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Investigation of fracture intersection behaviors in three-dimensional space based on CT scanning experiments

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Abstract: The generation of a fracture network in reservoir rocks for fluids to flow via hydraulic fracturing is important in shale oil and gas development, and the intersection between hydraulic and natural fractures is key in bridging natural fractures. In this work, the intersection behaviors between hydraulic and natural fractures and fracture propagation in a three-dimensional (3D) space were investigated. A hydraulic fracturing lab facility is designed and a series of fracturing tests on eight underground cores from the Kong shale reservoir are carried out. First, visualization analysis was conducted on each sample before and after fracturing with the assistance of an X-ray CT scan and the following up 3D reconstruction. Second, an extension model of fracture intersection between natural and hydraulic fractures is established in 3D through analytical calculations. Finally, the intersection behaviors are classified into six zones according to our model analysis. Apart from interesting results and findings, insights into the formation and propagation of fracture networks are also provided, which are of great value in characterizing shale reservoirs.

Keywords: fracture intersection, intersection criteria, true triaxial experiment, fracture propagation, X-ray CT scan

Abbreviations

3D	Three-dimensional
CT	Computerized tomography
HFs	Hydraulic fractures
NFs	Natural fractures
2D	Two-dimensional
DA	Dip angle
AA	Azimuth angle

List of symbols

τ_0	Shear stresses of natural fracture
K_f	Coefficient of friction
T	Shear stresses acting on NF
σ_n	Normal stresses acting on NF
p_0	Pore pressure imposed on the NF surface
σ_1	Maximum in-situ principle stress
σ_3	Minimum in-situ principle stress
p_σ	Treatment overpressure
T_0	Tensile stress
b	Coefficient
σ_{H1}	Stress along the HF plane and is perpendicular to the intersection line
σ_{v1}	Stress along the HF plane and the intersecting line

1. Introduction

Hydraulic fracturing has become a key stimulation technique to enhance the productivity in shale oil and gas reservoirs. Owing to the extremely low permeability and dominant pores at nano-scale, the major role of hydraulic fracturing is to generate connections among natural fractures, resulting in flow channels to be created and the distance of oil and gas seepage being reduced, which consequently produces a large stimulation reservoir volume (Zhang et al. 2018; Zhang and Sheng 2020). The fractures created by hydraulic fracturing are complex and form a fracture network for fluid to flow through (Fan and Zhang 2014; Hou et al. 2016). The intersection between hydraulic fractures (HFs) and natural fractures (NFs) during fracturing plays a key role in forming the fracture network (Hou et al. 2016; Rueda et al. 2020). Particularly, Gale et al. (2007) have investigated the importance of NFs in hydraulic fracturing treatments. When HFs meet NFs, the HFs will pass through, turn along NFs, or be arrested by NFs (Rueda et al. 2020; Kolawole and Ispas 2020; Janiszewski et al. 2019). Hence, it is important to understand the mechanisms of creating a complex fracture network in naturally fractured shale reservoirs.

Laboratory scale true triaxial hydraulic fracturing test is a popular approach to directly investigate fracture propagation behaviors during reservoir stimulation. There are several experimental studies on the intersection between HFs and NFs (Warpinski et al. 1982; Ruxin et al. 2019; Zou et al. 2016). Meanwhile, various visualization techniques have been adopted to monitor fracture propagation paths in rock samples, such as splitting artificial or outcrop rocks (Zou et al. 2016, Zhi et al. 2015), using acoustic emission and microseismic data to analyze fracture geometry (Bennour et al. 2015, Ma et al. 2017), adding tracers into fracturing fluid to track fracture extension in rock samples (Fu et al. 2016, Tan et al. 2020). These studies analyzed the impact of intersection angle, stress difference, fracturing fluid viscosity, and fracturing engineering parameters on fracture propagation, but neglected the effect of dip angle, which broadly exist in NFs in the formations (Gale et al. 2014). Following up, Dehghan et al. (2015) investigated the influence of the dip angle and azimuth on fracture propagation through performing splitting rock sample experiments. In addition, Heng et al. (2019) considered crack propagation with various dip angles via numerical simulation based on an acoustic emission monitoring experiment.

Over the past decades, as a non-destructive technique, X-ray computed tomography has been widely employed for the characterization of fracture propagation. Zou et al. (2016) analyzed the influence of field treatment and geological parameters on fracture propagation with partially opened bedding planes and provided suggestions on how to create complex fracture networks in shale formations. He et al. (2016) compared hydraulic fracture extension patterns in fractured shale, sandstone, and granite cores, and demonstrated the impact of bedding planes early developed in shale on fracture morphology. Guo et al. (2014) investigated the impact factors of stimulated shale reservoir volume by the high-energy CT scanning technique. Zou et al. (2016) studied the hydraulic fracture propagation in natural bedding using CT technology. However, the majority merely mention the plane expansion morphology of fractures because of the lack of three-dimensional (3D) reconstruction of fracture voids. Jiang et al. (2019) and Luo et al. (2019) used 3D reconstruction for analyzing fracture propagation morphology, nevertheless, they did not consider the interaction between HFs and NFs.

To understand the intersection behaviors, many scholars have conducted several theoretical studies. Zhuang et al. (2020) and Zheng et al. (2019) established a numerical model to analyze the intersection between HFs and NFs. Warpinski and Teufel (1987) proposed an analytical model to estimate whether NF will be dilated or fail in shear slippage due to approaching HFs. Based on linear elastic mechanics, Renshaw and Pollard (1995) had established across criterion for hydraulic fracture intersection with an orthogonal discontinuity. Gu et al. (2012) extended the criterion to the non-orthogonal interface. Fu et al. (2018) developed a new 3D analytical criterion to quantify the dependence of natural fracture tensile/shear failures on the properties of spatially-varied NFs, including the proportion of cemented region(s), natural fracture height, and cementation strength. Recently, Blanton (1986) created a model of HFs penetrating NFs with good agreement compared with experimental results.

In this study, several underground cores of the second Kong shale reservoir were used to prepare square-shaped samples for true triaxial fracturing experiments. Before the respective experiments, CT scanning and subsequent 3D reconstruction were used to characterize the spatial distribution of NFs. At the end of every test, CT scanning and 3D reconstruction are invoked again to expose the resultant fracture network after hydraulic fracturing, viewing and quantify fracture extension in terms of morphological properties and flow behaviors. Furthermore, an intersection extension model between HFs and NFs in 3D is established and an assessment chart is generated to distinguish various intersection extension zones for the second Kong shale reservoir.

2. Experiments

2.1 Specimen preparation

Eight core samples were taken from several wells located at shale oil reservoirs at depths between 2800 and 4200 m in Cangdong Sag, Bohai Bay Basin, China. The cylindrical cores have an identical diameter (100 mm) and length (95 mm). The measured porosities and permeabilities range from 5.09% to 10.51% and from 0.44 to 6.84 mD, respectively. Among all samples, Yong's modulus is 17,743 MPa, and Poisson's ratio is 0.267, on average. Regarding the triaxial hydraulic fracturing involved in our experiment, as shown in Fig.1(a), each original sample needs to be wrapped up with filling materials to make a cuboid-shaped sample of three dimensions of 105 mm × 105 mm × 95 mm, which is the same dimension as the true triaxial hydraulic fracturing testing holder. The filling materials are composed mainly of G-grade cement, water, and sand (60 mesh), made with a sand cement ratio of 1.8:1, and has similar properties as the core themselves (Table 1), which were used as core specimens.

A wellbore shown in Fig. 1 is located in the middle of each core sample with a steel case coupled with an open-hole section. The steel case has 20 mm in length, 10 mm in exterior diameter, and 8 mm in interior diameter, was glued in place by an epoxy adhesive, which generated a bonding strength several times greater than the tensile strength of the rock specimens.

2.3 Fracturing equipment

The true triaxial fracturing system shown in Fig. 2 was set up to perform our hydraulic fracturing tests with a loading capacity of 20 MPa in three orthogonal directions. To avoid unbalanced loading at boundaries, the maximum horizontal stress (σ_H), minimum horizontal stress (σ_h) and vertical stress (σ_v) were simultaneously applied incrementally but slowly on the specimen until a targeted value to be reached. During testing, rock specimens were first fractured under high hydraulic pressures. At the end of fracturing, i.e., stopping pumping water, the confining stresses were maintained for a couple of minutes until the generated tensile fractures are closed tightly. Over that duration, rock samples were then taken out for CT scanning.

2.4 Natural fracture before fracturing

A computer was used throughout the whole test procedure to control and monitor the experiments and collect data. A micro-CT scanning system was used to characterize the spatial distribution of NFs before pumping water and to capture the propagation of HFs at the end of water pumping. The system consists of an acquisition computer, a reconstruction computer, and a shielded cabinet that includes a 240-kV micro-focus X-ray tube, an X-ray detector array, and a rotatable sample holder. The two-dimensional (2D) cross-sectional images acquired by CT scanner (Luo et al. 2019) were further reconstructed into 3D images, which are obtained using a commercial software called VGStudio, to reveal the spatial distribution of fracture opening voids in rock samples.

The number, density, spreading direction, and angle of NFs in rock samples can be captured by CT scanning with fracture recognition software. To facilitate the observation of the spatial geometry of fractures, rock samples were sliced in three directions: facing up, side-looking, and overlooking, as shown in Fig. 3(a). Y-direction links to the "σ_H" direction, and X direction to the "σ_h" direction, as shown in Fig. 3(b). The dip angle (DA) and the azimuth angle (AA) of fractures are two key parameters, as shown in Fig. 3.

2.5 Experiment design

The in-situ horizontal stress difference ($\sigma_H - \sigma_h$) and intersection angle are the predominant elements (Gu et al. 2012; Yao et al. 2018) in fractures intersection. So, in our experiments, we maintained the vertical press σ_v at 16 Mpa while allowed the in-situ stress difference to change for evaluating the influence of the two factors. Table 2 lists the eight samples and the properties concerned with our experiments. Horizontal stress difference is set as one of four values: 0, 0.5, 2, and 4 MPa. The vertical stress difference (i.e., the difference between vertical and horizontal minimum stress) is set as one of four values: 5, 7.5, 10, and 15 MPa. For integrity, lick water of the viscosity of 5 CP was used as fracturing fluid, and a single pumping rate of 12 mL/min is fixed in every test.

3. Observations and results

3.1 3D visualization

Fig. 4 shows 3D fractures in eight samples before and after the hydraulic fracturing. Among all original samples, only samples 25–1 have no NFs, and the rest mainly contain horizontal NFs. Table 3 lists the dip and azimuth angles of NFs with interactive relationships before fracturing. Note that the measured angles may not be that accurate due to the difficult identification in discrete space. Apart from this observation, this paper analyze fracture intersection and propagation in Section 3.2 and further conduct an in-depth mathematical derivation of the interactive propagation of HFs and NFs in 3D in Section 4.

Shale is usually considered a transversely isotropic material in the experiment and theory (Sinha et al. 2006, Valente et al. 2012), and there are discontinuous structural planes such as bedding and NFs in shale. The direction of fracture propagation is affected by discontinuous structural planes (Jiang et al. 2019), thus forming a complex fracture network. This phenomenon is observed in Fig. 4 (b) - (h).

3.2 Fracture propagation analysis

3.2.1 Samples with two symmetric wing fractures

New NFs were created in the shale matrix, and HFs were extended toward horizontal maximum principal stress, without intersection with NFS to be observed, forming a single HF, so it suggests that fracture propagation is mainly controlled by in-situ stress. Such a phenomenon was found in sample 30 as well.

Sample 30 does not have NFs but has only one vertical symmetrical biplane fracture (see HF1 in Fig. 4(a)) generated under the horizontal stress difference of 0.5 MPa, indicating that complex fractures are difficult to form in the shale, even with the low-stress difference if there is no original NFs.

3.2.2 Hydraulic fracture extension

As there are NFs near or even directly connected to the wellbore, it is well-recognized that generating new HFs is rare in the rock matrix during fracturing, however, existing NFs can be opened and extended further. The fracture propagation within such sample is controlled by NFs, which is confirmed in experiments with samples 31, 34, and 25–1 too.

There are four NFs in sample 31. NF1, NF2, NF3, and NF4 are well connected to the wellbore, and consequently, no new HFs are generated through fracturing, instead, the four fractures are extended to some extent along with their original directions (Fig. 4 (c)).

There are three NFs in sample 34. As NF1 and NF2 are connected to the wellbore, HFs spread along with these two fractures during fracturing (Fig. 4 (e)). However, NF3 is connected to neither the wellbore, nor NF1 and NF2, and thus no new HFs can be generated in the experiment.

Five inter-connected NFs can be found in samples 25–1. As NF1, NF3 and NF4 are connected to the wellbore, and NF1 is intersected with both NF2 and NF5, the originally existing NFs spread along with these five fractures during fracturing (Fig. 4(f)). However, no new HFs were generated consequently.

3.2.3 Intersection between HFs and NFs

From these experiments, it can be observed that HFs can be created in the shale and be extended to intersect NFs. In addition, HFs can also cut through NFs or cause NFs to shear, slip, and spread along with natural fractures. As illustrated in Fig. 4 for samples 33–2, 25–2, 26, and 28, it is evident that fracture propagation is controlled by stress and NFs.

Four separated NFs exists in sample 33–2 (Fig. 4(d)). During hydraulic fracturing, two new vertical HF1 and HF2 are generated, indicating that complex fractures are likely to occur if the stress difference is 0. HF1 intersects NF2 at 48.5° upwards and NF3 at 35.6° downwards, causing them to shear slip and spread along with the NFs. HF2 intersects both NF2 and NF3 vertically and turns along with them. NF1 and NF4 are not connected as HF does not penetrate the NF. Limited by the view angle, this phenomenon may not be that clear to be seen in Fig. 4 but can be confirmed by observing the post-fractured rock sample in Fig. 5.

In sample 25–2 exists only one NF. Hydraulic fracturing triggers a new vertical HF1 along the direction of maximum horizontal stress and spread downwards and penetrate NF1 (Fig. 4(b)).

With two NFs in sample 26, hydraulic fracturing results in a new vertical HF1 that is parallel to the maximum horizontal stress. HF1 spreads with a higher aperture and cuts through NF2. The connection of NF2 with NF1 forces NF2 to spread upwards and open NF1 up (Fig. 4(g)).

There is no NFs near the wellbore although four NFs exist in sample 28, as a result, a new two symmetrical wing vertical fracture, HF1, is generated on the upper region of the sample along the direction of the maximum stress, which causes shear slip on NF1 (Fig. 4 (h)). As the HF is parallel to NF1, NF3 and NF4 are at the bottom regions of the rock sample. It can be observed that the new fracture is not connected with any of NF2, NF3, and NF4.

3.2.4 Insights into fracture propagation

The experimental results show that NFs have a big influence on fracture propagation and play a key role in the creation of complex fractures. If NFs do exist in rock samples, complex fractures are more likely to form after hydraulic fracturing.

(1) If NFs are not connected to the wellbore, new HFs can be created by fracturing, and the generation of new HFs are mainly controlled by stress and can expand along the direction of maximum horizontal stress.

(2) If NFs are connected or close to the wellbore, HFs are hardly generated. Instead, NFs can be opened up and even be extended further.

(3) If the intersection angle between HFs and NFs is small, newly-created HFs tend to spread along with NFs, as seen in samples 33–2. If the intersection angle is large, HFs are ready to cut through NFs, as seen in samples 26 and 25–2. This observation is consistent with the finding by Zhao et al. (2019).

(4) Due to the influence of natural fracture DA, the stress state of both HFs and NFs is unclear in 3D space, so the influence analysis of ground stress difference cannot be conducted effectively. Therefore, it is necessary to conduct further fracture propagation analysis in three-dimensional space.

4 Theoretical analysis of interaction behaviors

Through our experiments, the intersection behaviors of fractures were analyzed as described above. Fracture intersection is a collective result from various elements, such as ground stress, intersection angle, rock mechanics parameter, and fluid pressure in fracture.

4.1 Slippage and opening criterion

Fig. 6 shows a two-dimensional schematic of HF intersecting NF, which is a simplified diagram if the DAs are set to be 90°. For creating shear slippage in NFs, the condition can be found in (Luo et al. 2019; Warpinski and Teufel 1987) as:

$$|\tau| > \tau_0 + k_f(\sigma_n - p_0). \tag{1}$$

where τ_0 is the shear stress of natural fracture, K_f is the coefficient of friction, τ and σ_n are the shear and normal stresses acting on NF, respectively, p_0 is the pore pressure imposed on the NF surface.

Let the intersection angle between HF and NF in Fig. 6 is denoted by θ (0 < θ ≤ π/2), the shear stress, and normal stress acting on the plane of a natural fracture can then be obtained according to the 2D stress resolution in [Renshaw and Pollard 1995] as:

$$\tau = \frac{\sigma_1 - \sigma_3}{2} sin\, 2\theta, \tag{2}$$

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} cos2\theta. \tag{3}$$

where σ_1 is the maximum in-situ principle stress, σ_3 is the minimum in-situ principle stress.

From Warpinski and Teufel [Warpinski and Teufel 1987], if HF intersects NF, the tip can be blunted and the pressure at the intersection can be given by:

$$p_0 = p_\sigma + \sigma_3, \tag{4}$$

where p_σ is the treatment overpressure. Substituting Eqs. (2), (3) and (x4) into Eq. (1), the criterion for shear slippage can be described by Eq. (5),

$$(\sigma_1 - \sigma_3) > \frac{2\tau_0 - 2p_0k_f}{\sin(2\theta) - k_f + k_f\cos(2\theta)} \ , \tag{5}$$

and the criterion for natural fracture opening is simplified as:

$$p_0 > \sigma_3 \ , \tag{6}$$

further, substituting Eqs. (3) and (4) into Eq. (6) gives

$$(\sigma_1 - \sigma_3) < \frac{2p_\sigma}{1 - \cos(2\theta)} \ . \tag{7}$$

4.2 Crossing criterion

Based on the elastic solution of stress in the interaction zone and assumes that the initial interaction for HFs is to be blunted by the pre-existing NFs. Fracture crossing might occur if the stress difference, $\sigma_1 - \sigma_3$, exceeds the pressure required by Blanton [Blanton 1986] as:

$$\sigma_1 - \sigma_3 > -\frac{T_0}{cos2\theta - bsin2\theta}. \tag{8}$$

where T_0 is the tensile stress, b is a coefficient, and b = 0.2 in this work, which is determined by frictional slippage along the natural fracture and geometry of the interaction zone.

4.3 Stress distribution in 3D

As shown in Fig. 6, it is worth emphasizing that the interacting criteria presented above are established based on the fracture configuration in 2D. In our experiment, however, HFs and NFs are considered in 3D, as shown in Fig. 7, which indicates that the stress distribution in 3D is distinct from the counterpart in 2D. Hence, it is necessary to re-establish the stress distribution state of the cross-sections perpendicular to HFs and NFs, so that the stress state can meet the conditions of the previously established 2D model (Eqs. (5), (7), and (8)).

Fig. 7 demonstrates a common scenario of HFs intersecting NFs, where typical HFs are vertically inclined with a DA of 90° and in a direction that is parallel to the maximum principal stress. The NF has a DA of α and an angle of θ between the fracture plane and the maximum horizontal stress. σ_v is the vertical stress, σ_H is the maximum horizontal stress, and σ_h is the minimum horizontal stress. The red line in Fig. 7 stands for the intersection between HF and NF, on which the three stress values σ_{H1}, σ_{v1} and σ_h can be pinpointed as the distribution shown in Fig. 8. σ_{H1} is perpendicular to the intersecting line and passes through the natural fracture along the direction of the hydraulic fracture. σ_{v1} is along the intersecting line and σ_h is perpendicular to the hydraulic fracture plane. The plane determined by σ_{H1} and σ_h is perpendicular to both the HF and NF. This surface is the 2D plane in which the 3D space stress field is transformed into the 2D plane stress field. It is similar to the 2D plane stress field in Figure 6. Therefore, when σ_{H1} is obtained, the 2D fracture interaction model established above can be used for calculation.

Fig. 8 is a 2D diagram of stress distribution along the hydraulic fracture plane on the intersection line under the action of maximum principal stress, minimum principal stress, and natural fracture DA. According to the elastic mechanic's theory [Zhao et al. 2019], σ_{H1} and σ_{v1} can be obtained by:

$$\sigma_{H1} = \frac{\sigma_v+\sigma_H}{2} + \frac{\sigma_v-\sigma_H}{2} cos2\alpha, \tag{9}$$

$$\sigma_{v1} = \frac{\sigma_v+\sigma_H}{2} - \frac{\sigma_v-\sigma_H}{2} cos2\alpha. \tag{10}$$

where σ_{H1} is the stress along the HF plane and is perpendicular to the intersection line, σ_{v1} is the stress along the HF plane and the intersecting line. Therefore, comparing with the stresses in Fig. 7, The maximum and minimum in-situ principle stresses respectively are:

$$\sigma_1 = \sigma_{H1}, \quad \sigma_3 = \sigma_h. \tag{11}$$

let σ_H, σ_H and σ_h be 16, 10, and 6 MPa, respectively. The stress difference (Fig. 9) as a function of DA can be calculated using Eq. (11). Note that the DA has a significant influence on the stress difference. With the decrease in the DA, the stress difference increases accordingly. This is because as the dip angle decreases, the horizontal maximum stress gradually approaches the vertical stress (see Fig. 7).

3.3.4 Intersection behaviors

In our experiments, the intersections between newly-created HFs and original NFs were found only in four samples, i.e., 25–2, 33–2, 26, and 28. With the established model (Eq. (11)), Table 4 gives the detailed results of various intersections between HFs and NFs.

Mechanical strength tests of Kong shale show that the average value of tensile stress of rock, T_0, is 3.0 MPa, cohesion strength is 1.5 MPa, and the coefficient of friction, K_f, is 0.6, and the average treatment overpressure is 2.0 MPa. Combining the slippage, opening, and crossing criteria expressed in Eqs. (5), (7), and (8), a mapping can be created to mathematically predict the interaction behaviors with a module of computer codes. As a result, the corresponding critical slippage, opening, and crossing curves can be drawn on an angle-stress coordinate system as delineated in Fig. 10, which is also confirmed by our experimental results (dots and stars) to some extent.

Fig. 10 illustrates the intersection behaviors (e.g., slippage, opening, and crossing) between HFs and NFs for both intersection angle and in-situ stress, which may be subjective to the mechanical parameters of Kong shale though. The slippage, opening, and crossing curves are calculated according to Eqs. (5), (7), and (8), respectively. The shear (see blue dots in Fig. 10) and penetration (see the red stars in Fig. 10) of NFs in our experiments (see Table 4) agree well with our calculated results. Moreover, the intersection behaviors can be divided into six possible zones (represented by different colors in Fig. 10).

(1) Crossing zone: HFs directly penetrate NFs.

(2) Slippage and opening zone: Shear slippage and opening occurred in NFs and HFs could be extended along with NFs.

(3) Opening zone: NFs are opened wider and HFs can be extended along with NFs.

(4) Slippage zone: Shear slippage occurs in NFs, and HFs can spread along with NFs.

(5) Slippage and crossing zone: Upon the impact of hydraulic fracture tip stress and far-field in-situ stress, HFs can expand and cut through NFs. After the fluid enters NFs, shear slippage can occur in NFs.

(6) Arrested zone: No slippage or opening occurs in NFs, besides HFs cannot cut through NFs.

For the Kong shale oil reservoir, therefore, three predictions can be made: (a) if the intersection angle ranges from 0° to 4°, NFs might open up; (b) if the intersection angle is between 4° and 56°, shear slippage might occur; (c) if the intersection angle is greater than 56°, HFs likely cut through NFs.

5 Conclusions

(1) Hydraulic fracturing experiments on underground shale rock samples were conducted in a true triaxial fracturing system and examined visually and analytically before and after testing. The 3D images of the original samples before hydraulic fracturing shows that NFs can occur at different angles and dips.

(2) NFs and stresses are two controlling factors for fracture propagation. If NFs are not connected to a wellbore, fracturing can create HFs, which are determined by stress that further forces the new HFs to propagate along the direction of maximum horizontal stress. If the extended fracture intersects NFs, the intersection behaviors are then dictated by both stress difference and the morphology of NFs. If NFs are connected to or very close to a wellbore, HFs can be hardly generated, and HFs can expand only along with NFs even though HFs do occur.

(3) The intersection angle, DA, and stress difference are the key factors to intersection behaviors between hydraulic and NFs. If the intersection angle is small, the DA is large, and the stress differences are low, the resultant HFs tend to spread along with NFs. If the intersection angle is large, the DA is small, and the horizontal stress difference is high, the created HFs more likely to penetrate NFs.

(4) If an intersection between hydraulic and NFs occurs, the hydraulic fracture can force the natural fracture to open up wider, leading NFs to slip and even to be captured by HFs. According to the opening

boundary, slippage boundary, and crossing boundary curves calculated from our models, the intersecting behaviors can be divided into six zones: crossing zone, slippage and opening zone, opening zone, slippage and crossing zone, slippage zone and arrested zone, which can be employed as a tool to characterize shale reservoirs effectively.

Founding

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Compliance with Ethical Standards

Conflict of interest: The authors declare that there is no conflict of interest.

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