Fault Dynamic Stability Evaluation and Application Based on Slip Trend and Expansion Trend

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Abstract. Fault stability evaluation is an important process of geological integrity evaluation of underground gas storages (UGSs), which is the basis of safe and efficient operation of UGSs. In this paper, the M1 UGS in Jidong Oil Field is taken as the research object. Based on the study of faults characteristics, vertical sealing of fault and lateral sealing of fault and so on, the main faults affecting the geological integrity of the reservoir are screened and the rock mechanics parameters are determined. The theory is based on fault reactivity mechanism and rock fracture mechanism, the dynamic stability of faults in UGS is evaluated by fault slip trend and expansion trend. In this study, TrapTester software was used to construct a three-dimensional geological model, and combined with the present in-situ stress characteristics of block M. And specify the probability of reactivity and calculate additional minimum formation pressure of reactivity of major faults developed in the NgII–NgIV of M1 UGS under the condition of current reservoir pressure. It provides reference for the design of UGS operating pressure and storage capacity parameters.

Keywords: Fault stability · Slip trend · Expansion trend · Underground gas storage

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1 Introduction

Aiming at the construction target of gas reservoir with medium and high permeability reservoir, shallow burial and relatively complete structure, reservoir site evaluation methods have been gradually formed. However, for gas reservoir with complex geological conditions, the existing theories and technical methods cannot effectively guide the scheme design [1–3]. Most of China's geological structure faults are developed, especially in the gas storage high-speed injection and production, high and low pressure switching operation conditions, dynamic sealing evaluation technology of gas storage structure is particularly important, evaluation of sealing factors such as cap rock, fault limit pressure, reasonable optimization of upper pressure, is the primary scientific problem to be solved in reservoir gas storage site evaluation [4–6].

At present, relatively mature evaluation methods have been formed for the evaluation of lateral and vertical static sealing of faults, which are mainly based on the study of fault displacement pressure and mudstone smear, etc., while for the evaluation of dynamic stability of faults, no technical series of dynamic sealing evaluation has been formed yet [7, 8]. The theory is based on fault reactivity mechanism and rock fracture mechanism, the dynamic stability of faults in UGS is evaluated by fault slip trend and expansion trend. In this study, TrapTester soft-ware was used to construct a three-dimensional geological model, and combined with the present in-situ stress characteristics of block M. And specify the probability of reactivity and calculate additional minimum formation pressure of reactivity of major faults developed in the NgII–NgIV of M1 UGS under the condition of current reser-voir pressure. It provides reference for the design of UGS operating pressure and storage capacity parameters.

2 Faults Quantitative Analysis of 1M1 Underground Gas Storage

NgIV reservoir of M1 gas reservoir is located in the ascending wall of NPF1 fault. It is controlled by NPF1 fault and is complicated by the anticline of the fault. It is blocked up and down by igneous rock and sidewise, forming a structure-lithologic reservoir. The faults in the study area are well developed, including NPF1 fault and its derived F1–F9 sub-grade faults. The results of oil and gas accumulation and development show that the faults are originally well sealed.

According to the position relationship between fault and the target of reservoir construction, fault disconnection horizon and fault distance, the faults in the reservoir area are classified and evaluated. Using Traptest software, a three-dimensional geological model was established for the target layer NgIV of Nanpu M1 UGS, and fault sealing performance was evaluated. SGR (gouge ratio), SSF (smear factor), CSP (mudstone smear potential) of each fault and the connection relationship between two plates of each fault were calculated. See Table 1 and Fig. 1 for the calculation results.

The comprehensive evaluation results are as follows: the SGR of 10 faults such as NPF1, F1 and F2 are all greater than the critical sealing value, and the lateral sealing is good. Moreover, all faults are internal reservoir faults, which have little influence on the sealing property of geological body. The lateral sealing of NPF1 fault is equivalent to the gas breakthrough pressure (6.77 MPa), and the average sealing formation pressure is 27.9 MPa.

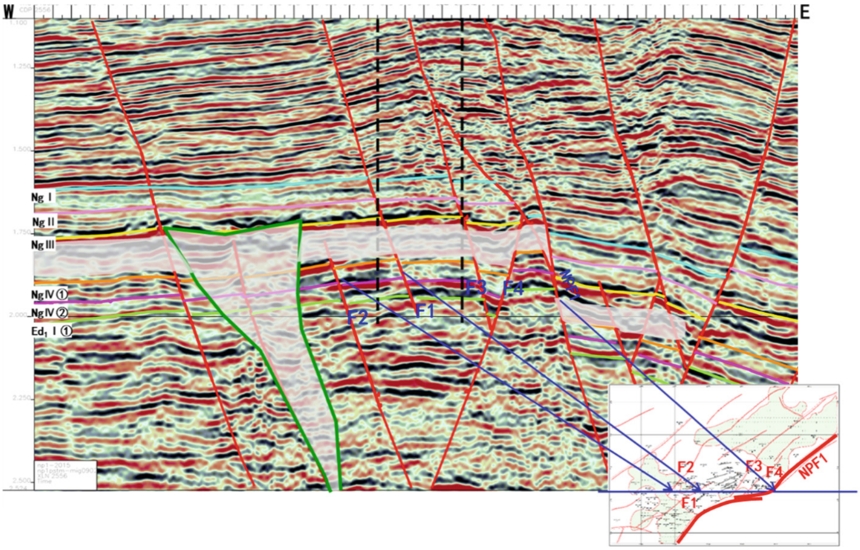

Fig. 1. Fracture pattern diagram of M1 fault block

Table 1. Evaluation results of fault lateral tightness of M1 gas storage

Fault class	Name		Extension length (km)	Direction	Break distance (m)	SGR%	SSF	CSP
I	NPF1	Western section	2.6	northeasterly	110–270	50–70	0.1–1	3–100
		Eastern section	1.7	northeasterly	270–300	20–50	7.5–10	25–90
II	F1		2.7	northeasterly	10–50	50–70	0.1–4	40–60
	F3		3.1	North north east	5–40	30–50	4–10	25–60
	F4		1.6	North north east	20–70	30–50	4–10	25–60
III	F2		3.2	North north east	5–20	20–30	2–10	25–60
	F5		1.7	northeasterly	5–15	20–30	4–10	25–60
IV	F6		0.9	North north east	5–10	20–30	4–10	25–60
	F8		0.7	northeasterly	5–10	20–30	4–10	25–60
	F9		1.1	Near east and west	5–10	50–70	0.1–4	40–60
	F7		2.7	northeasterly	5–10	20–30	4–10	25–60

3 Present Stress State

According to the measured data statistics of the in-situ stress of this structure (Fig. 2), it can be seen from the fitting relation of in-situ stress (Fig. 1) that the in-situ stress gradients of the three principal stresses of SHmax, SHmin and SV are respectively: 1.72 MPa/100 m, 1.99 MPa/100 m and 2.29 MPa/100 m, among which the vertical stress gradient is the largest. With the increase of buried depth, the vertical principal stress will gradually exceed the horizontal stress and become the maximum principal stress. When the buried depth H > 1500 m, SV > SHmax > SHmin, the vertical stress exceeds the maximum horizontal stress and becomes the maximum principal stress.

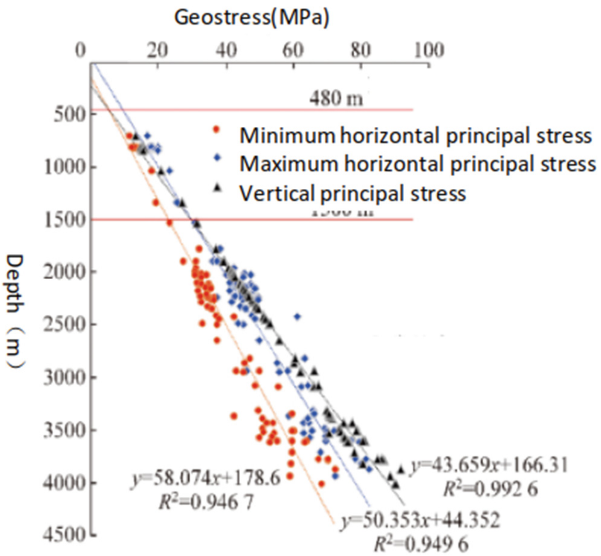

Fig. 2. Relation between present stress and depth of Nanpu Depression

According to the statistics of the vertical burial depth of different layers that have been drilled in the working area, the vertical burial depth of the main reservoir layer is 2100 m and the burial depth of the cap layer is 1800 m. Combined with previous studies, the fault section of M1 gas storage is mainly mudstone smearing, and the coefficient of internal friction is 0.45 and the cohesion is 0.5 MPa.

4 Stability Evaluation of Fault Slip Trend

Fault slip trend (Ts) is the ratio of shear stress to effective normal stress (Formula 1), which is between 0 and μ (fault friction coefficient), and is used to describe the strength of the slip (shear rupture) tendency of non-cohesive faults. When the ratio gradually increases and approaches the static friction coefficient, the slip tendency of faults is gradually enhanced, and the risk of rock fracture increases. When the static friction coefficient is exceeded, the fault begins to slip. The static friction coefficient at the

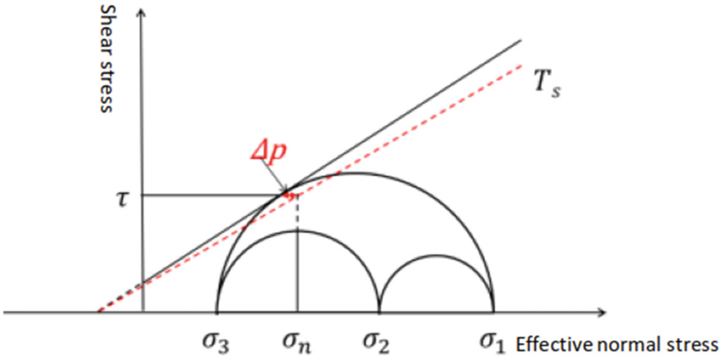

Fig. 3. Schematic diagram of quantitative evaluation of fault slip trend

beginning of slip is generally between 0.6 and 0.85, so the critical starting value of slip is τ ≥ (0.6 to 0.85) σn. The larger the Ts value is, the stronger the slip tendency (shear rupture) of the fault is. The horizontal distance (Δp) between the polar projection point of a unit and the fracture envelope represents the minimum fluid pressure required for the slip of the unit surface, namely, the slip stability. The fault slip trend analysis is shown in Fig. 3 in the stress Mohr circle [9, 10].

$$\mathrm{Ts} = \tau/\sigma n \tag{1}$$

Where, Ts is the slip trend (dimensionless), τis the shear stress (MPa), σn is the effective normal stress.

The slip trend evaluation of NPF1, F1–F10 in M1 area was carried out according to the mudstone coating of fault, the internal friction coefficient was 0.45, and the cohesive force was 0.5 MPa. TrapTester software was used to simulate the slip trend of fault under the current reservoir pressure condition. The calculation results were shown in Table 2,

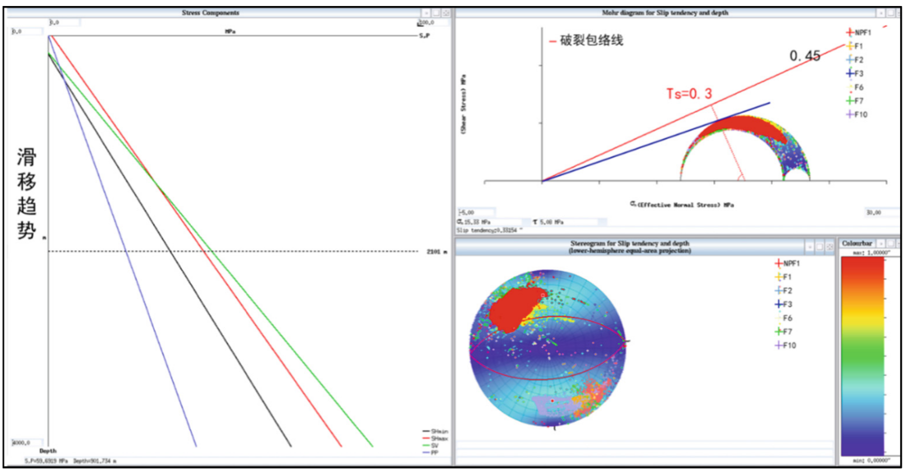

Fig. 4. Analysis Diagram of M1 fault slip trend (2100 m)

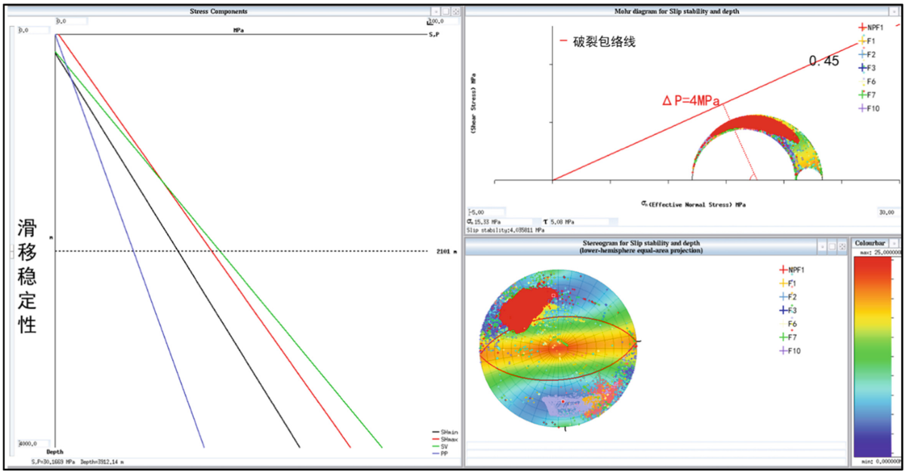

Fig. 5. Calculation result of M1 slip trend

Fig. 4 and Fig. 5. The results of fault slip trend analysis show that the Ts values of each fault surface range from 0.25 to 0.35, and are all less than 0.45, which indicates that the faults in the reservoir are stable under the condition of current in-situ stress, which is consistent with the actual situation of the reservoir. As shown in Fig. 6 and Fig. 7, at the depth of 2100 m, additional fluid pressure ΔP of at least 4 MPa is required to make the fault developed in the reservoir slip, so as to destroy the stability of the current fault.

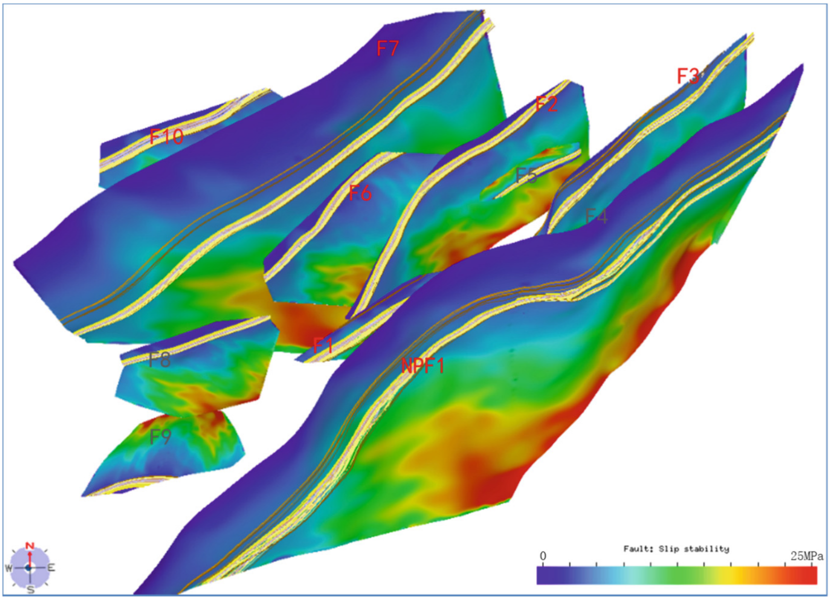

Fig. 6. Analysis Diagram of M1 fault slip stability

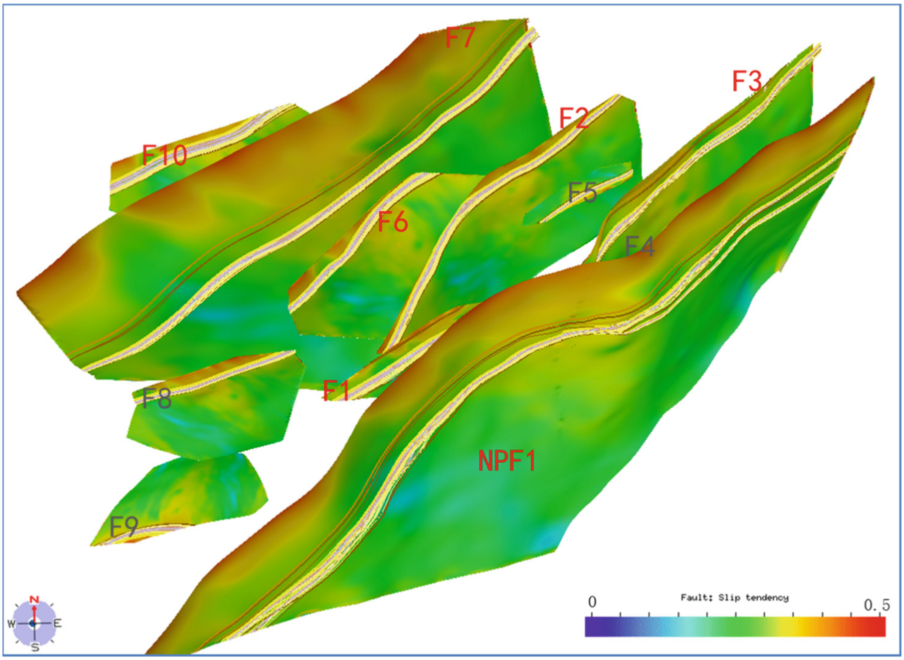

Fig. 7. Calculation result of M1 slip stability

5 Stability Evaluation of Fault Expansion Trend

Fault expansion trend is the ratio of maximum principal stress and effective normal stress difference to differential stress (Eq. 2), and the corresponding expansion trend value of stable fault is between 0 and 1. The larger Td value is, the stronger the fault expansion trend (tensile rupture) trend is, that is, the higher the risk of fault reactivity. However, this parameter can only qualitatively characterize the relative trend of fault tension rupture. When the expansion trend value is greater than 1, it does not mean that the fault will definitely have tensile rupture. Scholars know from the study of fault strength model that the fault without cohesion will reactivity in the form of shear slip before the tensile reactivity occurs. Therefore, the evaluation of fault expansion trend is more suitable for the comparative analysis of fault expansion trend under different stress fields or different occurrences. Combined with fault slip trend, the anisotropy of permeability caused by in-situ stress can be analyzed. The difference (Δp) between the polar projection point and the minimum effective stress of a certain element represents the minimum fluid pressure required for the slip of the element surface, namely the stability of the fault expansion. The fault expansion trend analysis is shown in Fig. 8 [11, 12] in the stress Moir circle.

$$Td = (\sigma 1 - \sigma n)/(\sigma 1 - \sigma 3) \tag{2}$$

Where, Td is the expansion trend (dimensionless), σ1, σ2 and σ3 are the maximum effective principal stress, intermediate effective principal stress and minimum effective principal stress (MPa) respectively, and σn is the effective normal stress (MPa).

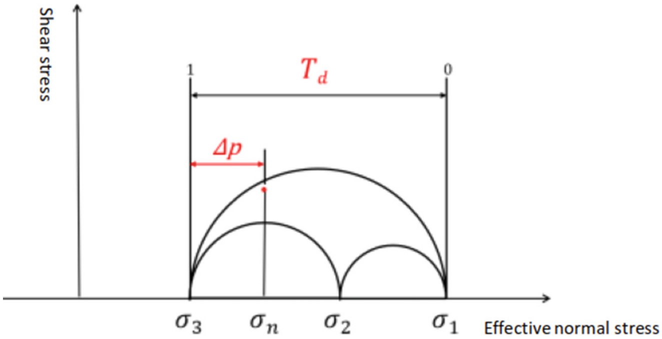

Fig. 8. Schematic diagram of quantitative evaluation of fault expansion trend

TrapTester software was used to simulate the fault slip trend under the current reservoir pressure condition. The calculation results were shown in Table 2, Fig. 9, and Fig. 10. The analysis results of fault expansion trend showed that Td values on each fracture surface ranged from 0.25 to 0.8, all of which were less than 1, indicating that each reservoir fault was stable under the current in-situ stress condition. It is consistent with the actual situation of reservoir. As can be seen from Fig. 11 and Fig. 12, at the depth of 2100 m, additional fluid pressure ΔP is at least 5 MPa to destroy the stability of the current fault in order to make the fault developed in the reservoir produce tensile rupture.

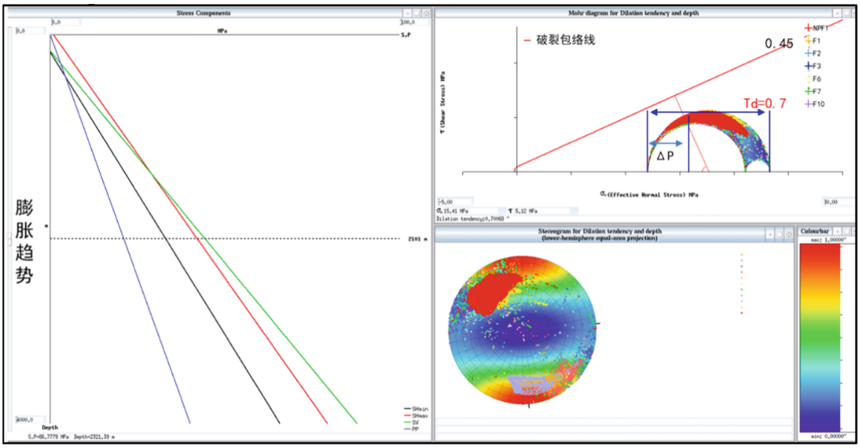

Fig. 9. Analysis Diagram of M1 Fault expansion trend (2100 m)

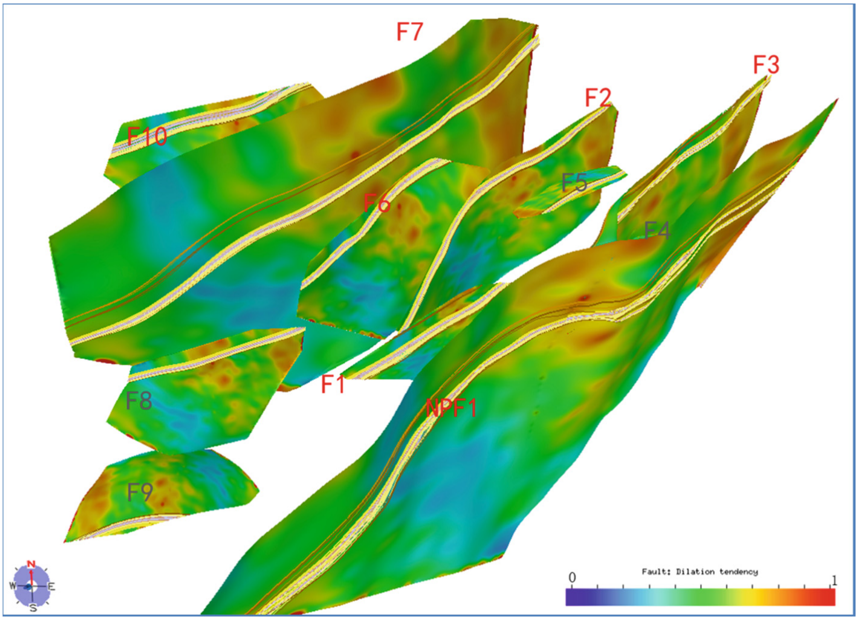

Fig. 10. Calculation result of M1 fault expansion trend

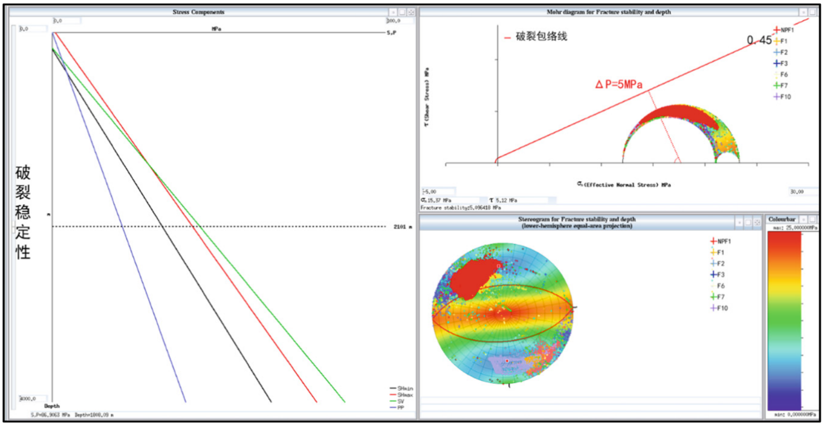

Fig. 11. Stability analysis of M1 fault tensile rupture

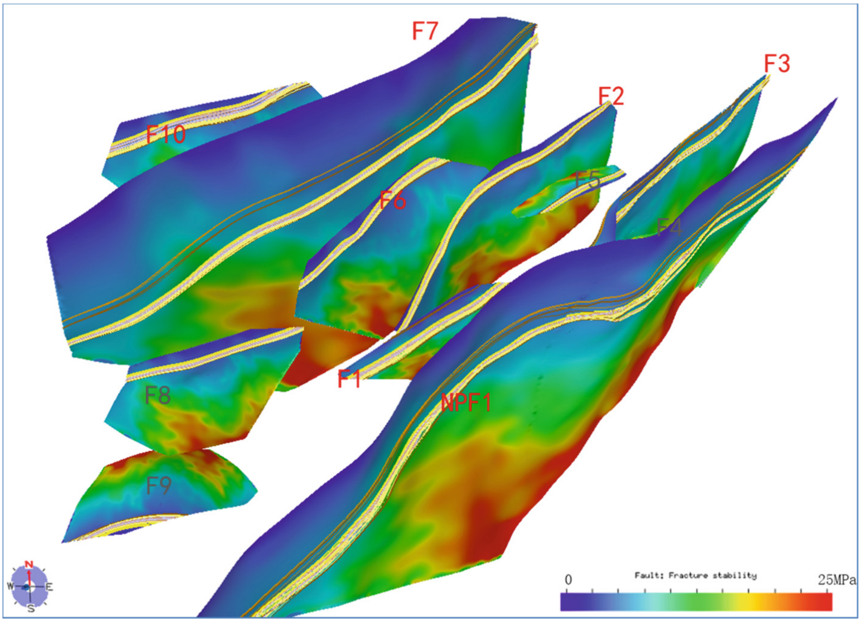

Fig. 12. Calculation result of M1 fault tensile fracture stability

Table 2. Statistical Table of calculation results of fault stability analysis in M1 Area (2100 m)

Name	Slip trend			Expansion trend			Slip stability (Mpa)			Rupture stability (Mpa)		
	σn	τ	Ts	σn	τ	Td	σn	τ	ΔP	σn	τ	ΔP
NPF1	15.37	5.08	0.33	15.41	5.12	0.70	15.41	5.12	4.02	15.37	5.12	5.09
F1	15.37	5.08	0.33	15.37	5.12	0.70	15.37	5.08	4.07	15.37	5.12	5.09
F2	15.37	5.08	0.33	15.37	5.08	0.70	15.41	5.12	4.02	15.37	5.12	5.09
F3	15.41	5.12	0.33	15.37	5.08	0.70	15.37	5.08	4.07	15.37	5.12	5.09
F4	15.37	5.12	0.33	15.37	5.04	0.70	15.37	5.08	4.07	15.37	5.12	5.09
F5	15.37	5.00	0.32	15.33	5.08	0.70	15.37	5.08	4.07	15.29	5.08	5.10
F6	15.37	5.08	0.33	15.33	5.04	0.70	15.37	5.08	4.07	15.37	5.12	5.09
F7	15.37	5.08	0.33	15.33	5.08	0.70	15.37	5.08	4.07	15.29	5.08	5.10
F8	15.33	5.08	0.33	15.33	5.08	0.70	15.37	5.08	4.07	15.37	5.12	5.09
F9	15.37	5.08	0.33	15.37	5.12	0.70	15.41	5.12	4.02	15.37	5.12	5.09
F10	15.41	5.08	0.33	15.41	5.04	0.70	15.37	5.08	4.07	15.45	5.17	5.08

6 Conclusion

1. By studying the basic characteristics, lateral sealing and vertical sealing of faults in the reservoir area, and classifying and evaluating the faults, the main faults affecting the integrity of the reservoir area are screened out, and it is concluded that the faults in the reservoir area have good sealing property.
2. Based on the statistics and analysis of the in-situ stress data, combined with the vertical depth of the reservoir horizon and the cap layer, it is determined that when the burial depth H > 1500 m, the vertical stress exceeds the maximum horizontal stress and becomes the maximum principal stress. The fault section in M1 gas storage is mainly mudstone smeared, and the coefficient of internal friction is 0.45 and the cohesion is 0.5 MPa.
3. The Ts values on the fracture surface range from 0.25 to 0.3, all of which are less than 0.45, indicating that the faults in the reservoir are stable under the current in-situ stress condition, and the occurrence of slip instability requires at least 4 MPa additional fluid pressure ΔP.
4. The Td of each fault section is less than 0.7, indicating that the faults in the reservoir are stable under the present in-situ stress condition, and the additional fluid pressure ΔP of tensile fracture is 5 MPa.

References

1. Ma, X., Zheng, D., Wei, G., et al.: Development directions of major scientific theories and technologies for natural gas underground storage in China. Nat. Gas Ind. **42**(05), 93–99 (2022)
2. Ding, G., Wei, H.: Review and prospect of underground gas storage construction in China in the past 20 years. Oil Gas Storage Transp. **39**(01), 25–31 (2020)
3. Ma, X., Zheng, D., Shen, R., Wang, C., Luo, J., Sun, J.: Key technologies and practice of building gas reservoirs for gas reservoirs with complex geological conditions in China. Pet. Exp. Dev. **45**(03), 489–499 (2018)
4. Wei, G., Zheng, Y., Qiu, X., Sun, J., Shi, L., Lai, X.: Geological theory and application of underground gas storage in China. Acta Petrolei Sinica **40**(12), 1519–1530 (2019)
5. Zheng, Y., et al.: Integrity connotation and evaluation techniques of geologic body of oil-gas reservoir. Nat. Gas Ind. **40**(05), 94–103 (2020)
6. Zhang, G., et al.: Evaluation of fault tightness of underground gas storage by in-situ stress and its application. Nat. Gas Geosci. **32**(06), 923–930 (2021)
7. Wang, M., Gai, C., He, H., Xin, C., Duan, B.: Trap sealing for building a complex fault block oil reservoir comprehensive evaluation technology. J. Complex Reserv. **03**, 94–99 (2022). https://doi.org/10.16181/j.carolcarrollnkifzyqc.2022.03.017
8. Zhao, Z.: Study on Mechanical stability and dynamic sealing of fault under fluid injection. Yangtze University (2021).https://doi.org/10.26981/,dcnki.GJHSC.2021.000346
9. Hu, G., Fan, T., Song, L., Hou, Y.: Fault Block Oil Gas Field **19**(04), 450–452 (2012)
10. Pang, J., Qian, G., Wang, B., Yang, Z., Wei, Y., Li, Y.: An evaluation of the airtightness of an underground gas storage in the H gas field, Xinjiang. Nat. Gas Ind. **32**(02), 83–85+120–121 (2012)
11. Sun, S., Tang, L.: Sealing evaluation of underground gas storage under multi-cycle alternating load. Sci. Technol. Eng. **16**(06), 23–28 (2016)
12. Li, R.: Fault trap sealing ability of comprehensive judging method and its application. J. Daqing Pet. Geol. Dev. **38**(4), 1–6 (2019). https://doi.org/10.19597/j.iSSN.1000-3754,201808053