel for gas migration; otherwise, it becomes a barrier boundary for gas.

The fluid pressure of gas is affected by three forces, including overlying rock pressure, static water column pressure, and structural stress. When the coal seam is connected to groundwater, it exhibits good permeability, and the pressure supported by the pore fluid in the coal seam is equivalent to the static water pressure in the pore channel. At this time, the gas pressure in the coal seam is equal to the static water pressure; If the coal reservoir is surrounded by impermeable formations, the reservoir fluid cannot flow freely, and the pore fluid pressure of the reservoir is balanced with the pressure of the overlying strata. At this time, the reservoir pressure is equal to the pressure of the overlying strata; In coal seams, the permeability is poor and the connectivity with groundwater is also poor. Due to the formation of local semi-closed states, the pressure of the overlying strata is jointly borne by the pore fluid and coal matrix blocks in the reservoir. At this time, the pressure of the coal reservoir is less than the pressure of the overlying strata but greater than the static water pressure. The formula is shown as Equation 2-1:

$$\sigma_v = p + \sigma \qquad (1)$$

In the formula

σ_v——Overburden rock pressure，Mpa

p——Coal reservoir pressure，Mpa

σ——Stress of coal seam skeleton，Mpa

The analysis steps for the opening and sealing of faults can be summarized as follows: (1) Investigating the geometric characteristics of faults, including their strike, dip, and cross-sectional shape; (2) Quantitatively calculating the structural stress field; (3) Determine the lithology on both sides of the fault and measuring the physical parameters of the rock layers; (4) Calculating the fluid pressure coefficient of the target layer.

2.2 Stress analysis of fault section

Fault sealing is primarily influenced by the pressure on the fault plane and the pressure of the coal reservoir. Therefore, a mathematical model is developed to analyze the stress direction on the fault plane. Extract the cross-section separately and make the following simplified assumptions: (1) The fault plane retains its inclination and dip angle and is considered a regular geometric plane without bends, folds, or faults; (2) The lithology of the fault displacement layer is consistent, and it is considered an isotropic rock layer with uniform texture and mechanical properties, without considering the impact caused by different lithologies; (3) The material properties of the fault zone are uniform, without considering changes in the thickness and physical properties of the fault zone.

The x-axis, y-axis, z-axis directions are respectively related to the maximum horizontal principal stress σ_h, minimum horizontal principal stress σ_H and vertical principal stress σ_z is parallel. OO' is the normal outside the fault plane,θ_H、θ_h、θ_z is respectively σ_H、σ_h、σ_z the angle with the normal outside the fault plane. As shown in Figure 1

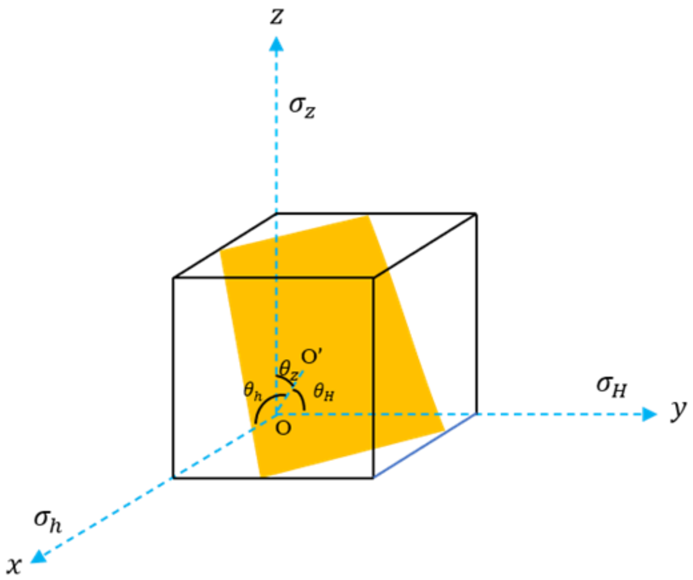

Figure 1: Mathematical model for stress analysis of fault planes

Solve the cross-section based on the principle of force superposition, the superposition of the normal stress components σ_H, σ_h, σ_z, as well as the superposition of the shear stress components, can respectively obtain the normal stress σ and shear stress τ on the cross-section.

Calculate the superposition of equal stresses in the vertical stress direction σ_z:

Assuming the cross-sectional area is S，So the projected area of the cross-section on the xOy plane is S', The combined force of σ_z acting on the cross–section is σ'. According to the equilibrium condition of force, the magnitude of the force acting on the cross-section in the negative z-axis direction σ_z is equal to the force projected on the xOy plane by the cross-section, expressed by the formula as follows:

$$\sigma' S = \sigma_z S' \quad (2)$$

So

$$\sigma' = \sigma_z \frac{S'}{S} \quad (3)$$

So, according to geometric relationships, it can be calculated that the resultant force σ' can be represented as:

$$\sigma' = \sigma_z \cos\theta_z \quad (4)$$

And the combined force σ' can also be decomposed into normal stress σ_z' and shear stress τ_z' based on geometric relationships:

$$\begin{cases} \sigma_z' = \sigma' \cos\theta_z = \sigma_z \cos^2\theta_z \\ \tau_z' = \sigma' \sin\theta_z = \sigma_z \cos\theta_z \sin\theta_z \end{cases} \quad (5)$$

Similarly, it can be concluded that the normal stress σ_H' and shear stress τ_H' generated by σ_H on the cross-section are:

$$\begin{cases} \sigma_H' = \sigma_H \cos^2\theta_H \\ \tau_H' == \sigma_H \cos\theta_H \sin\theta_H \end{cases} \quad (6)$$

Similarly, the normal stress σ_h' and shear stress τ_h' generated by σ_h on the cross-section are:

$$\begin{cases} \sigma_h' = \sigma_h \cos^2\theta_h \\ \tau_h' = \sigma_h \cos\theta_h \sin\theta_h \end{cases} \quad (7)$$

By superimposing various stress components, the normal stress σ can be obtained

$$\sigma = \sigma_z' + \sigma_H' + \sigma_h' = \sigma_z \cos^2\theta_z + \sigma_H \cos^2\theta_H + \sigma_h \cos^2\theta_h \quad (8)$$

The shear stress τ cannot be directly superimposed due to different directions. According to the principle of force synthesis, the shear stress τ can be obtained:

$$\tau = \sigma_z^2 \cos^2\theta_z + \sigma_H^2 \cos^2\theta_H + \sigma_h^2 \cos^2\theta_h - \sigma^2 \quad (9)$$

2.3 Fault sealing evaluation

2.3.1 Fault closure index（I_{FT}）

Fault closure index（I_{FT}）represents the ratio of the normal stress σ of the cross-section to the compressive strength σ_p of the rock in the fault zone, as:

$$I_{FT} = \frac{\sigma}{\sigma_p} \quad (10)$$

The compressive strength σ_p can be obtained from equations 2-11

$$\sigma_P = R_{SG}\sigma_{CM} + (1 - R_{SG})\sigma_{CS} \quad (11)$$

In the formula

R_{SG}-- Mudstone scraping ratio

σ_{CM}-- Compressive strength of mudstone，Mpa

σ_{CS}-- Compressive strength of sandstone，Mpa

Mudstone scraping ratio R_{SG}Can be obtained from 2-12 equation

$$R_{SG} = \frac{\sum_{i=1}^{n} H_i V_{ish}}{L} \times 100\% \quad (12)$$

In the formula

H_i--The thickness of the i th layer，m

V_{ish}-- The content of mudstone in the i th layer，%

L--Fault displacement，m

When I_{FT}>1, mudstone deformation causes the closure of fault fractures and fault sealing, and the larger the I_{FT} value, the better the sealing performance; When 0≤I_{FT}≤1, the normal stress of the cross-section is not sufficient to cause compression deformation of the material in the fault zone, and the impact on the fault sealing is relatively small; When I_{FT}<0, it indicates that the normal stress on the fault plane is tensile stress, and the fault opens.

2.3.2 Fault sealing coefficient（I_f）

The fault sealing coefficient I_f represents the ratio of the normal stress σ on the fault surface to the fluid pressure P, as

$$I_f = \frac{\sigma}{P} \quad (13)$$

Among them, the fluid pressure P can be expressed as

$$P = f\rho_w gh \quad (14)$$

In the formula

f--Abnormal pressure coefficient

ρ_w --Water density，kg/m^3

$\rho_w gh$--hydrostatic pressure，N

The abnormal pressure coefficient f is defined as the ratio of the actual formation pressure to the static water column pressure at the same depth. When the depth is less than 2000m, it is generally the static water pressure, and the pressure coefficient is 1.0; Abnormal pressure often occurs at depths of 2000-3500m, manifested as a pressure coefficient greater than 1.0, and in some cases can even reach around 2.45. In the presence of high abnormal overpressure, faults are prone to opening up.

When the fluid pressure is greater than the normal pressure on the cross-section, as $P > \sigma$, the cross-section can open up and become a channel for fluid transport. When I_f >1.0, the fault is sealed, and the larger the value, the higher the degree of sealing; When I_f <1.0, the fault opens, and the smaller the value, the greater the degree of opening.

2.3.3 Fault shear index（I_C）

Fault shear index I_C can be defined as the ratio of the shear stress τ on the fault plane to the shear strength σ_C of the material in the fault zone，as

$$I_C = \tau/\sigma_C \quad (15)$$

Among them, σ_C is the sum of the inherent shear strength of the fault zone material and the frictional force acting on the fault plane, as

$$\sigma_C = C + \omega\sigma \quad (16)$$

In the formula

C-- The inherent shear strength of the material itself，Mpa

ω-- Internal friction coefficient

The meaning represented by the fault shear index (I_C) is that when I_C>1, shear sliding occurs between the two walls of the fault, causing changes in the material properties of the fault zone. When I_C>1 and the normal stress on the fault plane is compressive stress (as σ>0), a compression type shear displacement occurs between the two walls of the fault, causing the material in the fault zone to be compressed while the original oil and gas seepage channels such as pores and fractures are closed under shear action, enhancing the sealing degree of the fault and improving its ability to seal oil and gas; On the contrary, when σ<0, tension type shear displacement occurs in the two fault zones, and the scale of existing oil and gas seepage channels such as pores and fractures will expand under tension. At the same time, due to the shear displacement of the two fault zones, it is possible to generate new fractures, increase the degree of fault opening, and become favorable channels for oil and gas migration. When I_C≤1, the fault only shows a trend of shear displacement, and there is no relative displacement between the two walls of the fault. The material properties of the fault zone do not change significantly, and the impact on the fault sealing can be ignored

3. Example analysis

Select the normal faults of the No. 3 coal seams in the 5th mining area and 6th mining area sections of the experimental mine Changping Mine Field, and the characteristic parameters of the faults are shown in Table 3-1

Table 1: Fault characteristic parameters

Fault number	Direction (degree)	Inclination(degree)	Dip angle（degree）	Drop(m)
DF60	NW	SW	70	0-6
DF62	NW	NE	70	0-6
DF64	NE	SE	70	0-6
DF82	N	W	65	3
DF83	N	E	65	3
DF84	E	N	65	7
DF85	EW	N	65	8
DF92	NE	NW	60	5
DF103	NE	SE	70	3
SF228	70	160	60	4.5
SF272	E	N	65	5-6

Taking the small normal fault DF60 as an example, after geological data research and simulation, the dip angle of the DF60 small normal fault is 70 °, with a drop of 3m. The maximum horizontal principal stress at the fault section is 3.61MPa, the minimum horizontal principal stress is 3.51MPa, and the vertical stress is 7.55MPa. By substituting the fault trend, dip angle, dip angle, and stress values into equations 2-8, the normal stress at the section of the DF60 small normal fault can be obtained to be 6.081MPa. According to the geological data of the Changping mine field, the direct roof of the No. 3coal seam in the 6th mining area is mudstone, with compressive strength σ_P is 11-53 MPa, with an average value of 35 MPa. The basic top is fine-grained sandstone, with a compressive strength of 53-122 MPa and an average value of 84 MPa. The calculated I_{FT} = 0.17. Therefore, for the fault closure index I_{FT}, the changes in the formation caused by the DF60 small normal fault are not sufficient to affect the gas sealing situation.

Calculate the fault sealing coefficient I_f. The average burial depth of the No. 3 coal seam in Changping Mine is 500 meters, and the abnormal pressure coefficient f is taken as the normal fluid pressure (hydrostatic pressure) pressure coefficient, which is 1.0. The fluid pressure P of the DF60 small normal fault can be calculated to be 4.9 MPa, and I_f=1.24. According to the fault sealing coefficient, the DF60 normal fault has a sealing effect on gas.

Based on rock mechanics and geological data, the shear strength of the rock in the fault zone can be obtained. The shear stress of the DF60 fault can be calculated as 6.70MPa using equations 1-9. Substituting the shear stress and shear strength into equations 2-15, It can be obtained that I_C=0.2. And the normal stress on the fault is compressive stress, which can be judged that the fault only shows a trend of shear displacement, and there is no relative displacement between the two walls of the fault. The rock properties in the fault zone do not change significantly, and the impact on the fault sealing can be ignored.

Based on the above three evaluation parameters, it can be concluded that the fault sealing coefficient and fault shear index of the DF60 small normal fault are not affected by stress, and the influence of stress on the fault sealing coefficient is not significant. Therefore, it can be concluded that the sealing effect of the DF60 small normal fault is less affected by stress, and the impact of the fault zone on coal seam gas is roughly reflected as a weaker sealing effect. It can be inferred from this that the gas content inside the fault will decrease to a certain extent compared to the original gas content, but it still belongs to the gas enrichment area. In the prevention and control of coal and gas outbursts, it is necessary to focus on preventing the affected area of the fault.

3.1 Engineering verification

Analyze the remaining faults according to the above method, evaluate their sealing effect on gas, and summarize the results as shown in Table 4

Table 2: Fault sealing evaluation

Fault number	Normal pressure /MPa	Compressive strength /MPa	Fluid pressure /MPa	Shear stress /MPa	Shear strength /MPa	Closed nature
DF60	6.08	35.7	4.9	6.70	33.5	Weak closure
DF62	6.08	35.7	4.9	6.70	33.5	Weak closure
DF64	6.08	35.7	4.9	6.70	33.5	Weak closure
DF82	4.24	35.7	4.9	1.98	33.5	Weak closure
DF83	4.24	35.7	4.9	1.98	33.5	Weak closure
DF84	3.54	20.3	4.9	2.00	33.5	Weak closure
DF85	3.54	20.3	4.9	2.00	33.5	Weak closure
DF92	4.54	14.5	4.9	2.13	33.5	Weak closure
DF103	6.08	35.7	4.9	6.70	33.5	Weak closure
SF228	5.01	14.5	4.9	3.32	33.5	Weak closure
SF272	3.90	14.5	4.9	5.06	33.5	Weak closure

By summarizing and analyzing the above faults, it can be seen that the sealing properties of the selected faults are basically not affected by the faults. Therefore, the gas content in the area near the fault section should be roughly the same as that in the area without faults, without significant differences.

The field measurement of fault gas content was carried out using the drilling chip method, and the layout of measurement points is shown in Figure 2

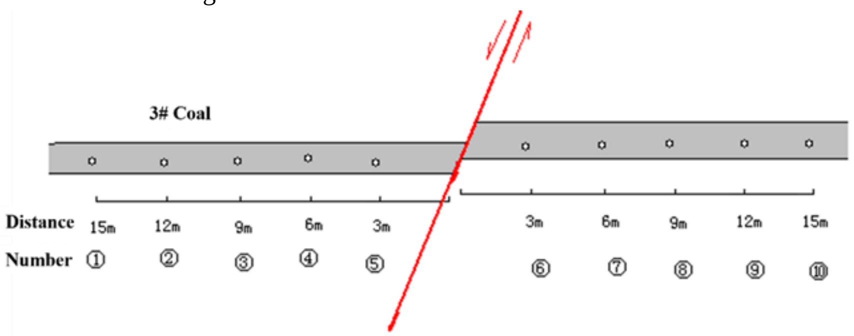

Figure 2:Schematic diagram of drilling and sampling point layout for two fault zones

Drill holes at designated locations and take samples from coal sample tanks, measure the desorption amount, calculate the loss amount based on the gas desorption law, and finally measure the residual gas content in the laboratory. Add the above data to calculate the coal seam gas content. The results are shown in Table 3

Table 3: Measurement results of coal seam gas content

Name	Number	Measurement location	Coal seam gas content （m^3/t）
Gas content in DF82 fault coal seams	1#	DF82 Broken surface hanging wall 3m	4.12
	2#	DF82 Broken surface hanging wall 6m	4.01
	3#	DF82 Broken surface hanging wall 9m	4.28
	4#	DF82 Broken surface hanging wall 12m	4.47
	5#	DF82 Broken surface hanging wall 15m	4.63
	6#	DF82 Broken surface foot wall 3m	4.55
	7#	DF82 Broken surface foot wall 6m	4.25
	8#	DF82 Broken surface foot wall 9m	4.50
	9#	DF82 Broken surface foot wall 12m	4.72
	10#	DF82 Broken surface foot wall 15m	4.89

Overall, the phenomenon of gas accumulation is not significant, and the impact of small faults on gas occurrence is consistent with the previous conclusion, which proves the correctness of the previous closure calculation.

4. Discussion

In engineering practice, prevention and control measures are often implemented in areas prone to coal and gas outbursts to ensure production safety. Studying the sealing effect of small normal faults on gas is of great significance for achieving precise prevention and control of coal and gas outbursts.

Regarding the research in this article, the burial depth, lithology, and characteristic parameters of faults in coal-bearing normal faults play a decisive role in the sealing of faults, and thus change the gas occurrence situation around normal faults. This has certain guiding importance for coal mines to achieve accurate prediction of outburst prevention prediction. However, the complexity of faults makes research beyond this. Other types of faults and fault parameters, such as combined faults, coal rock types, and the impact of different periods on faults, are potential areas for future research.

5. Conclusion

This article selects three mechanical-related parameters, namely the fault closure index I_{FT}, fault sealing coefficient I_f, and fault shear index I_C, to link geostress and fault sealing, and establish a quantitative evaluation system. The evaluation criteria are as follows: ⑴When $I_{FT}>1$, the fault is closed; When $0 \leq I_{FT} \leq 1$, the fault sealing is less affected by normal stress; When $I_{FT}<0$, the fault opens.⑵When $I_f > 1$, the fault is closed, and the larger its value, the better the sealing performance; When $I_f \leq 1$, the fault opens, and the smaller its value, the higher the degree of fault opening. ⑶When $I_C>1$ and the normal stress of the cross-section is compressive stress, the fault sealing is enhanced, and the degree of fault opening is increased when it is under tensile stress; When $I_C \leq 1$, the shear stress of the cross-section has little effect on fault sealing. The selected small normal fault sealing in the Changping mine field is less affected and basically maintains the sealing of faultless strata, so the predicted gas content basically maintains the original gas content.

Further analysis reveals that the following factors play a crucial role in evaluating the sealing of fault sections:

（1） The burial depth of a fault not only affects the stress distribution, peak size, and surrounding rock texture around the fault, but also directly controls the fluid pressure of coal seam gas. When the fluid pressure is greater than the normal stress on the coal rock section, the fault becomes a channel for gas escape.

（2） Fault lithology: When there is a thick mudstone layer at the top of the fault, or when the top is thin and the basic top has thick mudstone, it is easy to form a seal with a sealing effect, which is not conducive to gas escape.

（3） The fault attitude, strike, dip, and dip angle jointly determine the stress situation of the fault. The dip angle of the fault plays a crucial role in the stress component, so it directly controls the normal stress and shear stress on the fault. This is reflected in the compression basin, where the sealing of the fault decreases as the decrease of dip angle.

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