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The effect of geological features on hydraulic fracture propagation guided by radial boreholes in the thin interbedded reservoirs

Xiao-Guang Wu^a, Teng-Da Long^{a,*}, Zi-Xiao Xie^{a,**}, Rui Yang^a, Zhong-Wei Huang^a, San-Li Peng^a, Zhao-Wei Sun^a, Tao Pan^a, Nai-Kun Hu^b, Xiao-Hua Wang^c, Song-Long Lv^d

^a State Key Laboratory of Deep Geothermal Resources, China University of Petroleum (Beijing), Beijing, 102249, China

^b Tianjin Geothermal Exploration and Development-Designing Institute, Tianjin, 300250, China

^c College of Civil Engineering, Tongji University, Shanghai, 200092, China

^d Petroleum Engineering School, Southwest Petroleum University, Chengdu, 610500, Sichuan, China

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ABSTRACT

High-strength interlayers and lithological interfaces limit vertical fracture height and stimulation efficiency in the thin interbedded reservoir. This paper proposes a novel radial borehole fracturing approach to enhance hydraulic fracture cross-layer ability. A multilayered model was developed to simulate radial borehole fracturing based on the discrete lattice method. Under different geological features, the mechanism of hydraulic fracture cross-layer propagation was determined by analyzing the evolution of in-situ stress and rock displacement around radial boreholes. Research indicates that the radial borehole effectively reduces the effect of the minimum principal stress around the near-wellbore zone, thereby decreasing the interlayered stress difference and promoting hydraulic fractures to propagate in straight paths across interlayers. When the radial borehole penetrates across lithological interfaces, rock displacement readily facilitates cross-layer propagation, thereby significantly alleviating constraints on the vertical fracture height. Furthermore, multiple pay zones could achieve effective skip-layer stimulation when radial boreholes connect multiple interlayers. The ability of hydraulic fractures to propagate across interlayers increases significantly with higher interlayered horizontal stress difference, interlayered fracture toughness difference, interlayered elastic modulus difference, interlayered tensile strength difference, and natural fracture density, or with reduced interfacial shear strength. Among these, the interlayered tensile strength difference predominantly controls the vertical fracture height based on the Spearman correlation algorithm. A propagation criterion was established for identifying a hydraulic fracture crossing a lithological interface in radial borehole fracturing under various geological factors. If the thin interbedded reservoir exhibits interlayered horizontal stress differences exceeding 10 MPa, interfacial shear strengths below 4 MPa, or natural fracture densities greater than 1 fractures/m, radial boreholes should be extended into adjacent barrier layers to stimulate outer pay layers. When radial boreholes interconnect multiple pay layers, hydraulic fracture skip-layer initiation could achieve overall reservoir stimulation and mitigate the constraints of formation conditions. This study provides theoretical foundations and engineering implementation guidelines for radial borehole fracturing in thin interbedded reservoirs.

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* Corresponding author.

** Corresponding author.

E-mail addresses: tengda_long@163.com (T.-D. Long), xiezxcup.edu.cn (Z.-X. Xie).

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1. Introduction

Vertically superimposed multiple pay zones in thin interbedded reservoirs serve as the primary hosts for unconventional hydrocarbon resources (Zhao et al., 2015; Zou et al., 2015). Reservoirs such as shale oil, coalbed methane, and tight oil commonly exhibit such multilayered structural characteristics. However,

these reservoirs often contain multiple high-strength barrier layers and lithological interfaces among pay layers (Wang et al., 2025). These geological structures constrain the hydraulic fracture height in conventional horizontal well fracturing, thereby impeding the effective interconnection of multiple production zones for commingled development (Lei et al., 2022; Li et al., 2020). To enhance vertical connectivity in thin interbedded reservoirs, a novel method of radial borehole-guided hydraulic fracture cross-layer growth has been proposed. This approach begins with the drilling of radial branch boreholes that extend vertically for tens of meters from the main horizontal wellbore, thereby enabling precise, targeted connectivity among multiple production zones. Subsequently, hydraulic fracturing is performed to promote fracture initiation and propagation preferentially along the radial borehole direction. They tend to penetrate barrier layers and lithological interfaces, and ultimately achieve vertical effective coverage efficiency in thin interbedded reservoirs (Long et al., 2026a, 2024; Wu X. et al., 2025; Xie et al., 2025).

Previous studies have determined that hydraulic fractures primarily exhibit four propagation patterns: arrest, deflection, penetration, and composite during conventional hydraulic fracturing in thin interbedded formations (Zhang et al., 2023b). The interlayer stress difference is the dominant factor controlling fracture height growth (Lyu et al., 2024; Xie et al., 2024). Hydraulic fractures tend to propagate within lower stress interlayers, while higher stress differences restrict hydraulic fracture penetration (Guo et al., 2025). Additionally, geological parameters such as elastic modulus, rock brittleness, interlayer thickness, interlayer dip angle, and vertical stress difference significantly impact hydraulic fracture vertical propagation behavior (Cong et al., 2024; Huang et al., 2025; Zhang et al., 2023a). In actual operation, higher injection rate and higher fluid viscosity can enhance hydraulic fracture extension height but reduce fracture network complexity (He et al., 2022; Kong et al., 2023; Liu et al., 2025; Tan et al., 2019). Furthermore, alternating injections of higher and lower viscosity fluids can effectively improve reservoir stimulation performance (Cong et al., 2024). Weak planes like lithological interfaces and natural fractures constitute another critical barrier to hydraulic fracture cross-layer growth in the thin interbedded reservoir (Wang et al., 2021). When hydraulic fractures intersect weak planes, generated pressure pulses can induce interfacial shear slip, thereby leading to interaction modes dominated by penetration, deflection, or arrest (Dahi Taleghani et al., 2016; Huang et al., 2024; Wang et al., 2025; Xi et al., 2022; Zhao et al., 2022). Weak plane strength, in-situ stress, and approach angle are key parameters that govern these interactions (Liao et al., 2024; Long et al., 2026b; Zheng et al., 2020). Under conditions of larger approach angles, higher horizontal stress differences, and increased injection rates, hydraulic fractures tend to penetrate weak planes. Conversely, they more readily activate weak planes and deflection (Wang et al., 2021). The above research systematically analyzes the mechanisms of hydraulic fracture cross-layer propagation in conventional hydraulic fracturing. However, when radial boreholes connect multiple interlayers, the initiation and extension behavior of hydraulic fracture becomes more complex. In thin interbedded reservoirs under radial borehole fracturing conditions, the hydraulic fracture growth is jointly affected by the stress reconstruction from the radial borehole, lithological interface disturbance, and interlayered stress difference. The presence of radial boreholes shifts the core science of fracture–interface interactions to competitive initiation across multiple interlayers and radial borehole-guided hydraulic fracture cross-layer propagation (Long et al., 2024; Wu X. et al., 2025; Xie et al., 2025).

The development of numerical methodologies has provided diverse approaches for investigating the mechanisms governing hydraulic fracture propagation within multilayered reservoirs. Continuum methods treat rock as an equivalent continuum, commonly employing the finite element method (FEM) and extended finite element method (XFEM) to simulate the fracture growth behaviors. The FEM excels in linear elastic problems but struggles to accurately model complex fracture paths and interactions with lithological interfaces (Guo et al., 2025; Liao et al., 2024; Lyu et al., 2024). XFEM can handle discontinuous propagation, yet it incurs high computational costs and exhibits strong mesh dependency (Lecampion, 2009). Among discontinuous methods, the discrete element method (DEM) represents the medium as independent particles or blocks, naturally simulating fracture initiation, deflection, and branching without predefined paths (Zheng et al., 2022). However, full 3D simulations demand substantial computational resources. The continuum-discontinuum element method (CDEM) couples continuous and discrete approaches, enabling dynamic simulation of fracture cross-layer propagation, though it suffers from mesh sensitivity (Huang et al., 2025; Wang et al., 2025). In contrast, the discrete lattice method (DLM) is based on the simplified cohesive particle model from the synthetic rock mass (SRM) approach and discrete lattice theory (Shen et al., 2020). This method directly characterizes heterogeneous structures like multi-lithological layers and weak planes (i.e. bedding plane, natural fracture, and lithological interface) at the multi-scale (Bakhshi et al., 2019; Zhang et al., 2023a). It can accurately perform 3D non-plane fracture simulations with low computational cost, thereby modeling the competitive initiation and cross-layer propagation of hydraulic fractures guided by radial boreholes (Gu et al., 2024).

This study develops a multilayered model based on the DLM to simulate the fracture growth guided by the radial borehole. The typical fracture initiation and propagation patterns are revealed by performing hydraulic fracturing simulations with different interlayer sequences and radial borehole lengths. The rock displacement and in-situ stress evolution are analyzed to determine the mechanisms of hydraulic fracture growth by radial borehole guidance. Reservoir stimulation performance is evaluated by quantifying vertical fracture height (VFH) and stimulated reservoir area (SRA). Key geological parameters are systematically investigated for their influence on radial borehole-guided hydraulic fracture extension, while dominant controlling factors affecting VFH are identified. A propagation criterion was established to determine whether a hydraulic fracture would cross a lithological interface during radial borehole fracturing, accounting for various geological factors. These findings provide theoretical foundations and engineering guidance for radial borehole fracturing in thin interbedded reservoirs.

2. Numerical modeling approaches

2.1. Discrete lattice method

The DLM demonstrates significant advantages in simulating radial borehole-guided hydraulic fracture cross-layer propagation, as it directly captures complex non-planar fracture networks without requiring predefined fracture paths. Within the SRM framework (Fig. 1(a)), the DLM models hydraulic fracture dynamic growth in naturally fractured reservoirs: the bonded particle model (BPM) characterizes heterogeneous rock matrices, while the discrete fracture network (DFN) explicitly represents pre-existing lithological interfaces and natural fractures (Pierce et al., 2007; Potyondy and Cundall, 2004). Through the evolution of

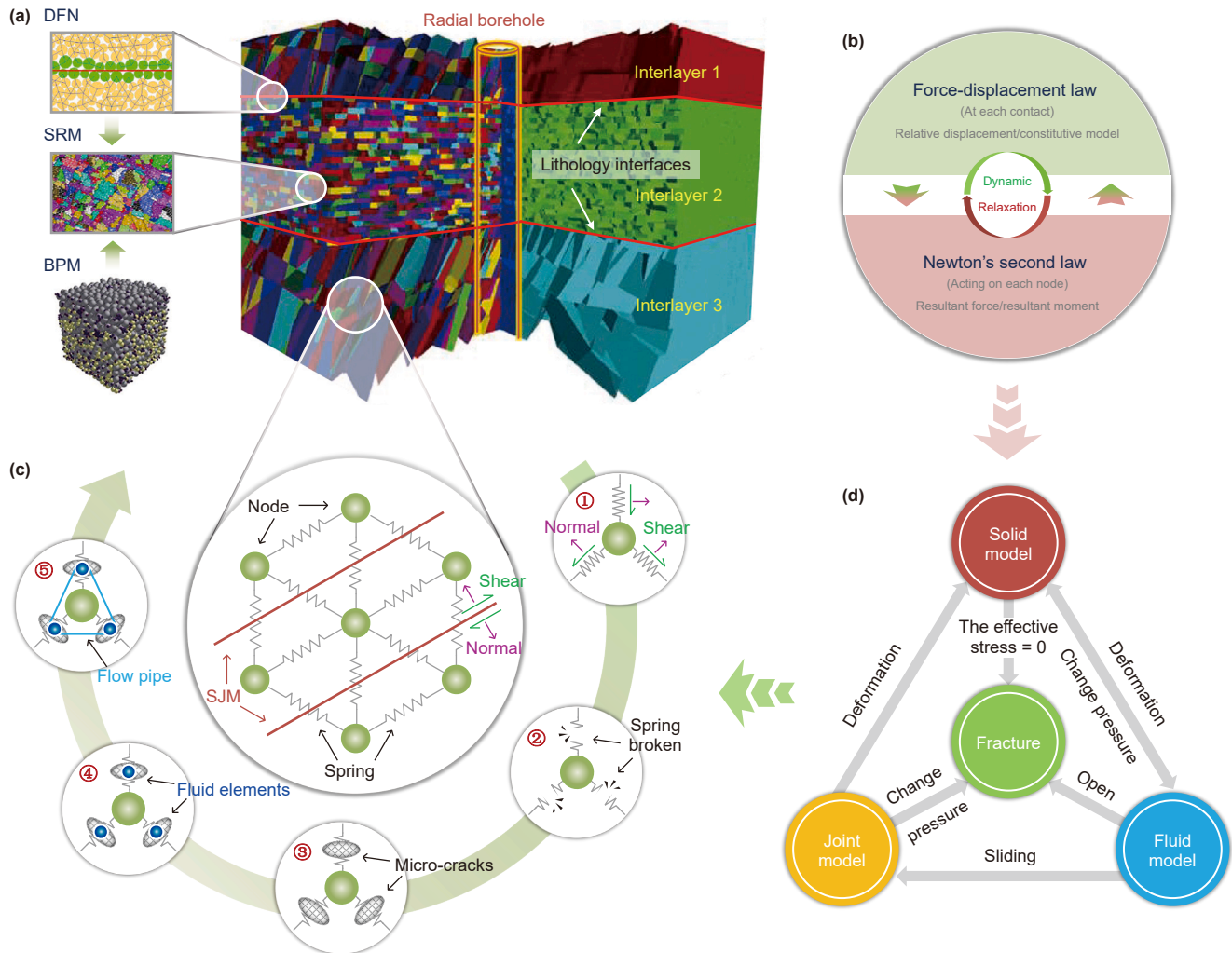


Fig. 1. Schematic diagram of the DLM. (a) Application of SRM in multilayered modeling; (b) mechanical model; (c) spring-node network within the discrete lattice; (d) hydro-mechanical coupling (Haryono et al., 2023).

nodal forces and displacements within discrete lattices, it quantifies the interaction mechanisms between hydraulic fractures and lithological interfaces induced by radial boreholes. This system supports fluid injection simulations for arbitrary wellbore geometries. Furthermore, it allows presetting of radial boreholes with varying dimensions and spatial orientations. Leveraging these capabilities, this study investigates the effect of key geological parameters on the cross-layer growth of hydraulic fractures guided by the radial borehole.

The DLM employs a spring-node network to simulate coupled processes of fluid flow, fracture evolution, and fluid leak-off. Microscopic-scale spring stiffness and strength parameters govern macroscopic rock mechanical behavior. Discrete lattices enhance computational efficiency while preserving DLM's bonding principles. Nodal displacements and forces continuously characterize rock mechanical responses based on Newton's second law (Fig. 1(b)), with the smooth joint model (SJM) simulating lithological interface activation behaviors (i.e. joint sliding, opening, and closure). Hydro-mechanical coupling interactions manifest through three mechanisms (Fig. 1(d)): fluid pressure drives fracture opening/sliding; fracture deformation alters joint pressure fields; joint aperture variations regulate rock mass permeability. Hydraulic fracturing follows a sequential evolution (Fig. 1(c)): ① springs between nodes withstand tensile/shear

stresses; ② fractures initiate upon reaching strength limits; ③ fluid-driven damage accumulation forms micro-cracks that coalesce; ④ fluid elements generate at fractured spring centers; ⑤ dynamically constructed interconnected channel networks simulate fracturing fluid flow (Shen et al., 2020).

2.2. Numerical model

Multi-lithology thin interbedded reservoirs refer to complex heterogeneous formations formed by the vertical superimposition of pay layers and barrier layers, separated by lithological interfaces (Huang et al., 2025). The thickness of a single lithological layer does not exceed 10 m, with the majority distributed within 2 m (Jiang et al., 2025; Li et al., 2024; Wu G. et al., 2025). The engineering challenge for conventional horizontal well fracturing lies in the limitation of hydraulic fracture cross-layer propagation by high-strength barrier layers. Furthermore, hydraulic fractures tend to deflect along prevalent weak lithological interfaces and natural fractures within the reservoir (Wu X. et al., 2025).

Aiming at the geological characteristics of thin interbedded reservoirs where individual layer thickness is generally less than 2 m, this study established a five-layer geological model composed of alternating barrier and pay layers, with a single layer thickness

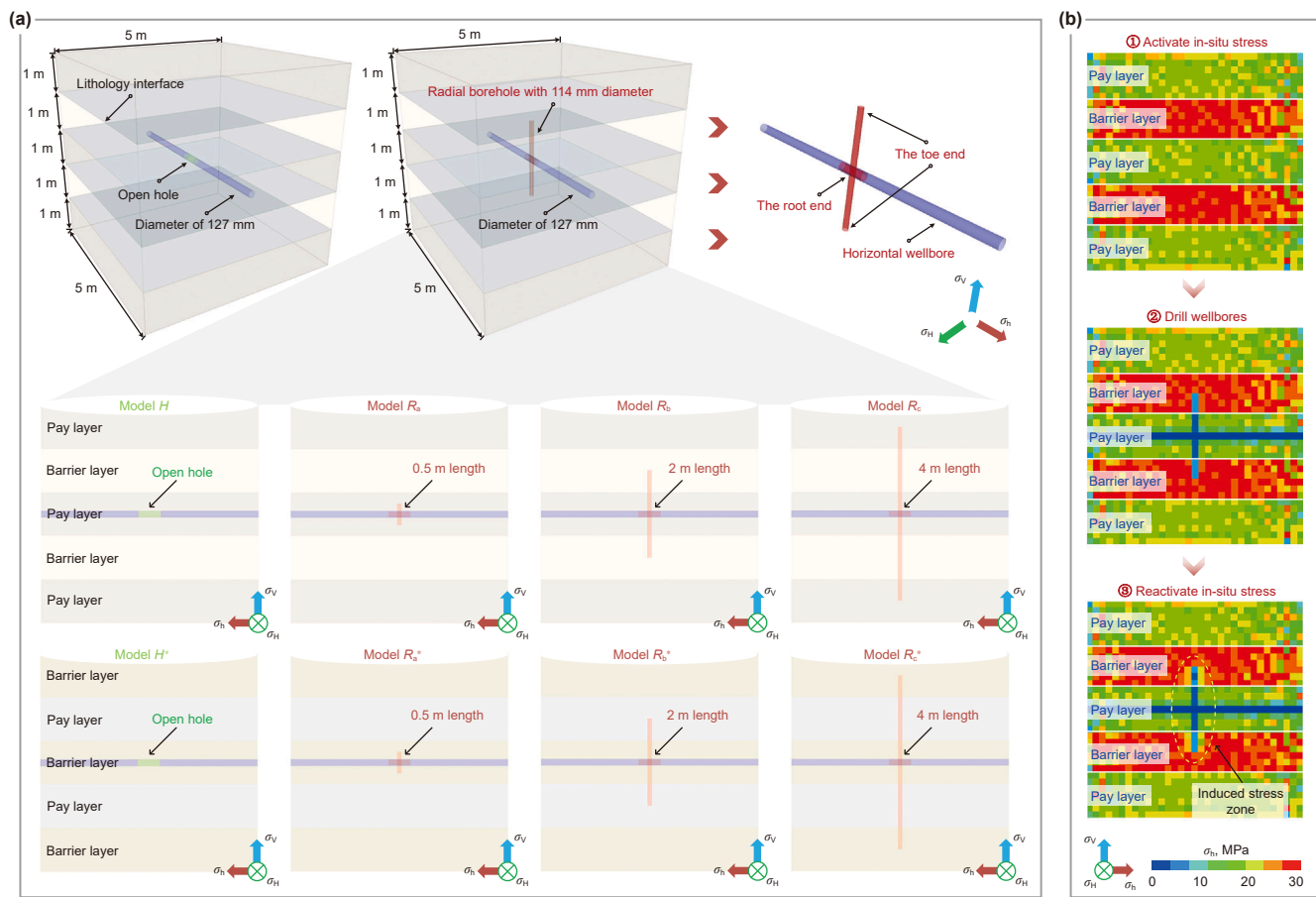


Fig. 2. The multilayered numerical model. (a) Model dimension and radial borehole configuration scheme; (b) in-situ stress state during the hydraulic fracturing with radial boreholes. σ_v , σ_H , and σ_h represent vertical stress, maximum horizontal principal stress, and minimum horizontal principal stress, respectively.

of 1 m. Finally, a numerical model measuring 5 m × 5 m × 5 m was constructed (Fig. 2). A horizontal wellbore with a diameter of 127 mm is positioned at the center of the intermediate interlayer, oriented along the direction of minimum principal stress. At the midpoint of the main wellbore's major axis, radial boreholes with a diameter of 114 mm are pre-set along the vertical stress direction. The junction between radial boreholes and the main wellbore is defined as the root end, while the farthest location is termed the toe end. It is imperative to highlight that this research establishes a conceptual model, simplifying practical engineering issues by assuming radial boreholes are perpendicular to the horizontal wellbore and neglecting the build rate radius during radial drilling operations.

In this work, a total of eight numerical models are defined based on different radial borehole lengths and interlayer sequences. Model *H* and Model *H*^{*} represent conventional horizontal

well fracturing, while Models *R* and Models *R*^{*} represent radial borehole fracturing. Specific configurations are detailed in Table 1 and Fig. 2(a). To simulate actual formation boundary conditions, displacement constraints are applied at model boundaries. The fracturing fluid flows into the formation from the radial boreholes through the surface injection approach. All models employed a constant injection rate of 0.02 m³/s with a viscosity of 20 mPa·s, sustained for 0.4 s. To ensure computational accuracy, the lattice size is set at 20 mm (less than 1/5 of the radial borehole diameter). The hydraulic fracturing simulation procedure comprises the following steps: ① activate different in-situ stress between interlayers in the initial model; ② drill the horizontal wellbore, main wellbore cementing, and drill radial boreholes; ③ reactivate in-situ stress to form induced stress around radial boreholes; ④ inject fracturing fluid and simulate hydraulic fracture growth (Fig. 2(b)).

Table 1
The spatial relationship between radial borehole and interlayer in different numerical models.

Model	Fracturing approach	The location of the borehole root end	The location of the borehole toe end
Model <i>H</i>	Horizontal well	Pay layer	Pay layer
Model <i>H</i> [*]	Horizontal well	Barrier layer	Barrier layer
Model <i>R</i> _a	Radial borehole	Pay layer	Pay layer
Model <i>R</i> _a [*]	Radial borehole	Barrier layer	Barrier layer
Model <i>R</i> _b	Radial borehole	Pay layer	Pay layer
Model <i>R</i> _b [*]	Radial borehole	Barrier layer	Barrier layer
Model <i>R</i> _c	Radial borehole	Pay layer	Pay layer
Model <i>R</i> _c [*]	Radial borehole	Barrier layer	Barrier layer

This study conducted 44 sets of numerical simulations for hydraulic fracturing. Among them, models H #1, H #2 and R-B #1–6 compared the hydraulic fracture initiation and propagation characteristics between horizontal well fracturing and radial borehole fracturing. The remaining models investigated the effect of geological parameters on the hydraulic fracture cross-layer extension performance in the radial borehole fracturing. In each parameter study, a total of 9 numerical simulations were established. This scheme is based on an orthogonal design combining three models (Model R_{a-c}) with three gradient values of the geological parameters. The suffix numbers 1 to 3 in the model identifiers correspond sequentially to Model R_{a-c} , with all parameters set to lower gradient values; similarly, suffix numbers 4 to 6 correspond to Model R_{a-c} , but with parameters at higher gradient values. Subsequently, these simulations are combined with model R-B #1–3, together constituting the complete set of 9 hydraulic fracturing simulations. It should be noted that interlayered stress differences and rock parameter variations were calculated by subtracting the parameters of pay layers from those of barrier layers. Detailed simulation schemes are presented in Table 2. To quantitatively analyze the fracturing performance, we computed the VFH, tensile failure area (TFA), shear failure area (SFA), and stimulated reservoir area (SRA) for each model. Herein, the VFH is calculated by measuring the vertical propagation distance of macroscopic fractures. The TFA and the SFA are derived by tracking the total area of microcracks generated during tensile and shear failure processes, respectively. Meanwhile, the SRA is the sum of the TFA and the SFA, representing the overall reservoir stimulation efficiency.

2.3. Model validation

To validate the theoretical feasibility and model accuracy, numerical and analytical solutions for penny-shaped fractures were compared. Hydraulic fracture propagation is primarily controlled by two competing mechanisms: the viscosity of the fracturing fluid and the toughness of the rock formation. A dimensionless toughness parameter (κ) is employed to distinguish between the viscosity-dominated (M) and toughness-dominated (K) propagation regimes. According to the established criterion, fracture propagation is viscosity-dominated when $\kappa < 1$, and toughness-dominated when $\kappa > 3.5$. The κ is defined by the following expression (Detournay, 2016; Dontsov, 2016; Dontsov and Suarez-Rivera, 2020):

$$\kappa = K' \left(t^2 / (\mu'^5 Q_0^3 E^{13}) \right)^{1/18} \quad (1)$$

Table 2
Radial borehole cross-layer fracturing simulation scheme.

Number	Model	S_D , MPa	F_D , MPa·m ^{0.5}	E_D , GPa	T_D , MPa	I_{SS} , MPa	N_T , fractures/m
H #1	Model H	5	0.5	5	2	8	0
H #2	Model H*	5	0.5	5	2	8	0
R-B #1–3	Model R_{a-c}	5	0.5	5	2	8	0
R-B #4–6	Model R_{a-c}^*	5	0.5	5	2	8	0
R-S #1–6	Model R_{a-c}	0, 10	0.5	5	2	8	0
R-F #1–6	Model R_{a-c}	5	0, 1	5	2	8	0
R-E #1–6	Model R_{a-c}	5	0.5	0, 10	2	8	0
R-T #1–6	Model R_{a-c}	5	0.5	5	0, 4	8	0
R-I #1–6	Model R_{a-c}	5	0.5	5	2	4, 16	0
R-N #1–6	Model R_{a-c}	5	0.5	5	2	8	1, 2

Notes: S_D , interlayered horizontal stress difference; F_D , interlayered fracture toughness difference; E_D , interlayered elastic modulus difference; T_D , interlayered tensile strength difference; I_{SS} , interfacial shear strength; N_T , natural fracture density.

$$K' = (32/\pi)^{0.5} K_{IC}, \mu' = 12\mu, E' = E / (1 - \nu^2) \quad (2)$$

where t is the injection time, s; Q_0 is the injection rate, m³/s; K_{IC} is the fracture toughness, Pa·m^{0.5}; μ is the fracturing fluid viscosity, Pa·s; E is the elastic modulus, Pa; ν is Poisson's ratio.

The analytical solution governing viscosity-dominated fracture propagation in the penny-shaped model is defined by the following set of equations (Dontsov, 2016):

$$w(\rho, t) = 1.1901 (\mu'^2 Q_0^3 t / E^2)^{1/9} (1 + \rho)^{0.487} (1 - \rho)^{2/3} \quad (3)$$

$$p(\rho, t) = 2.4019 (\mu' E^2 / t)^{1/3} F(\rho, 0.487, 2/3) \quad (4)$$

$$R_F(t) = 0.6944 (Q_0^3 E^4 t / \mu')^{1/9} \quad (5)$$

The analytical solution governing toughness-dominated fracture propagation in the penny-shaped model is defined by the following set of equations (Dontsov, 2016):

$$w(\rho, t) = 0.6537 (K'^4 Q_0 t / E^4)^{1/5} (1 - \rho^2)^{1/2} \quad (6)$$

$$p(\rho, t) = 0.3004 (K'^6 / E' Q_0 t)^{1/5} \quad (7)$$

$$R_F(t) = 0.8546 (E' Q_0 t / K')^{2/5} \quad (8)$$

where w is the fracture width, m; p is the fluid pressure within the fracture, Pa; R_F is the fracture radius, m; $\rho = r/R_F$ is the dimensionless radius ($0 \leq \rho \leq 1$); r is the distance between the calculation point and the injection point (center point of the penny-shaped fracture), m.

Table 3
The input parameters of the theoretical validation models.

Input parameters	Case A	Case B
Elastic modulus, GPa	30	30
Poisson's ratio	0.2	0.2
Tensile strength, MPa	5	5
Compressive strength, MPa	80	80
Fracture toughness, MPa·m ^{0.5}	0.77	50
Maximum horizontal principal stress, MPa	3	3
Minimum horizontal principal stress, MPa	1	1
Vertical stress, MPa	3	3
Injection rate, m ³ /min	0.006	0.03
Injection time, s	0.1	1
Viscosity of fracturing fluid, mPa·s	10	1

A viscosity-dominated fracture (Case A, $\kappa = 0.42 < 1$) and a toughness-dominated fracture (Case B, $\kappa = 50.9 > 3.5$) were established, with their input parameters summarized in Table 3. These cases serve to benchmark the numerical simulation results against analytical solutions. Based on the analytical solution for fracture radius, the R_F values for Case A and Case B after fluid injection cessation are 0.22 and 0.34 m, respectively. To accommodate this, we established a $0.8 \text{ m} \times 0.8 \text{ m} \times 0.8 \text{ m}$ numerical model to ensure complete hydraulic fracture extension. A vertical wellbore with a radius of 0.005 m is located at the center of the model, containing a perforation cluster (equivalent radius = 0.015 m) embedded in its mid-section. Under hydro-mechanical coupling conditions, fracturing fluid is injected at a constant rate from the perforation cluster to simulate penny-shaped fracture propagation. It is worth emphasizing that upon concluding the simulation, we gathered data on hydraulic fracture width and fluid pressure at 11 equidistant points corresponding to ρ -values of 0, 0.1, 0.2, ..., up to 1. These values were then compared with the analytical solution curve, while the detailed spatial distribution of each calculation point is illustrated in Fig. 3. Under both viscosity-dominated and toughness-dominated regimes, the hydraulic fracture propagation exhibited penny-shaped patterns in the numerical simulations. The relative errors between the numerical simulations and the analytical solutions were 7.9% for fracture width in Case A and 17.2% in Case B. The corresponding errors for fluid pressure were 5.5% and 17.6%, respectively. The close agreement between numerical and analytical results validates the accuracy of the hydraulic fracture propagation model proposed in this work.

To further validate the radial borehole fracturing model, simulation results were compared against experimental observations from Wu X. et al. (2025). Their experiment employed a cubic rock sample measuring $200 \times 200 \times 200 \text{ mm}$, consisting of five alternating sandstone and shale interlayers. A central borehole was drilled along the side face of the central shale interlayer to simulate the horizontal main wellbore, with a diameter of 16 mm and a length of 120 mm. At the mid-section of this open hole, two

lateral boreholes were drilled perpendicular to the main wellbore, spaced 180 degrees apart, to simulate radial boreholes intersecting the lithological interfaces vertically. Accordingly, the multi-lithology formation, horizontal main wellbore, and radial boreholes were modeled using the DLM for hydraulic fracturing simulation (models V #1–4). The simulation conditions and material parameters of the numerical model are meticulously aligned with the experimental conditions, with the specific input parameters detailed in Table 4. As shown in Fig. 4, fracture network geometries obtained from CT scans of experimental samples H #1, R-S #5, R-M #7, and R-L #5 were compared with those simulated by the corresponding numerical models V #1–4 under identical conditions. The numerical models successfully reproduced key hydraulic fracture propagation behaviors, including fracture passivation, cross-layer propagation, and skip-layer growth guided by radial boreholes in the multilayered formation. These results further demonstrate the reliability of the numerical model.

3. Results and analysis

3.1. Fracture morphology characteristics

3.1.1. Fracture initiation and propagation behaviors

When the horizontal wellbore is deployed in the pay layer, the propagation of hydraulic fractures across layers is suppressed by high-strength barrier layers (Fig. 5). Moreover, the opening of hydraulic fractures increases the minimum principal stress in the intermediate interlayer, further restricting the VFH growth (Model H). Compared to conventional horizontal well fracturing, radial borehole fracturing achieves a greater VFH and a wider range of rock displacement. As radial borehole length increases, more pay layers are activated. When radial boreholes are confined to the intermediate interlayers, hydraulic fractures initiate from the borehole root end. Subsequently, hydraulic fracture penetrates lithological interfaces and terminates in the barrier layer (Model R_a). If radial boreholes extend into barrier layers, the hydraulic

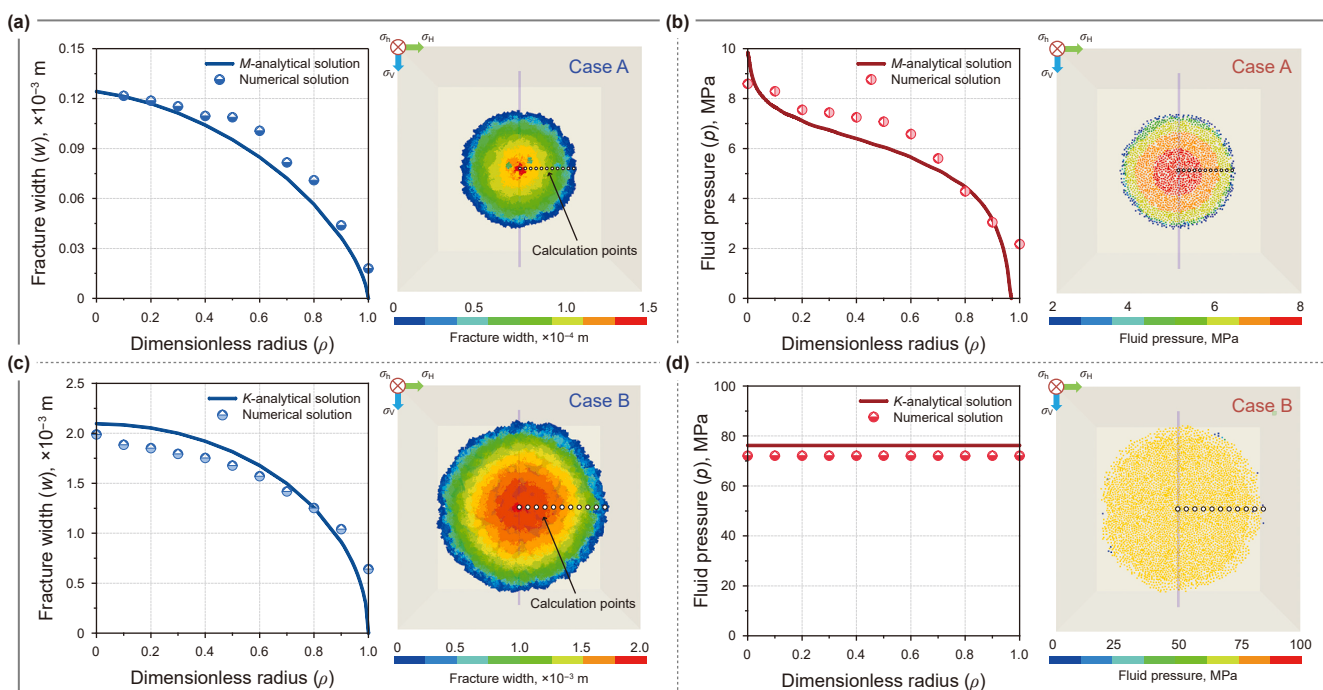


Fig. 3. The comparison between numerical and theoretical solutions in penny-shaped fracture growth. (a) Fracture width under viscosity-dominated regimes; (b) fluid pressure under viscosity-dominated regimes; (c) fracture width under toughness-dominated regimes; (d) fluid pressure under toughness-dominated regimes.

Table 4
The input parameters of the experimental validation models (Wu X. et al., 2025).

Fluid parameters	Model V #1	Model V #2	Model V #3	Model V #4
Injection rate of fracturing fluid, m ³ /min	0.00002	0.00002	0.00002	0.00002
Injection time of fracturing fluid, s	600	600	600	600
Viscosity of fracturing fluid, mPa·s	30	50	30	30
Rock parameters	Shale interlayer		Sandstone interlayer	
Elastic modulus, GPa	18.43		27.18	
Poisson's ratio	0.22		0.23	
Tensile strength, MPa	4.71		7.03	
Compressive strength, MPa	111.33		183.98	
Maximum horizontal principal stress, MPa	14		14	
Minimum horizontal principal stress, MPa	12		12	
Vertical stress, MPa	24		24	

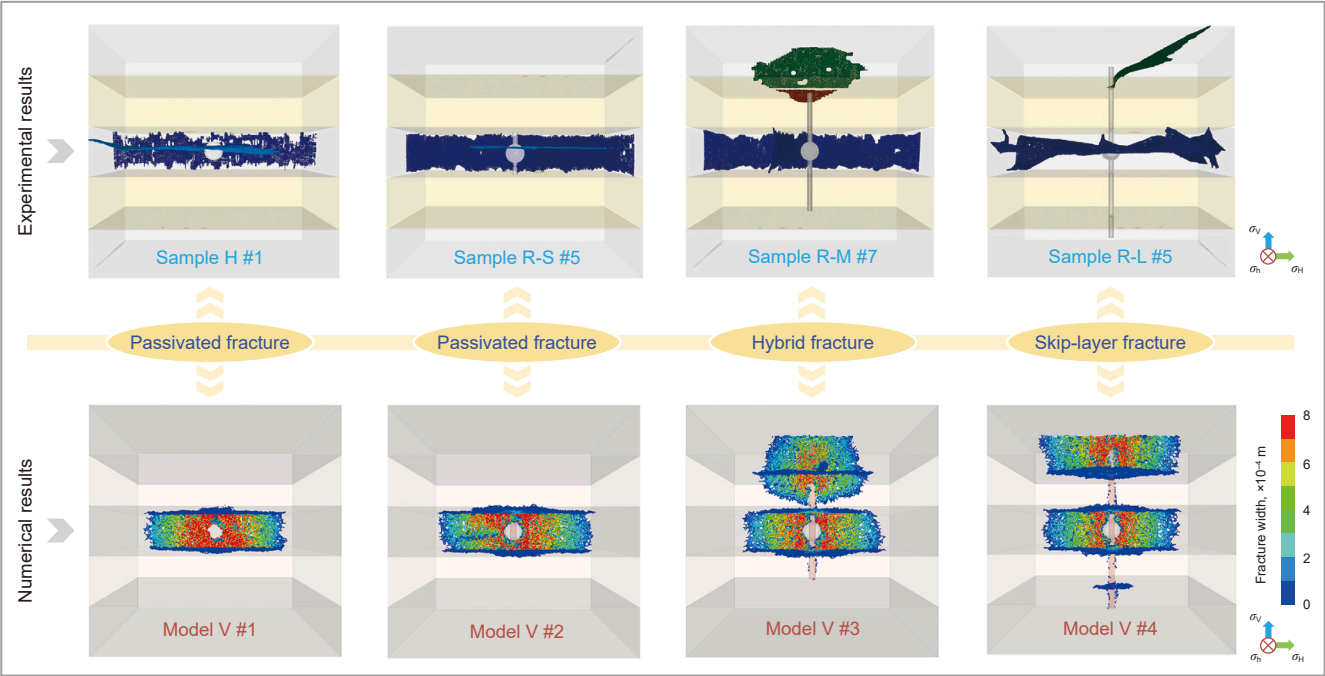


Fig. 4. The comparison of fracture morphology between simulation results and experimental observation of Wu X. et al. (2025).

fracture will penetrate the barrier layers and activate outer pay layers in straight paths (Model R_b). Radial boreholes connecting outer pay layers enable comprehensive skip-layer cracking across all pay layers. Rock displacement evolution reveals competitive fracture initiation at radial borehole roots and toes in the Model R_c . Notably, radial borehole redistributes the near-wellbore in-situ stress, resulting in a significant reduction in the minimum principal stress. When radial boreholes connect multiple interlayers, fractures cross-layer propagate along low-stress paths. Additionally, after radial boreholes penetrate lithological interfaces, rock displacement tends to propagate across interlayers, substantially reducing the VFH limitation. Crucially, by distributing fluid pressure across multiple pay zones, radial boreholes achieve effective skip-layer cracking while avoiding barrier layer activation.

When the horizontal wellbore is set within the barrier layer, hydraulic fractures in all models can cross-layer propagation (Fig. 6). However, conventional horizontal well fracturing still yields limited SRA in pay layers and generates narrower hydraulic fracture widths (Model H^*). If radial boreholes are confined within intermediate interlayers, hydraulic fractures will initiate from the borehole roots, penetrate through lithological interfaces, and extend into adjacent pay layers on both sides (Model R_3^*). When

radial boreholes simultaneously connect multiple low-strength pay layers, hydraulic fractures competitively initiate across these interlayers (Model R_{b-c}^*). Optimal reservoir stimulation occurs when radial boreholes extend within outer pay layers (Model R_b^*). In this scenario, concentrating fluid stress creates wider fractures in the pay layers and only activates the intermediate barrier layer. However, when radial boreholes connect all interlayers, hydraulic fractures propagate along low-stress zones around the borehole and activate barrier layers, significantly diminishing pay zone stimulation effectiveness.

3.1.2. Typical fracture growth patterns

Based on the evolution of rock displacement and fracture morphology characteristics, the hydraulic fracture initiation and propagation modes in radial borehole fracturing can be analyzed (Fig. 7). In conventional horizontal well fracturing, hydraulic fractures typically initiate from the open hole of the horizontal wellbore and exhibit penetration or capture behaviors upon reaching lithological interfaces. In contrast, radial borehole fracturing tends to form more complex and variable fracture growth patterns in different models. When radial boreholes are confined within the intermediate interlayer, hydraulic fractures initiate at

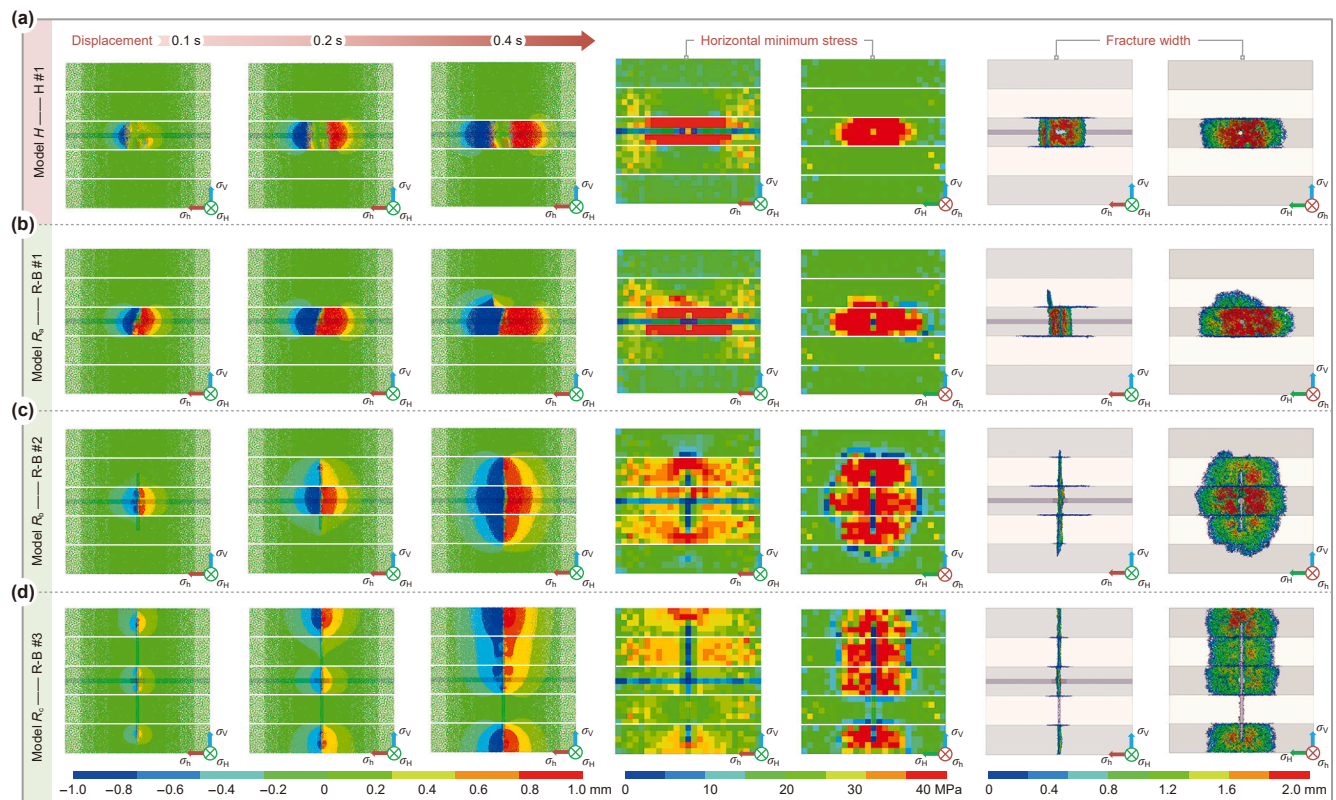


Fig. 5. Fracture morphology and stress/displacement evolution characteristics when the horizontal wellbore sets in the pay layer. (a) Model H; (b) Model R_a; (c) Model R_b; (d) Model R_c.

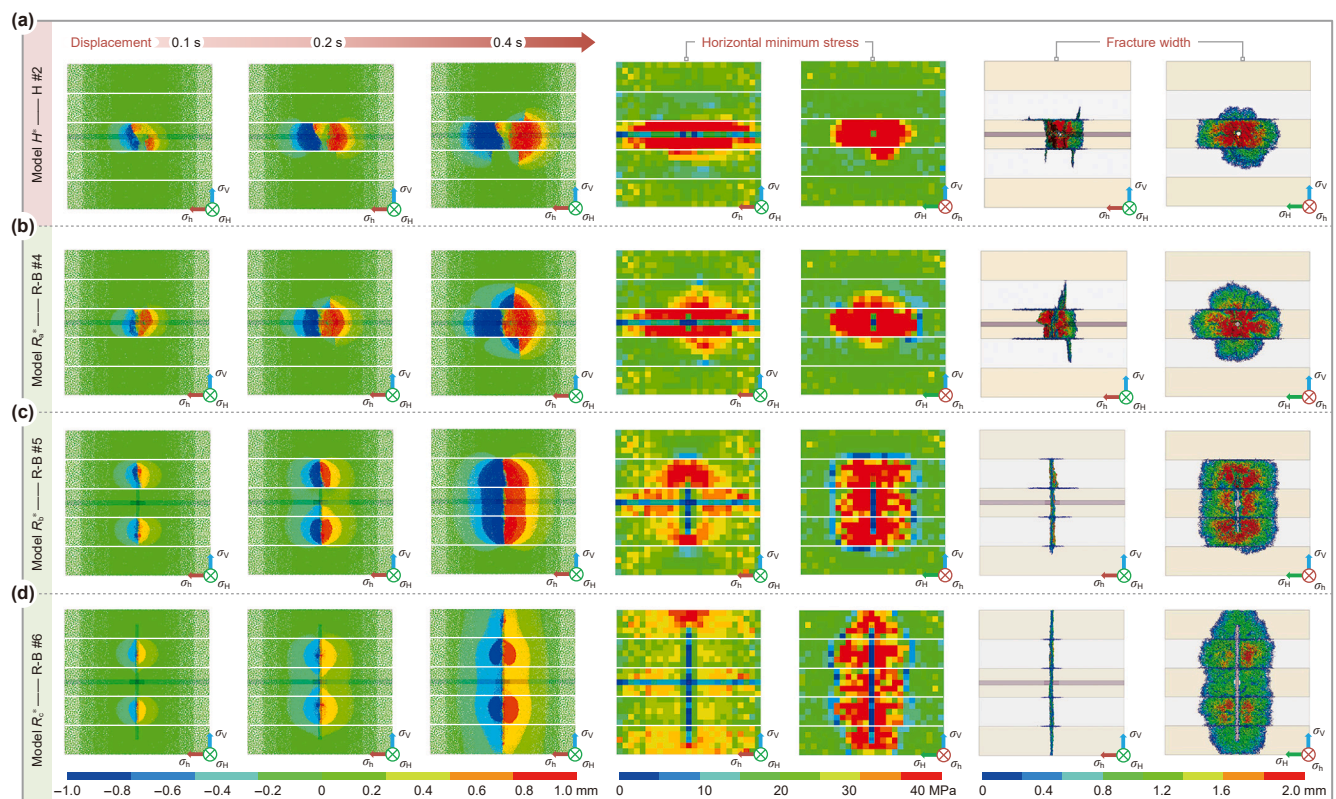


Fig. 6. Fracture morphology and stress/displacement evolution characteristics when the horizontal wellbore sets in the barrier layer. (a) Model H^{*}; (b) Model R_a^{*}; (c) Model R_b^{*}; (d) Model R_c^{*}.

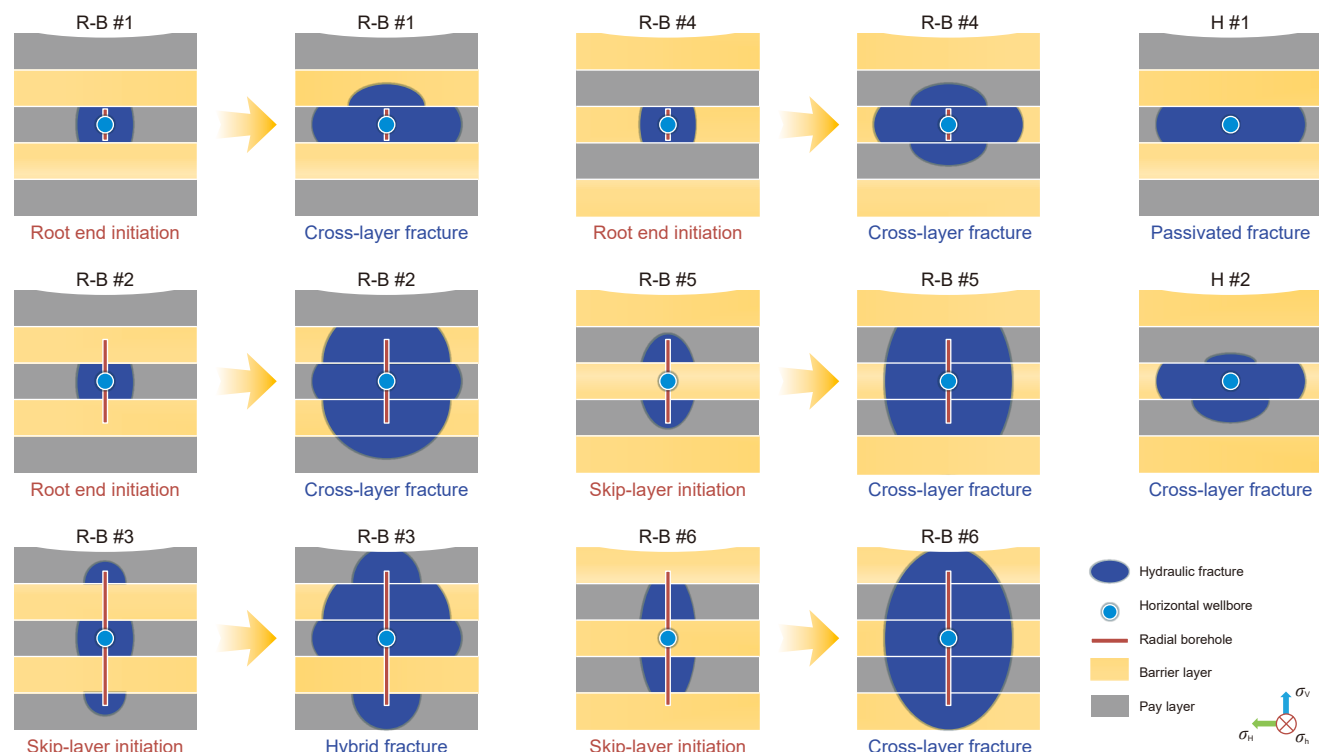


Fig. 7. Fracture initiation and propagation pattern under horizontal well fracturing and radial borehole fracturing.

the borehole root ends and propagate into outer interlayers. However, the VFH and SRA are limited in this condition. If radial boreholes connect multiple interlayers, fractures initiate selectively across multiple low-strength interlayers (skip-layer cracking). In such models, initiation points may occur at various locations, including the root end, toe end, or mid-section of the radial borehole. Ultimately, the cross-layer, skip-layer, and hybrid pattern hydraulic fracture networks are formed.

Compared to conventional horizontal well fracturing, radial borehole fracturing enables effective guide fracture cross-layer propagation, increasing the VFH by 110% and the number of activated pay layers by 33% (Fig. 8). When radial boreholes are confined within the intermediate interlayer, placing the horizontal wellbore within the barrier layer generates greater VFH, thereby activating more pay zones. If radial boreholes connect multiple

interlayers, positioning horizontal wellbores within pay layers maximizes pay zone activation and achieves optimal fracturing efficiency. Furthermore, radial borehole fracturing increases the TFA by 31%, while reducing the SFA by 21% compared with horizontal well fracturing in the thin interbedded reservoir. This phenomenon indicates radial boreholes guide hydraulic fractures to penetrate interlayer propagation dominated by rock tensile failure. In contrast, hydraulic fractures from horizontal well fracturing are captured at lithological interfaces, triggering large-range shear slippage along lithological interfaces.

3.2. Interlayered horizontal stress difference

As the S_D increases, the hydraulic fracture cross-layer propagation guided by radial boreholes becomes increasingly

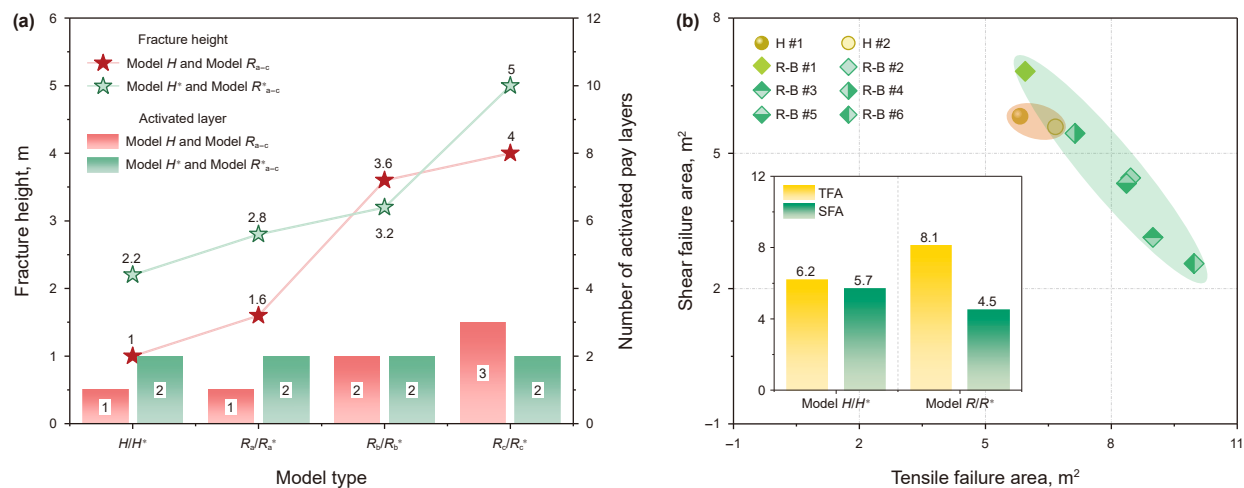


Fig. 8. Reservoir stimulation performance under horizontal well fracturing and radial borehole fracturing.

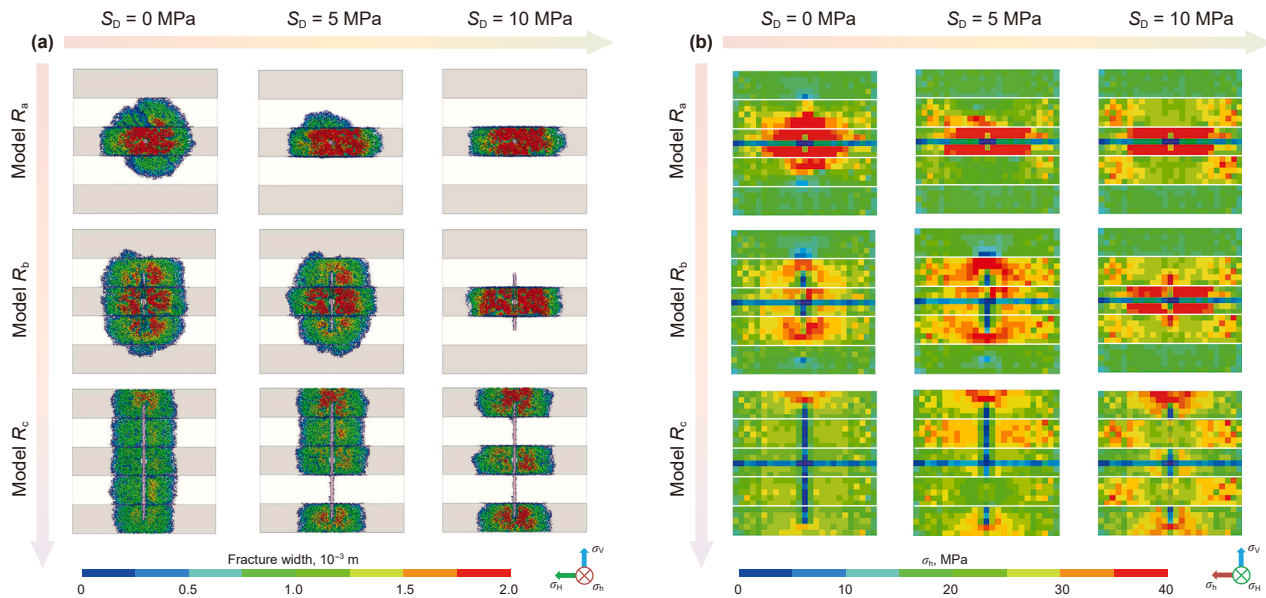


Fig. 9. Fracture morphology and in-situ stress evolution characteristics under different interlayered stress differences. (a) Fracture propagation morphology; (b) in-situ stress field evolution.

challenging (Fig. 9). When radial boreholes are confined to the intermediate interlayer (Model R_a), with the S_D rising from 0 to 10 MPa, the fracture morphology transitions sequentially from double-wing cross-layer fractures to single-wing cross-layer fractures, ultimately exhibiting passivation. When radial borehole toe ends extend into outer barrier layers, the SRA and VFH slightly improve, but the stimulation effectiveness in outer pay layers remains limited. In contrast, when radial boreholes connect outer pay layers, comprehensive stimulation across all target layers can be achieved. Under these conditions, increasing the S_D transforms fracture morphology from double-wing cross-layer fractures to hybrid fracture networks, eventually evolving into skip-layer fractures. At 10 MPa of the S_D , hydraulic fractures become entirely confined within pay layers, achieving the maximum SRA and fracture width for target zones. In-situ stress field analysis reveals that radial boreholes can reconstruct the near-wellbore in-situ stress. When radial boreholes penetrate lithological interfaces and connect adjacent interlayers, the minimum horizontal principal stress decreases significantly, thereby promoting hydraulic fracture cross-layer propagation along low-stress pathways. However, as the S_D increases, the range of stress distribution in high-stress barrier layers decreases, leading to a reduced capability of radial boreholes to guide fracture cross-layer propagation.

3.3. Interlayered rock property differences

3.3.1. Fracture toughness

As shown in Fig. 10, increasing the F_D inhibits VFH in the thin interbedded reservoir. When the F_D is $0 \text{ MPa}\cdot\text{m}^{0.5}$, the model R_{a-c} forms double-winged cross-layer fractures guided by radial boreholes. Increasing the F_D limits the vertical propagation of rock displacement and prevents hydraulic fracture penetration into barrier layers. For models R_a and R_b , the F_D thresholds for unilateral fracture passivation are 0.5 and 1 $\text{MPa}\cdot\text{m}^{0.5}$, respectively. Conversely, increasing the F_D has a beneficial effect on the model R_c . The hydraulic fracture transitions from double-winged cross-layer fractures to hybrid fracture networks. Rock displacement is effectively confined to the pay zones by the lower barrier layer, thereby optimizing reservoir stimulation efficiency

($F_D \geq 0.5 \text{ MPa}\cdot\text{m}^{0.5}$). The hydraulic fracture opening and propagation need to consume fluid energy to overcome the rock's fracture toughness, while the barrier layers with higher fracture toughness can absorb more energy before failure occurs, thereby significantly reducing the propagation efficiency of rock displacement along radial boreholes.

3.3.2. Elastic modulus

The E_D is a key factor controlling hydraulic fracture cross-layer propagation in the thin interbedded reservoir. An increase in the E_D significantly inhibits the propagation of rock displacement across lithological interfaces. Concurrently, it results in a substantial attenuation or even complete elimination of the displacement amplitude within the barrier layer. In Model R_a , as the E_D increases from 0 to 10 GPa, the fracture morphology evolves from a single-wing cross-layer fracture to a passivated fracture (Fig. 11). Model R_b forms double-wing cross-layer fractures under $E_D = 0$ GPa conditions, effectively stimulating both adjacent pay layers. When E_D reaches 5 GPa, the double-wing fracture can only stimulate the intermediate and the lower pay layers. Increasing the E_D to 10 GPa, the hydraulic fracture degenerates into a single-wing cross-layer pattern, further reducing the VFH and SRA. Model R_c exhibits a positive trend in stimulated area with increasing the E_D for pay layers. When the E_D reaches 5–10 GPa, the hydraulic fracture pattern transforms from a cross-layer fracture to a hybrid fracture network, and fracture width significantly increases in all pay layers.

3.3.3. Tensile strength

As shown in Fig. 12, with the increase of the T_D , the VFH and SRA decrease in the radial borehole cross-layer fracturing. In Model R_a , as the T_D rises from 0 to 4 MPa, hydraulic fracture morphology transitions from double-wing cross-layer fractures to single-wing cross-layer fractures. For Model R_b , although double-wing cross-layer fractures form when the T_D is below 2 MPa, only the intermediate and the lower pay layers are activated. At 4 MPa of the T_D , hydraulic fractures achieve unilateral cross-layer propagation exclusively, with rock displacement strictly confined to the mid-lower reservoir. Model R_c meets activation across all pay layers

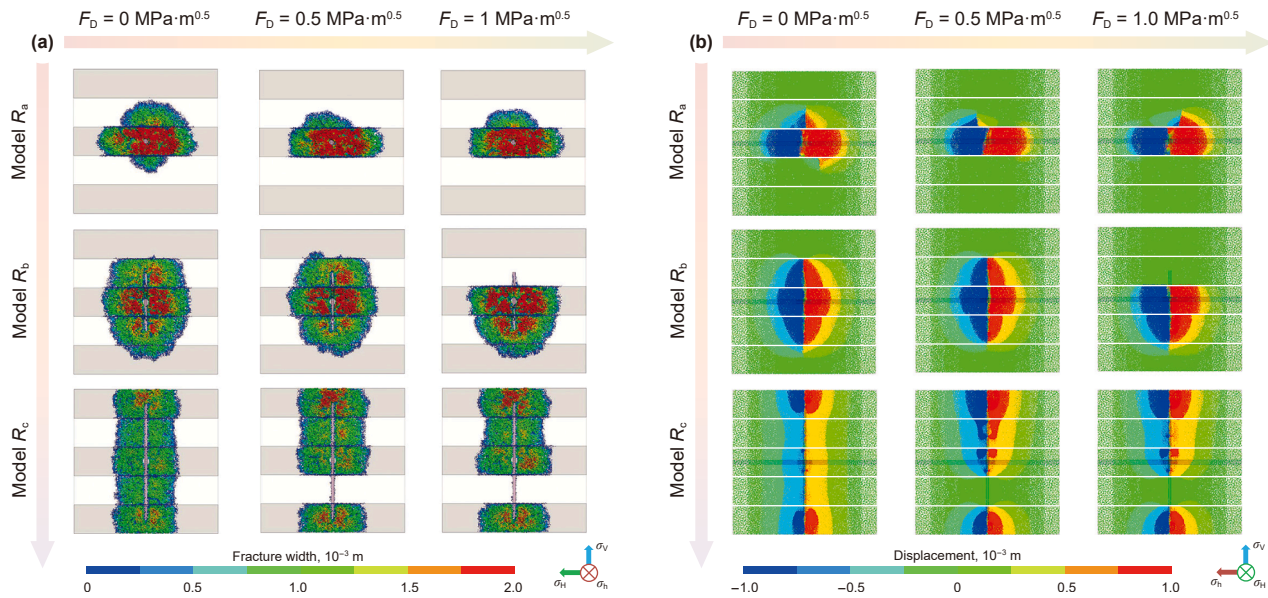


Fig. 10. Fracture morphology and rock displacement evolution characteristics under different interlayered fracture toughness differences. (a) Fracture propagation morphology; (b) rock displacement field evolution.

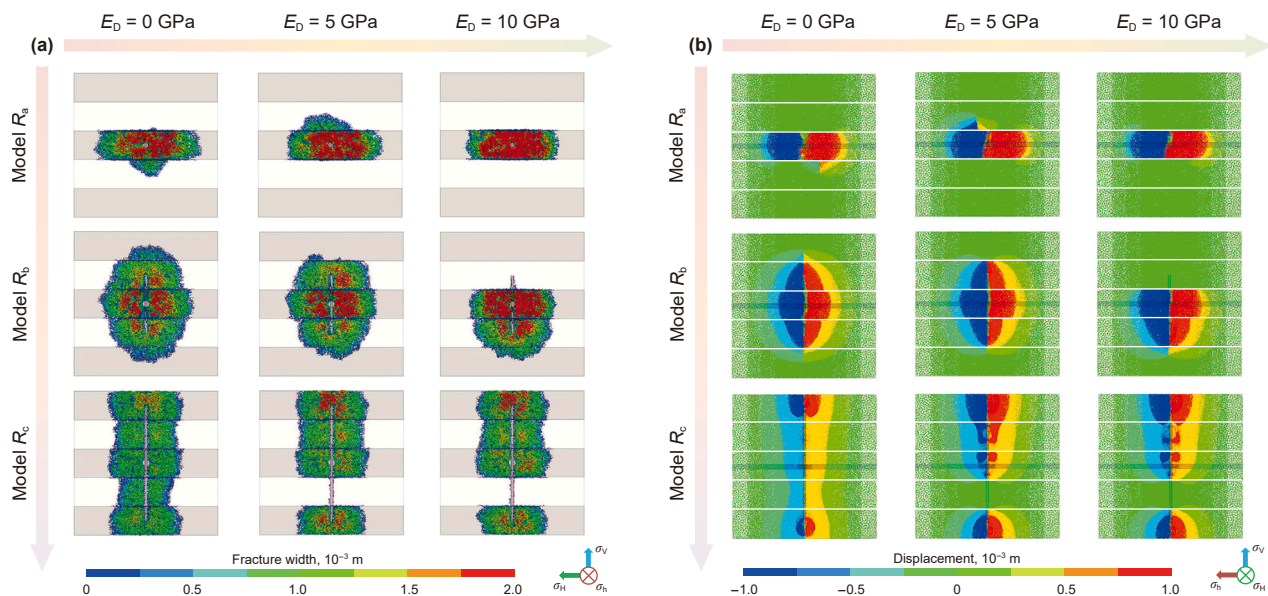


Fig. 11. Fracture morphology and rock displacement evolution characteristics under different interlayered elastic modulus differences. (a) Fracture propagation morphology; (b) rock displacement field evolution.

under the T_D range of 0–4 MPa. Notably, as the T_D increases, hydraulic fracture morphology transitions from cross-layer fractures to hybrid fractures and ultimately to the skip-layer pattern. Analysis of rock displacement evolution reveals that when T_D falls below 0 MPa, the toe end of the lower radial borehole loses cracking capability. The hydraulic fractures only initiate in the upper and intermediate pay layer, and ultimately connect into a main fracture plane. The limited SRA and VFH were formed in the lower pay layer. It is noteworthy that this study involves modulating the tensile strength of pay layers to alter the T_D . When the tensile strength of pay layers is high (indicating a significant T_D), the hydraulic fracture breakdown pressure increases accordingly, and the fluid pressure distribution within the fracture and radial boreholes becomes more concentrated, thereby promoting hydraulic fracture cross-layer extension. However, pay layers with

higher tensile strength can exacerbate the hydraulic fracture's competitive initiation behavior, making it difficult to achieve effective cracking and activation in localized pay zones. To simultaneously optimize hydraulic fracture width and stimulation effectiveness across all pay layers, thin interbedded reservoirs with T_D exceeding 2 MPa demonstrate superior performance in the Model R_c .

3.4. Effect of weak planes

3.4.1. Shear strength of lithological interface

With the I_{ss} increases, the vertical propagation range of hydraulic fractures significantly expands, but the activated lithological interface area gradually decreases (Fig. 13). For Model R_a , as the I_{ss} increases from 4 to 16 MPa, hydraulic fracture morphology

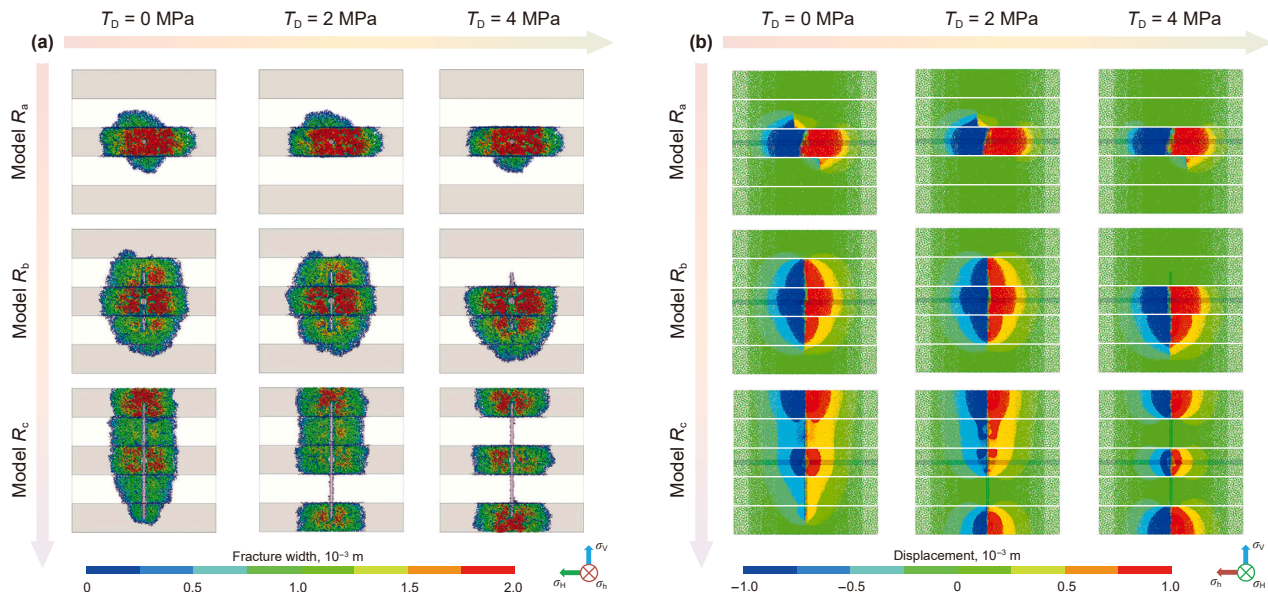


Fig. 12. Fracture morphology and rock displacement evolution characteristics under different interlayered tensile strength differences. (a) Fracture propagation morphology; (b) rock displacement field evolution.

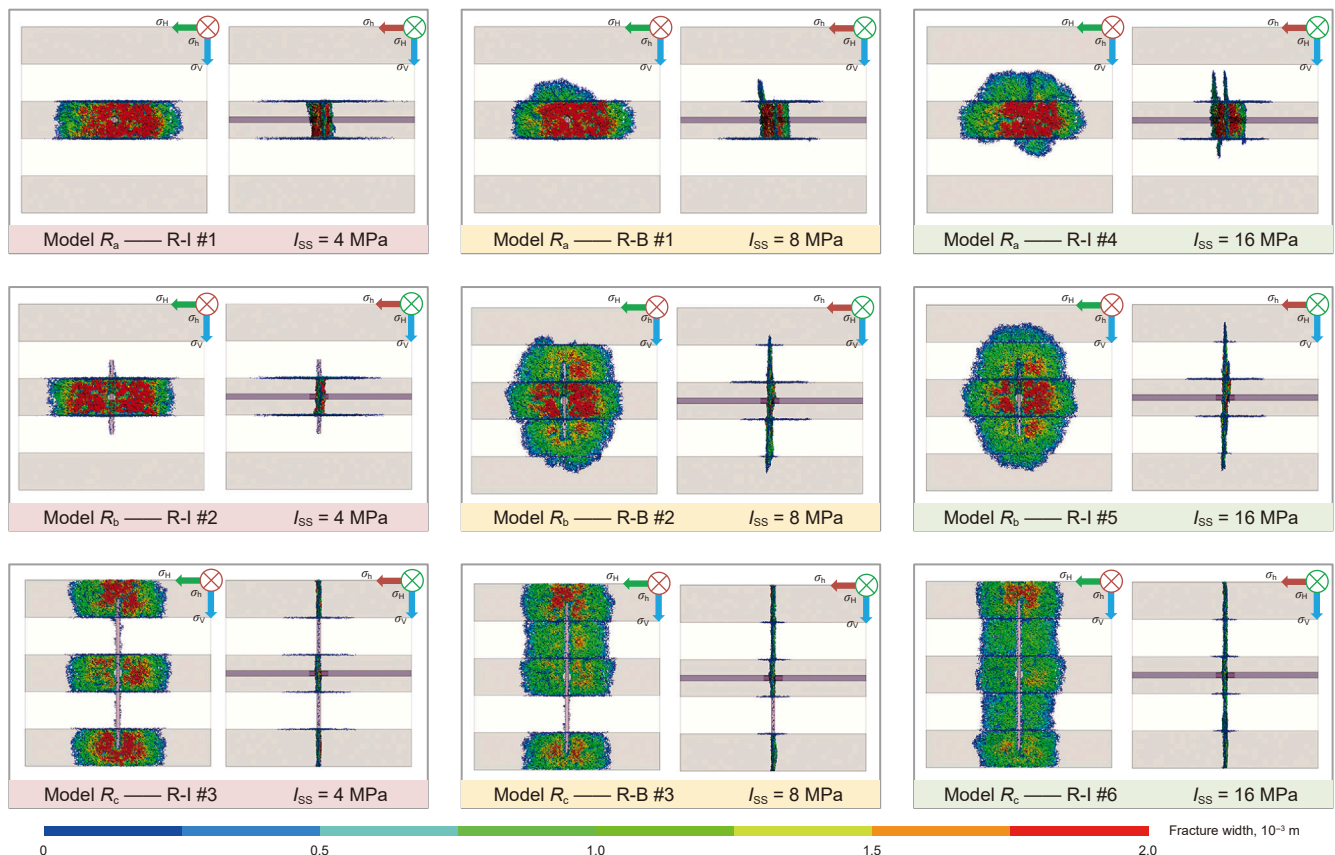


Fig. 13. Fracture morphology under different shear strengths of the lithological interface.

transitions sequentially from passivated fractures to single-wing cross-layer fractures, ultimately evolving into double-wing cross-layer fractures. In Model R_b , when the I_{ss} is below 4 MPa, the hydraulic fracture activates the lithological interfaces and deflects along them. At 8 MPa of the I_{ss} , hydraulic fractures penetrate

barrier layers and activate the lower pay layer. Further increasing the strength to 16 MPa enables hydraulic fractures to penetrate both adjacent barrier layers and activate all pay layers. Model R_c effectively stimulates all pay layers under all I_{ss} conditions. Increasing the I_{ss} drives hydraulic fracture evolution from skip-

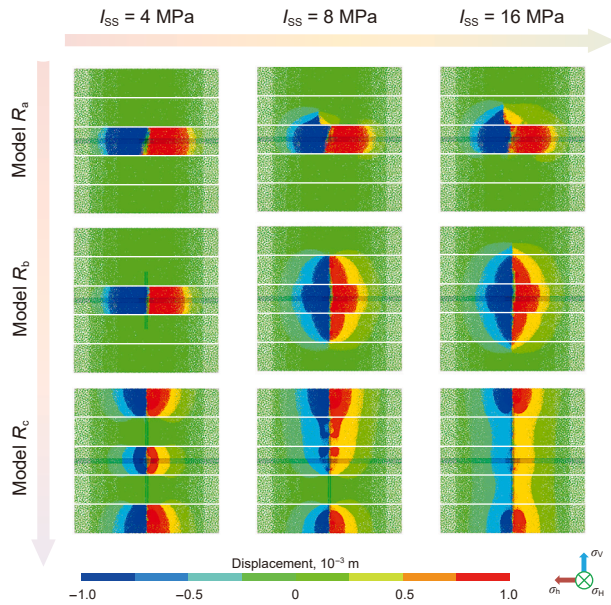


Fig. 14. Rock displacement evolution characteristics under different shear strengths of the lithological interface.

layer fractures to hybrid fractures, culminating in double-wing cross-layer fractures. Shear sliding of lithological interfaces significantly dissipates the fluid energy that drives fracture growth, thereby severely impeding or even limiting the

propagation of rock displacement into adjacent barrier layers. As shown in Fig. 14, radial borehole cross-layer fracturing can effectively suppress interfacial shear slippage, facilitating the vertical propagation of rock displacement. When the I_{ss} falls below 4 MPa, rock displacement struggles to propagate along the radial boreholes to adjacent barrier layers. Under such geological conditions, connecting multiple pay zones via radial boreholes represents the optimal approach for reservoir stimulation. This approach confines rock displacement within multiple pay zones, facilitating higher SRA and fracture widths for production zones.

3.4.2. Natural fracture density

When natural fractures exist within interlayers, the VFH will be significantly constrained (Fig. 15). Conversely, in the thin interbedded reservoir devoid of natural fractures, radial boreholes can effectively guide hydraulic fractures to penetrate across the lithological interfaces, forming a double-wing cross-layer pattern. In these models, the rock displacement distribution exhibits excellent continuity (Fig. 16). However, when the N_T reaches 1–2 fractures/m, the vertical propagation range of hydraulic fractures decreases substantially while the laterally SRA increases. The combined effect of natural fractures and lithological interfaces obstructs the vertical propagation of rock displacement, resulting in diminished vertical displacement continuity and consequently promoting the development of tortuous fracture growth paths. Research indicates that increasing radial borehole length can effectively mitigate the constraining effects of natural fractures and lithological interfaces on rock displacement. Therefore, it is recommended to maximize radial borehole length to guide effective hydraulic fracture cross-layer propagation while

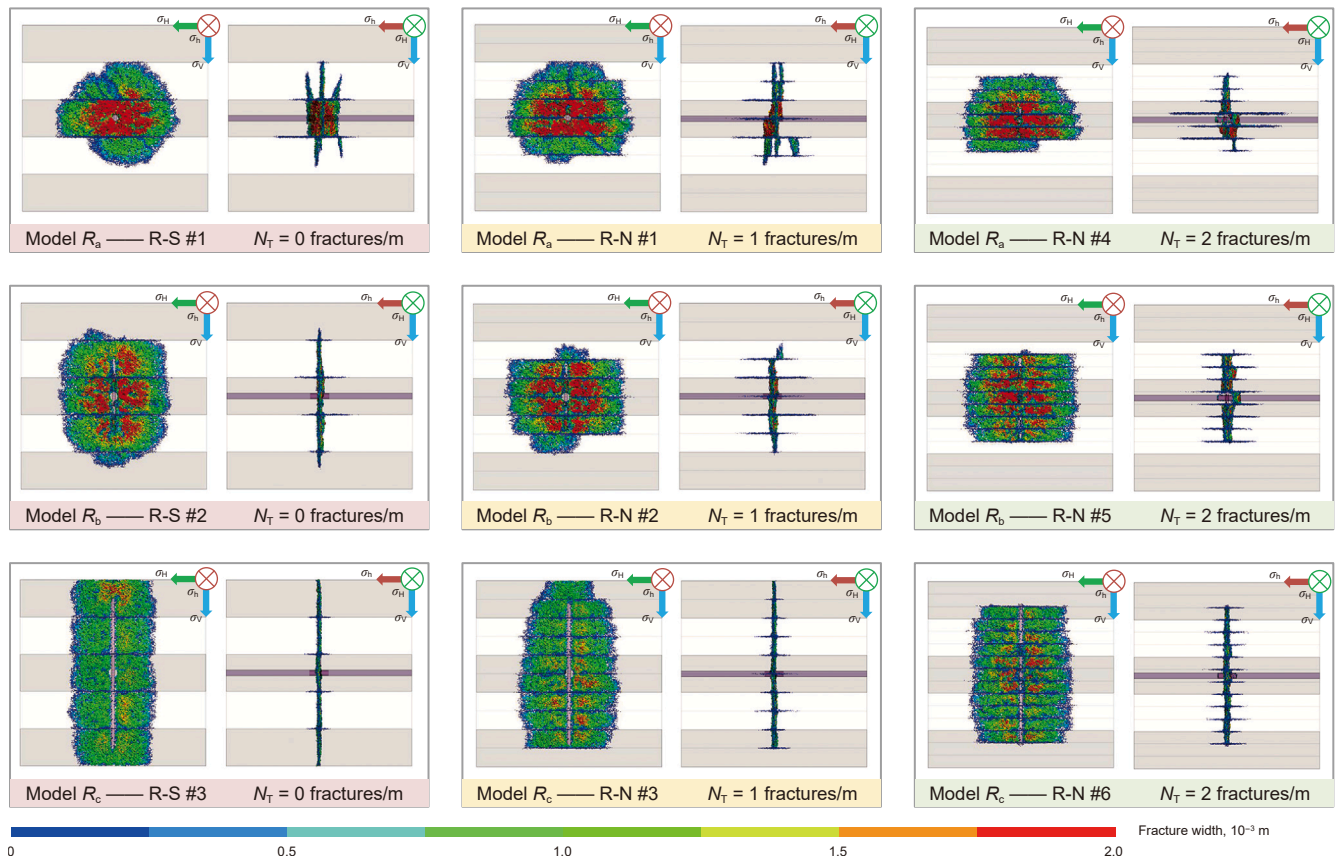


Fig. 15. Fracture morphology under different natural fracture densities.

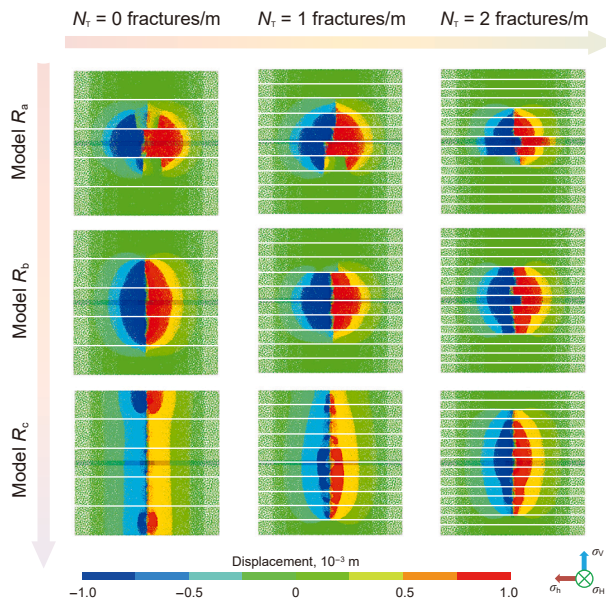


Fig. 16. Rock displacement evolution characteristics under different natural fracture densities.

suppressing deflection upon encountering natural fractures. Moreover, extended radial boreholes can connect and activate more natural fractures, thereby substantially enlarging the laterally SRA in the thin interbedded reservoir.

3.5. Quantitative analysis of fracture networks

3.5.1. Vertical fracture height

As illustrated in Fig. 17, the S_D , F_D , E_D , T_D , and N_T exhibit negative correlations with the VFH, whereas the I_{SS} shows a positive correlation. Among these, the S_D and I_{SS} demonstrate the most

pronounced inhibitory effects on fracture height. When the S_D increases from 0 to 10 MPa, or the I_{SS} decreases from 16 to 4 MPa, the VFH decreases by 56.1% and 55.8%, respectively. In contrast, the N_T exerts a relatively minor impact on radial borehole-guided fracture height growth, with the VFH consistently exceeding 2 m. The VFH in Model R_c significantly surpasses that of Models R_a and R_b by 125% and 46%, respectively. By drilling radial boreholes across multiple pay zones, hydraulic fractures can be induced to initiate in multiple interlayers, thereby achieving cross-layer extension and effectively enhancing the VFH.

3.5.2. Stimulated reservoir area

The variation trends of the TFA with geological parameters align with the VFH, indicating that radial borehole-guided hydraulic fractures primarily induce tensile failure during propagation (Fig. 18). The S_D emerges as the dominant factor affecting the TFA. When it increases from 0 to 10 MPa, the TFA decreases by 42%. The SFA predominantly originates from shear slip along lithological interfaces and natural fractures. Under radial borehole fracturing, the TFA and SFA demonstrate an inversely proportional relationship. During hydraulic fracture propagation by radial borehole guidance, weak plane activation remains lower. Conversely, restricted VFH induces greater shear slip along weak planes. The I_{SS} and N_T constitute key factors governing the SFA. In naturally fractured reservoirs, increasing the N_T enhances the SFA, thereby expanding SRA. Moreover, the enhanced N_T exerts minimal effect on the TFA without compromising hydraulic fracture propagation efficiency. It demonstrates radial boreholes' capability to activate natural fractures while guiding fracture cross-layer growth effectively. Crucially, radial borehole length correlates positively with the TFA and guided fracture cross-layer propagation capability. Provided that drilling conditions permit, performing long-distance radial borehole fracturing can effectively enhance the multiple pay zone connectivity and the SRA in the thin interbedded reservoir.

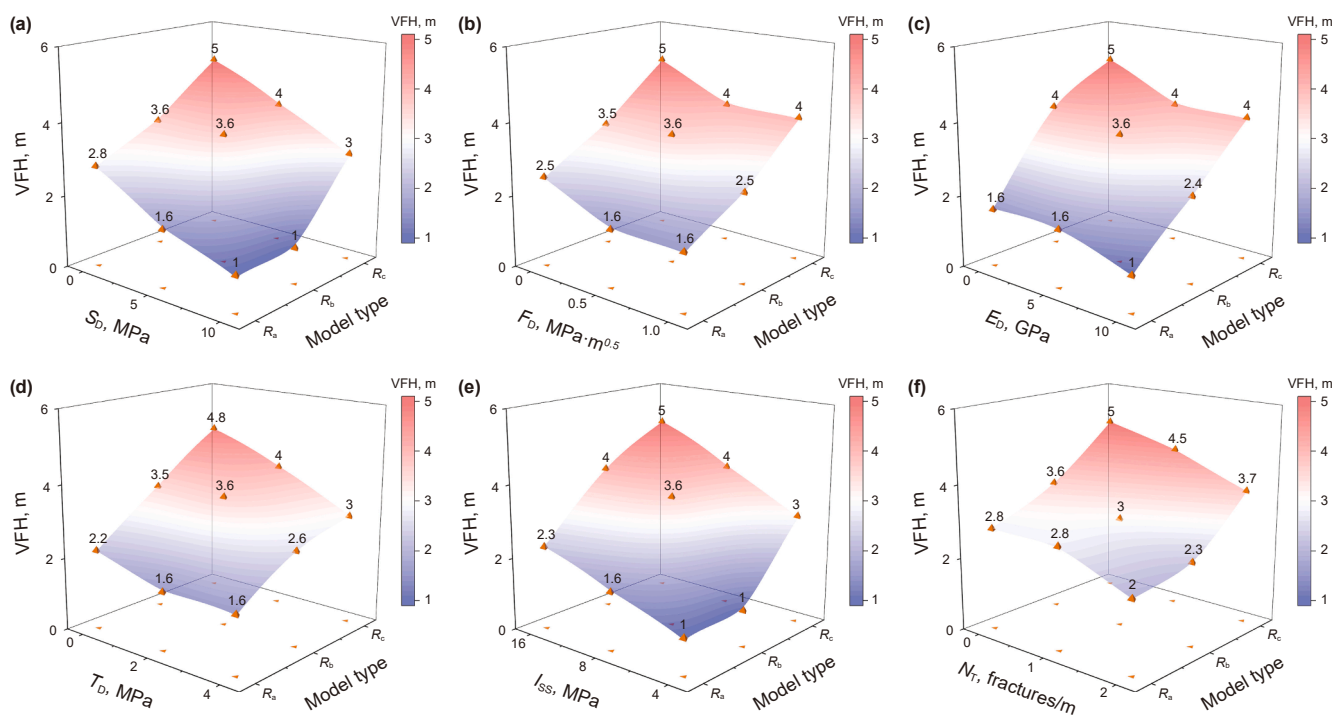


Fig. 17. The VFH under different geological parameters. (a) Interlayered stress difference; (b) interlayered fracture toughness difference; (c) interlayered elastic modulus difference; (d) interlayered tensile strength difference; (e) shear strength of lithological interface; (f) natural fracture density.

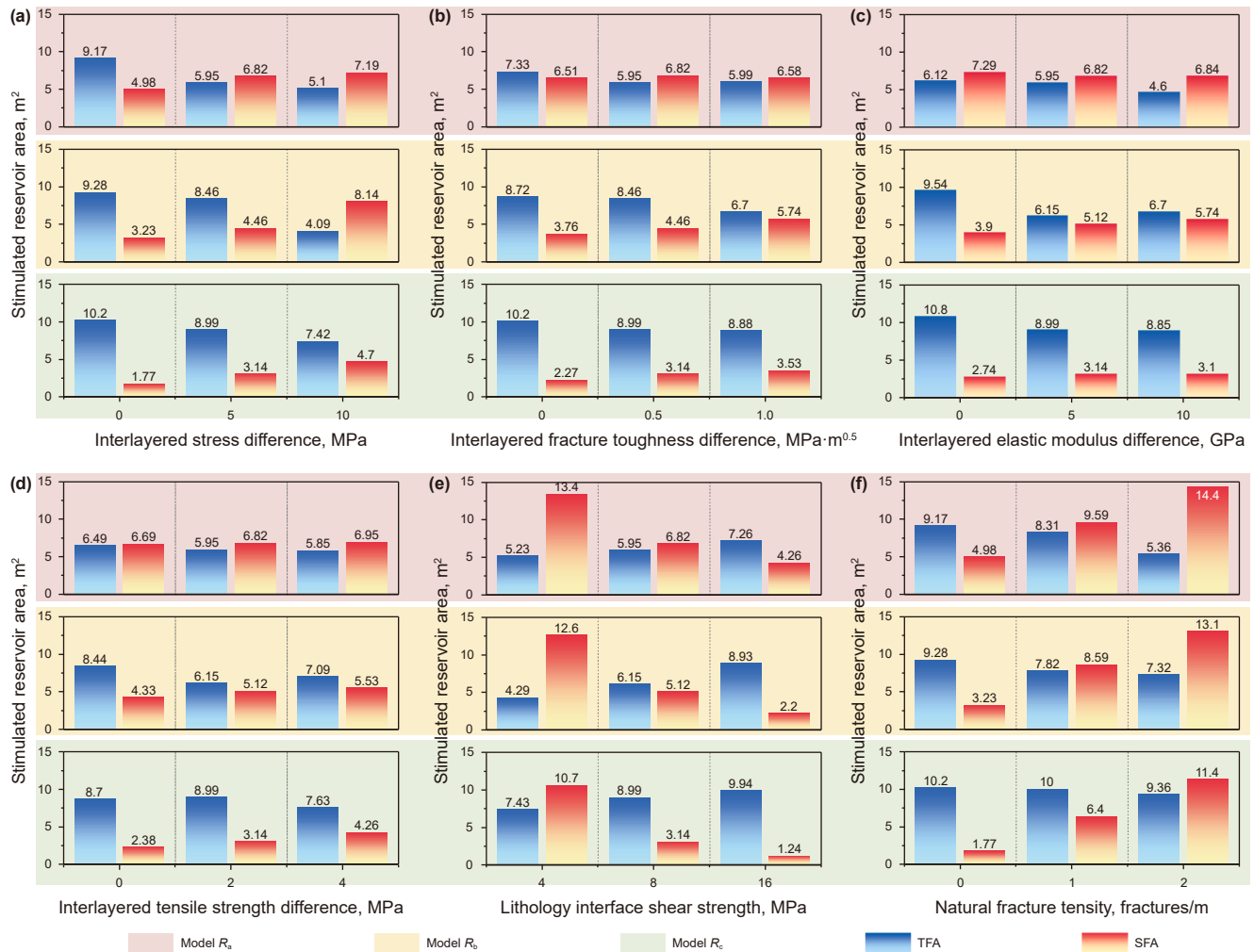


Fig. 18. Fracture network growth mode under different geological parameters. (a) Interlayered stress difference; (b) interlayered fracture toughness difference; (c) interlayered elastic modulus difference; (d) interlayered tensile strength difference; (e) shear strength of lithological interface; (f) natural fracture density.

3.5.3. Parameter sensitivity

The effect of geological parameters on VFH, TFA, and SFA exhibits a nonlinear monotonic relationship. Therefore, the Spearman correlation algorithm was employed for parameter sensitivity analysis (Asuero et al., 2006). In this analysis, the correlation coefficient (CC) value ranges from -1 to 1 , where positive values indicate positive correlations (marked with red ellipses) and negative values signify negative correlations (marked with blue ellipses). Parameter sensitivity increases with the absolute value of CC. Results demonstrate that the I_{SS} and S_D most significantly affect the VFH in radial borehole fracturing, with CC values of 0.66 (positive) and -0.61 (negative), respectively (Fig. 19). Additionally, the S_D shows a strong negative correlation (CC = -0.9) with TFA. This indicates that the I_{SS} and S_D are dominant factors controlling hydraulic fracture cross-layer propagation in radial borehole fracturing. To enhance vertical stimulation performance, the thin interbedded reservoir with lower I_{SS} and S_D is recommended for radial borehole fracturing. Meanwhile, the I_{SS} and N_T exhibit strong correlations with SFA (CC = -0.9 and 0.95 , respectively). For achieving broader lateral stimulation, reservoirs with high N_T and low I_{SS} are preferable for radial borehole fracturing. In contrast, parameters such as the F_D , E_D , and T_D show weaker sensitivity to the VFH, TFA, and SFA. It indicates they are not critical factors determining the reservoir stimulation in radial borehole fracturing.

3.5.4. Fracture propagation criteria

A propagation criterion was established for identifying a hydraulic fracture crossing a lithological interface in radial borehole fracturing under various geological factors. The simulation results within geological parameter spaces are compiled into fracture pattern charts as shown in Fig. 20. Radial borehole fracturing predominantly generates cross-layer fractures, but may also produce passivated fractures, skip-layer fractures, and hybrid fracture networks. Notably, passivated fractures only occur when radial boreholes fail to penetrate across lithological interfaces. When radial boreholes connect multiple pay layers, some simulation cases yield unique hybrid fractures and skip-layer fractures. This phenomenon is consistent with the experimental results of Wu X. et al. (2025). Furthermore, skip-layer fractures effectively prevent barrier layer activation while maximizing the SRA and fracture width in pay zones. When radial boreholes are confined within the intermediate pay layer, even cross-layer fractures struggle to activate outer pay zones. However, radial boreholes extending into barrier layers can activate outer pay layers on one or both sides. Radial boreholes connecting multiple pay layers fully stimulate outer and intermediate pay zones. Under conditions where the reservoir exhibits an S_D greater than 10 MPa, an I_{SS} lower than 4 MPa, or an N_T greater than 1 fractures/m, the radial boreholes need to extend into the barrier layers. This configuration enables effective stimulation of the outer pay layer on at least one side.

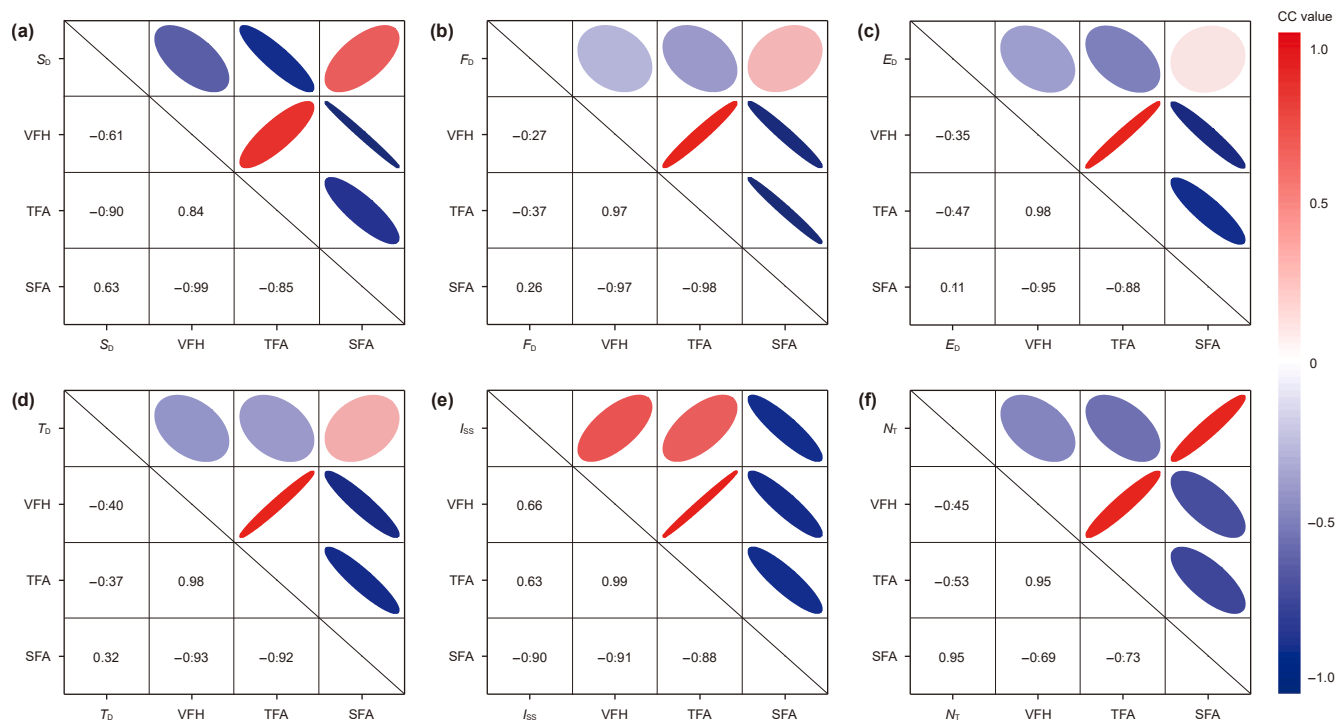


Fig. 19. The VFH, TFA, and SFA sensitivity under different geological parameters. (a) Interlayered stress difference; (b) interlayered fracture toughness difference; (c) interlayered elastic modulus difference; (d) interlayered tensile strength difference; (e) shear strength of lithological interface; (f) natural fracture density.

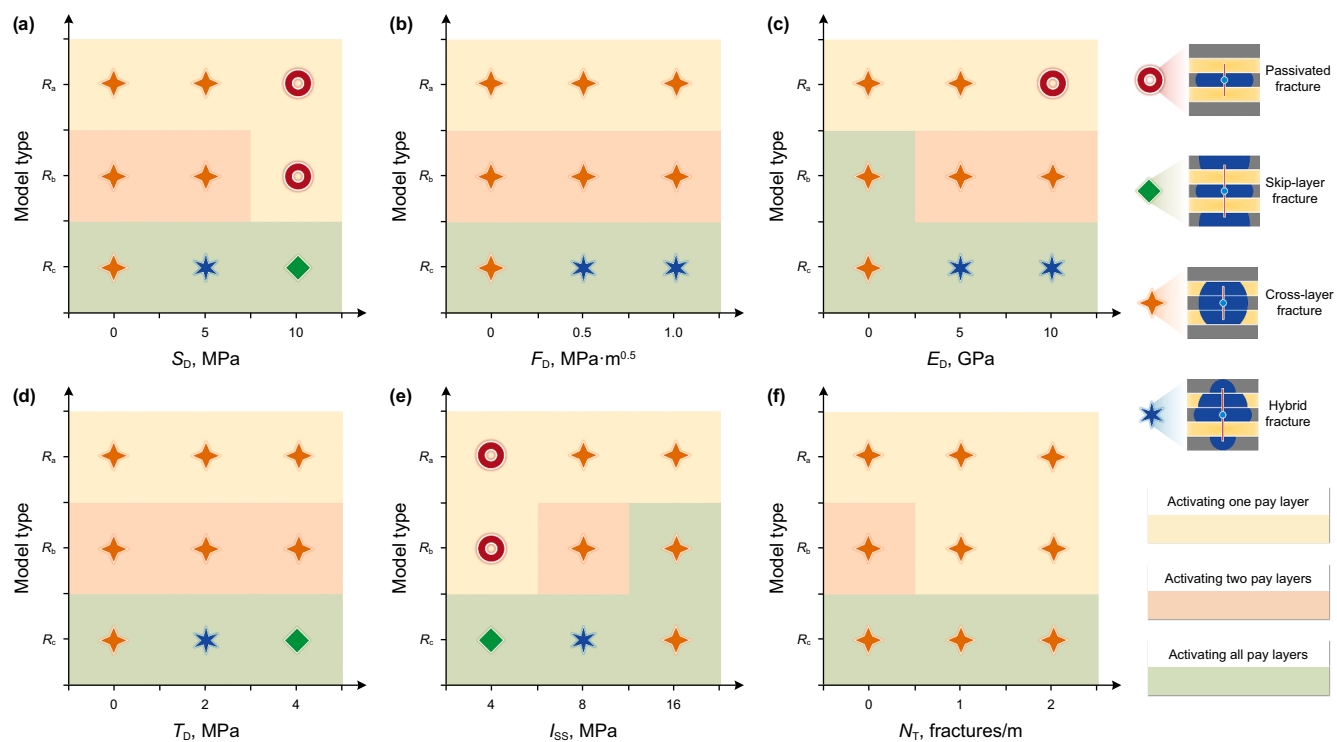


Fig. 20. The fracture propagation criteria in radial borehole fracturing under different geological parameters. (a) Interlayered stress difference; (b) interlayered fracture toughness difference; (c) interlayered elastic modulus difference; (d) interlayered tensile strength difference; (e) shear strength of lithological interface; (f) natural fracture density.

Moreover, when radial boreholes connect multiple pay layers, the skip-layer cracking enables the successful stimulation of all target zones and mitigates the constraints of formation conditions.

4. Discussion

Studying the effect of geological parameters on cross-layer fracture behavior is crucial for optimizing radial borehole fracturing designs in thin interbedded reservoirs. Previous research has predominantly focused on hydraulic fracture growth characteristics in conventional hydraulic fracturing, whereas this paper emphasizes the mechanisms by which geological parameters affect the VFH by radial borehole guidance (Cong et al., 2024; Huang et al., 2025; Kong et al., 2023; Liao et al., 2024). Our research team has conducted extensive radial borehole fracturing experiments on multilayered samples and determined the propagation characteristics of hydraulic fractures guided by radial boreholes. We have also performed in-depth investigations into the effect of parameters such as the vertical stress difference, fracturing fluid injection rate, and viscosity on the controlled hydraulic fracture growth (Wu X. et al., 2025; Zou et al., 2025). However, due to the inherent randomness and variability in the mechanical and physical properties of the experimental samples, it is challenging to conduct quantitative studies on geological parameters based solely on experimental approaches. As an extension of prior research, this study develops a DLM model to systematically analyze the initiation and propagation behaviors of hydraulic fractures in radial borehole fracturing under different geological conditions. Compared to conventional horizontal well fracturing, radial borehole fracturing significantly alleviates the constraints of formation heterogeneity and interlayered stress differences on hydraulic fracture cross-layer propagation. It is mainly attributed to its two major advantages: skip-layer initiation and cross-layer propagation. When radial boreholes penetrate lithological interfaces, high-pressure fluid can act simultaneously on multiple interlayers via these boreholes, achieving multiple pay zone cracking and stimulation. Furthermore, during radial borehole hydraulic fracturing, the interaction mechanism between hydraulic fractures and lithological interfaces undergoes fundamental changes. Under conventional fracturing conditions, hydraulic fractures are prone to deflection upon contacting weak planes due to shear slip of the interface, formation heterogeneity, and interlayered stress differences. In radial borehole fracturing, a tensile stress concentration zone develops, which traverses multiple interlayers and substantially alters the near-wellbore in-situ stress state, thereby mitigating the influence of interlayered stress differences. Furthermore, fracturing fluid is continuously supplied to the hydraulic fractures through the radial boreholes, enabling sustained vertical propagation along the borehole trajectory. Critically, the incompressible nature of the fracturing fluid within the radial boreholes enables it to act as a rigid medium, thereby significantly enhancing the efficiency of rock displacement propagation across lithological interfaces. This mechanism substantially strengthens the cross-layer propagation capability of hydraulic fractures.

Prior research has demonstrated that significant stress concentration occurred at radial borehole root ends within homogeneous formations, where the hydraulic fracture is prone to initiate (Gu et al., 2024; Guo et al., 2017, 2022; Yong et al., 2024). Nevertheless, this study further demonstrates that the stress concentration surrounding radial boreholes is not the sole determinant of the location where hydraulic fractures initiate. Within the thin interbedded reservoir, critical factors such as the interlayered stress differences and rock properties exert a substantial influence on hydraulic fracture initiation dynamics. Integrated analysis

demonstrates that hydraulic fractures tend to competitively initiate across multiple low-strength and low-stress interlayers, rather than remaining confined to radial borehole root ends. It should be noted that this study addresses single-cluster radial borehole fracturing behavior, whereas field applications typically employ stimulation with multi-cluster radial boreholes. Thus, investigating the competitiveness of hydraulic fracture extension and stress shadow effects under multi-cluster radial borehole fracturing in thin interbedded reservoirs emerges as a critical research frontier. Furthermore, this study still has several limitations. First, the curvature of radial borehole trajectories in field drilling operations was not considered during modeling. Second, radial boreholes were assumed to extend perpendicular to the main horizontal wellbore. Additionally, due to model scale constraints, the effects of fracturing fluid loss were not considered. Subsequent research will focus on field-scale numerical simulations to accurately reproduce the curvature radius and inclination angle characteristics of radial borehole trajectories, coupled with seepage effects, to systematically analyze the vertical reservoir stimulation effectiveness of radial borehole fracturing.

5. Conclusions

Based on the DLM, this study simulates hydraulic fracturing of thin interbedded reservoirs assisted with radial boreholes under different geological conditions. It analyzes the evolution of induced stress to determine the mechanisms of hydraulic fracture skip-layer initiation and cross-layer propagation by radial borehole guidance. The effect of key geological parameters on hydraulic fracture height was systematically investigated, identifying dominant controlling factors for the VFH. Furthermore, a propagation criterion was established for identifying a hydraulic fracture crossing a lithological interface in radial borehole fracturing under various geological factors. Main conclusions are as follows:

- (1) Radial borehole effectively reduces the near-wellbore minimum principal stress and prompts hydraulic fractures to cross-layer propagation in straight paths. When the radial borehole penetrates across lithological interfaces, rock displacement propagates vertically across lithological interfaces and activates adjacent interlayers. Furthermore, multiple pay zones achieve effective skip-layer stimulation when radial boreholes connect multiple interlayers.
- (2) With the increase in S_D , the range of stress redistribution around radial boreholes progressively narrows, thereby limiting the hydraulic fracture cross-layer propagation. Furthermore, increasing the F_D , E_D , and T_D inhibits the vertical propagation of rock displacement and the radial borehole guidance. When radial boreholes connect multiple pay layers, a decrease in T_D exacerbates the competitive effect of skip-layer initiation, resulting in difficulties for outer pay layers to achieve effective stimulation.
- (3) The lithological interfaces and natural fractures induce a significant discontinuity in rock displacement along radial boreholes, thereby limiting the VFH in the thin interbedded reservoir. Among these geological factors, the I_{SS} serves as the most dominant factor controlling the VFH. When the formation contains multiple low-strength weak planes, the implementation of long-distance radial borehole fracturing can effectively enhance VFH and facilitate the activation of more weak planes.
- (4) If the reservoir exhibits an S_D exceeding 10 MPa, an I_{SS} falls below 4 MPa, or an N_f is greater than 1 fractures/m, radial boreholes should be extended to the barrier layers to effectively stimulate the outer pay layers. When radial boreholes

interconnect multiple pay layers, hydraulic fracture skip-layer initiation could achieve overall reservoir stimulation and mitigate the constraints of formation conditions.

CRediT authorship contribution statement

Xiao-Guang Wu: Writing – review & editing, Investigation, Funding acquisition. **Teng-Da Long:** Writing – original draft, Supervision, Investigation. **Zi-Xiao Xie:** Supervision, Investigation, Funding acquisition. **Rui Yang:** Investigation. **Zhong-Wei Huang:** Supervision, Funding acquisition. **San-Li Peng:** Investigation. **Zhao-Wei Sun:** Validation. **Tao Pan:** Investigation. **Nai-Kun Hu:** Validation. **Xiao-Hua Wang:** Software. **Song-Long Lv:** Writing – review & editing.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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