



# Study on the Characteristics of Fracturing Fracture Propagation and Turning in Carbonate Dry Hot Rock

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**Abstract.** Thermal reservoir stimulation is a necessary means to achieve effective development of dry hot rocks. Carbonate rock is a typical type of dry hot rock reservoir, it has strong heterogeneity and natural fractures and holes. Fracturing and controlling of hydraulic fracture propagation path is necessary to effective development of Carbonate rockd reservoir. At present, there was relatively little research on the propagation law of directional fracturing fractures in carbonate rocks. In response to the above issues, based on the analysis of the pore characteristics of carbonate rock salt reservoirs in a certain geothermal field, a method for preparing samples with vuggy characteristics was established. The true triaxial hydraulic fracturing physical test was used to study the interference characteristics between the propagation path of hydraulic fracturing fracture and the vuggy under different in-situ stress differences. The propagation path of fracturing fracture was quantitatively studied by using the extended finite element method. The results show that: 1. Under low horizontal in-situ stress difference ( $K \leq 0.15$ ), the hydraulic fracturing fracture will expand non-plane when encountering the hole, the smaller the horizontal geo-stress difference is, the larger the turning distance is, and the more complex the fracture morphology is. 2. Under medium horizontal in-situ stress difference ( $0.15 < K < 0.36$ ), the horizontal geo-stress difference will overcome the stress concentration of the vuggy and carry on the plane expansion, but it will be caught by the hole after encountering the hole,

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and cannot continue to expand. 3. Under high horizontal in-situ stress difference ( $K \geq 0.36$ ), the horizontal in-situ stress difference will overcome the stress concentration of the vuggy and carry on the plane expansion, and will directly pass through the vuggy and continue to expand after encountering the hole. 4. With the increase of horizontal in-situ stress difference, the fracture pressure corresponding to hydraulic fracture decreases gradually. The related research results can be used in optimization design of carbonate dry hot rock thermal storage fracturing process.

**Keywords:** Dry hot rock · Carbonate rock · Geo-stress difference · Hydraulic fracturing · Fracture propagation · Fracture turing

## 1 Introduction

Geothermal resources are rich in China, which can be divided into hydrothermal geothermal and dry thermal geothermal resources. Dry thermal geothermal resources, namely dry hot rocks, mainly include carbonate rocks and granite, which generally require thermal reservoir stimulation to have commercial development value. The characteristics of carbonate reservoirs, such as deep burial, ultra-high temperature, ultra-high pressure, strong heterogeneity, and the development of pores and fractures, make it difficult to stimulate thermal reservoirs. Due to the presence of natural fractures, pore bodies, and the combination of natural fractures and pore bodies to form a fracture cavity system, it could cause changes in the stress field near the pore body, thereby affecting the propagation mode and path of hydraulic fractures. Therefore, it was necessary to conduct research on the mechanism of fracture propagation in carbonate rocks with pore characteristics, in order to provide technical support for the economic and efficient development of carbonate dry hot rocks.

At present, scholars have conducted extensive research on the mechanism of hydraulic fracture initiation and propagation in tight reservoirs [1–17]. Due to the presence of pores and natural fractures in carbonate reservoirs, the expansion of hydraulic fractures generated by fracturing during reservoir stimulation was very complex and might not necessarily extend along predetermined paths, making it difficult to achieve the goal of full reconstruction. In this paper, a simulation method of directional fracture propagation in carbonate rocks with pores was established through physical simulation experiments, and the mechanism of horizontal crustal stress difference on fracture propagation path under different pore body characteristics was studied with numerical methods, so as to clarify the influence of the existence of pores on the fracturing fracture initiation and propagation of reservoirs.

## 2 Sample Preparation and Experimental Methods

### 2.1 Sample Preparation

Due to the difficulty in obtaining natural outcrops of carbonate rocks, even if natural outcrops were obtained, it was difficult to identify and evaluate the distribution of natural fractures and pore systems within large-sized samples. Therefore, artificial carbonate

rock simulation samples with pore characteristics were used to conduct hydraulic fracturing experiments. Combined with the physical parameters and geological characteristics of fracture cavity carbonate rock, PC52.5R composite Portland cement was selected, and the sand was 70 mesh quartz sand. By comparing the uniaxial compressive strength and tensile strength of cement samples with different proportions, it was obtained that when the mass ratio of cement to quartz sand was 1:1, the artificial sample had the highest compressive strength and tensile strength. The average uniaxial compressive strength reach 64.07 MPa, the average elastic modulus was 15.40 GPa, and the tensile strength was 5.08 MPa. 300 mm × 300 mm × 300 mm artificial sample with pore characteristics using this ratio was prepared and used for conducting directional fracturing experiments on pore type samples. By marking the position of the mold, place the eggshell in the middle of the maximum horizontal principal stress direction on both sides of the prefabricated wellbore, and ensure that the center of the egg was located in the center plane of the cube specimen. The pouring method was a one-time overall pouring, as shown in Fig. 1.

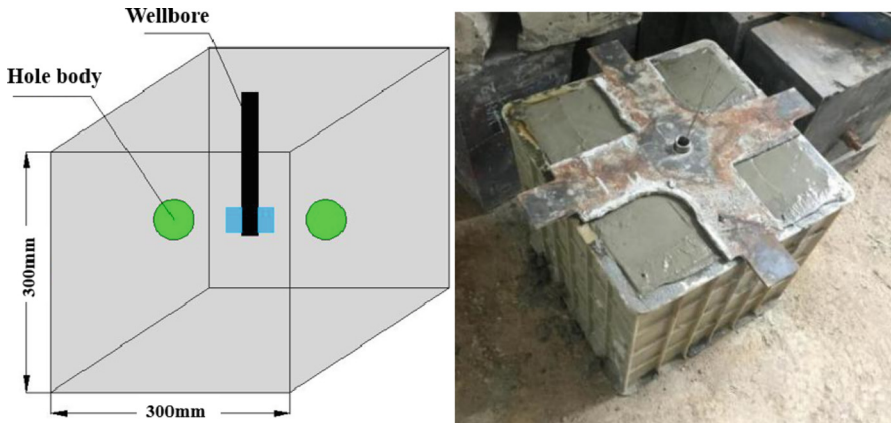


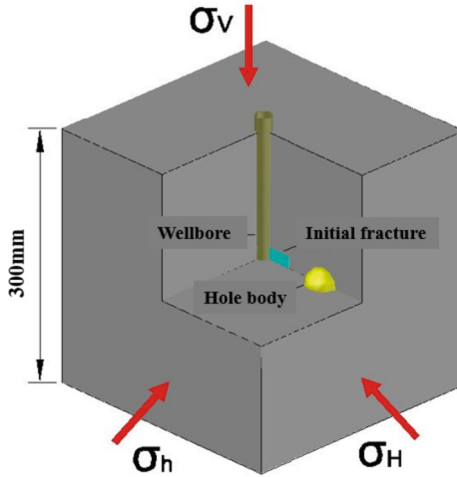
Fig. 1. Preparation of sample with hole

## 2.2 Experimental Methods

In order to study the influence of horizontal crustal stress difference on the propagation path of fracture in porous carbonate rocks, artificial samples with fixed pore size were prefabricated with eggs. Combined with the actual situation of crustal stress in carbonate reservoir in Shunbei area, the triaxial stress value of indoor fracturing experiment is set, and on this basis, the difference coefficient of crustal stress is changed. The experimental parameters are shown in Table 1, the three-dimensional crustal stress loading is shown in Fig. 2, and the viscosity of fracturing fluid is 50 mPa. s.

**Table 1.** Fracturing test parameters of carbonate rock

Sample Number	Coefficient of crustal stress difference/k	$\sigma_v/\sigma_H/\sigma_h$ (MPa)	Q (mL/min)
D1	0.36	18/15/11	5
D2	0.25	18/15/12	5
D3	0.15	18/15/13	5
D4	0.07	18/15/14	5

**Fig. 2.** Hole distribution and crustal stress loading direction

### 3 Analysis of Hydraulic Fracturing Experimental Results

#### 3.1 Analysis of Pump Pressure Curve Characteristics

The pump pressure time curve of fracture propagation under different stress difference coefficients was shown in Fig. 3. The pump pressure curve corresponding to sample D1 showed two peaks, indicating that the sample ruptured at the first peak pressure, but did not form a through channel. Then the pump pressure fell down, as the fracturing fluid was pumped, the pump pressure curve rose to a second pump pressure high point, but was lower than the first peak. After the second peak fell, the pump pressure remained at a relatively stable value, the pump pressure mainly overcame the applied three-dimensional crustal stress, and the penetration channel had been formed. The pump pressure curve of sample D2 showed only one peak, indicating that when the pump pressure reached the peak rupture pressure for the first time, the fracture formed a penetrating channel. Due to the existence of confining pressure, the pump pressure remained at a relatively stable value. The pump pressure curves of samples D3 and D4 both exhibit multiple peaks. The fracture initiation and propagation occur during the first peak pressure, followed by multiple drop rise processes in the pump pressure curve, indicating that the hydraulic

fracture was continuously expanding and opening new crack channels. Moreover, the time range of the pump pressure curve corresponding to sample D4's reverse drop rise was greater than that of sample D3. The comparison of sample rupture pressure under different crustal stress difference conditions was shown in Fig. 4. As the minimum horizontal crustal stress decreased, the horizontal stress difference increased, and the corresponding rupture pressure of the sample gradually decreased.

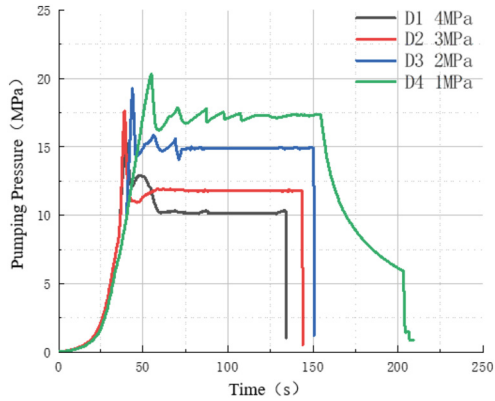


Fig. 3. Pressure-time curve of fracture extension under different crustal stress difference

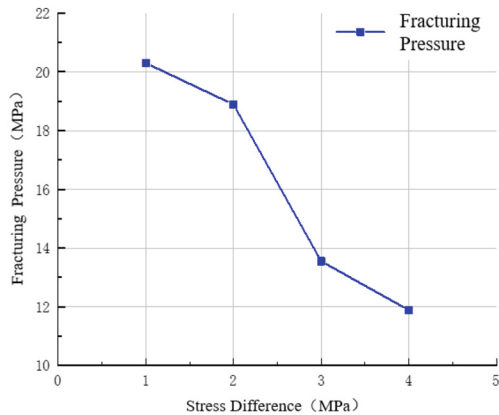


Fig. 4. Comparison of fracturing pressure of specimens under different crustal stress difference

### 3.2 Morphological Characteristics of Carbonate Rock Fractures

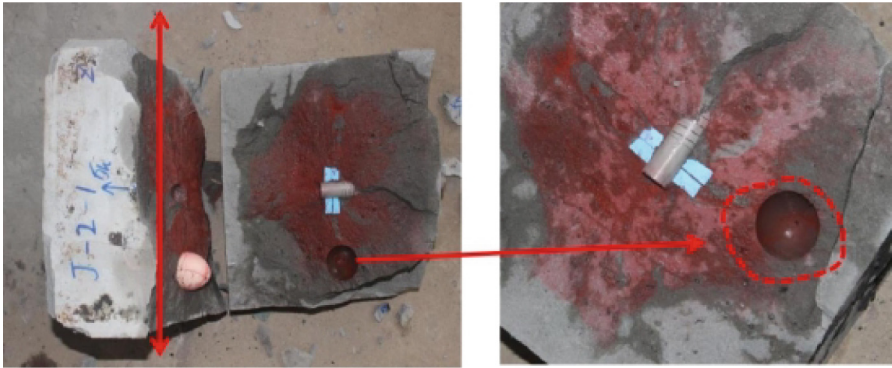
The fracture morphology of sample D1 was shown in Fig. 5(a). The hydraulic fracture expanded along the direction of the maximum horizontal principal stress. After encountering the hole, it directly passed through and continued to extend along the original

expansion direction. The fracture did not turn, thus forming a fracture surface perpendicular to the minimum horizontal crustal stress. The fracture morphology of sample D2 was shown in Fig. 5(b). The hydraulic fractures expanded along the direction of the maximum horizontal principal stress, and the propagation path of the hydraulic fractures near the hole remained unchanged. From the distribution range of tracer on the surface of the fracture, it could be seen that there was no tracer distribution on the right side of the hole, indicating that the hydraulic fractures extended along the maximum horizontal principal stress to the boundary of the hole body, and then stopped expanding due to the presence of the hole body, and a fracture surface perpendicular to the horizontal minimum crustal stress was formed. The fracture morphology of samples D3 and D4 were shown in Figs. 5(c) and (d). There was no red tracer around the D3 hole, but the existence of the hole body could be observed, indicating that when the fracture extended near the hole, it turned in the direction of the minimum principal stress but the deflection distance was not large. The left half of the fracture surface of sample D4 was completely stained with red tracer, and the presence of the pore body could not be observed, indicating that the hydraulic fracture underwent a turning when it extended near the pore, and the propagation path completely bypassed the pore body. It could be observed that the fracture turning effect of sample D4 was more obvious than that of sample D3, and the position where the fracture started turning was closer to the wellbore position.

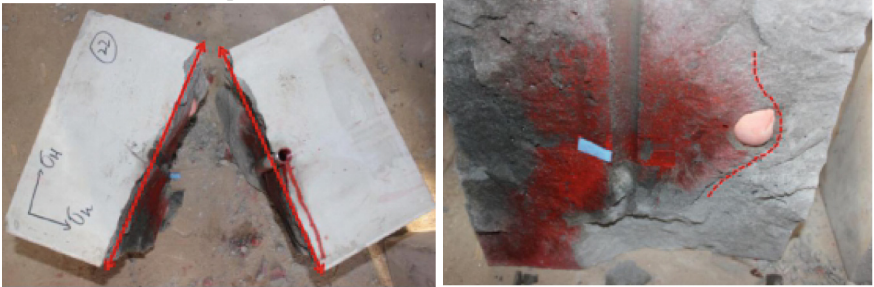
### 3.3 The Influence of Horizontal Crustal Stress Difference on Hydraulic Fracture Propagation

The fracture morphology under different crustal stress differences in the hydraulic directional fracturing experiment was summarized in Fig. 6. When the crustal stress difference coefficient  $k = 0.07$ , the existence of the hole body changed the dominant position of the horizontal crustal stress difference on the fracture propagation. When the crustal stress difference coefficient  $k = 0.15$ , the horizontal crustal stress difference played a leading role in the propagation path of the hydraulic fracture. Because the stress concentration generated by the hole body could not change the dominant position of the crustal stress difference on the fracture propagation, the hydraulic fracture expanded along the direction of the maximum horizontal principal stress, forming a complete fracture surface perpendicular to the horizontal minimum crustal stress, but the interaction between the hole body and the fracture was different under different conditions. When the crustal stress difference coefficient  $k = 0.25$ , if the hydraulic fracture extended to the boundary of the hole body, it would be caught by the existing hole body and would not continue to expand along the original path. When the crustal stress difference coefficient  $k = 0.36$ , if the hydraulic fracture extended to the hole body, it would pass through the hole and continued to expand forward. Within the range of stress difference here, the smaller the difference of crustal stress was, the more obvious the repulsion of the hole body to the fracture was, the easier the hydraulic fracture turned, the larger the corresponding turning radius was, and the hydraulic fracture would continue to expand around the hole body.

The interaction between hydraulic fracture propagation process and natural pores in the direction of maximum horizontal principal stress could be simplified as three interaction modes shown in Fig. 7.



(a) Sample D1: Hydraulic fracture passing through the hole



(b) Sample D2: Hydraulic fracture captured by the hole

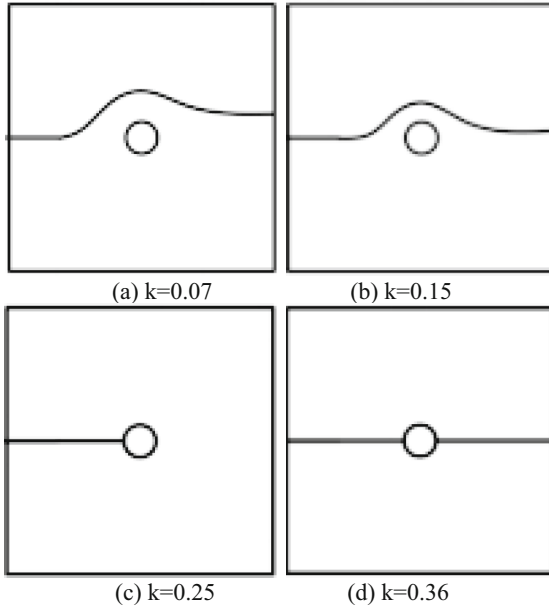


(c) Sample D3: Hydraulic fracture turn when encountering the hole

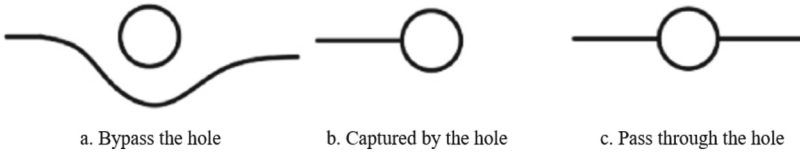


(d) Sample D4: Hydraulic fracture turn when encountering the hole

**Fig. 5.** Fracture morphology characteristics under different crustal stress differences



**Fig. 6.** Diagram of fracture morphology under different crustal stress differences



**Fig. 7.** Three interaction modes of fracture and hole

According to the directional fracturing experiment analysis of samples with prefabricated holes under different horizontal crustal stress, the influence of horizontal crustal stress difference on fracture propagation was as follows.

1. When the crustal stress difference was low( $k \leq 0.15$ ), hydraulic fractures would produce non-planar expansion when encountering holes, and the smaller the horizontal crustal stress difference was, the larger the turning radius was, and the more complex the fracturing fracture morphology was.
2. When the crustal stress difference was medium( $0.15 < k < 0.36$ ), the horizontal crustal stress difference would overcome the stress concentration of the hole body and form a plane expansion main fracture. Under experimental conditions, the main fracture would be caught by the hole body after encountering it, and could not continue to expand through the hole body.
3. When the crustal stress difference was high ( $k \geq 0.36$ ), the horizontal crustal stress difference would overcome the stress concentration and generate plane expansion, and the main fracture would continue to expand through the hole body directly after



encountering it on the expansion path. With the increase of horizontal crustal stress difference, the fracture pressure gradually decreased.

## 4 Numerical Simulation Analysis of Hole Type Directional Fracturing

The horizontal crustal stress difference had an obvious impact on the fracture propagation path. Since the true triaxial fracturing physical model experiment cannot simulate the fracture propagation characteristics on a larger scale, the numerical simulation method was used to analyze the propagation pattern of hydraulic fractures after encountering the hole body under different horizontal crustal stress differences. At present, hydraulic fracturing expansion simulation mostly used finite element method [17], which converted a solid model into a series of interconnected small elements through discrete method. In this paper, the fluid solid coupling analysis model of hydraulic fracturing was established by using the extended finite element method to simulate the influence of different crustal stress states and hole distribution characteristics of porous carbonate rocks on the propagation path of hydraulic fractures.

Using extended finite element method for hydraulic fracturing simulation did not require setting the fracture propagation path in advance. Instead, the initial fractures should be prefabricated on the established model, and then liquid injection points should be set inside the grid nodes. The size of a single hole model was  $40\text{ m} \times 40\text{ m}$ , the grid size was set to  $0.3\text{ m}$ , and the initial fracture length was  $2\text{ m}$ . It was perpendicular to the left boundary of the model and deviated  $0.4\text{ m}$  from the center of the model. The injection point was between the grid nodes. The model boundaries were all constrained by displacement and were permeable boundary conditions.

### 4.1 The Influence of Horizontal Crustal Stress Difference on Hydraulic Fracture Propagation

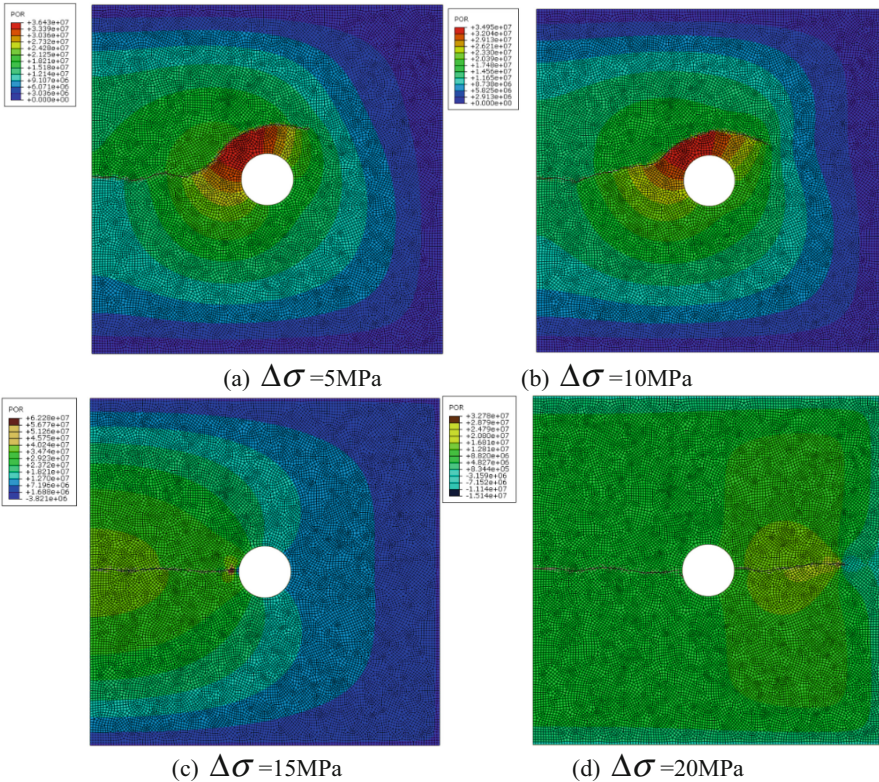
The setting of crustal stress parameters was shown in Table 2. The hole radius was  $3\text{ m}$ , the fracturing fluid viscosity was  $50\text{ mPa}\cdot\text{s}$ , the injection displacement was  $5\text{ m}^3/\text{min}$ , and the reservoir pressure coefficient was  $1.8\text{ MPa}/100\text{ m}$ . The simulation results were shown in Fig. 8.

By comparing the hydraulic fracture propagation paths under different horizontal crustal stress differences, it could be seen that the smaller the horizontal crustal stress difference was, the greater the displacement distance of hydraulic fracture propagation path was, and the more obvious the effect of stress concentration generated by the hole body on the hydraulic fracture propagation path was. On the contrary, the greater the difference of horizontal crustal stress, the more difficult it was to deviate from the direction of maximum horizontal principal stress. When the crustal stress difference was greater than  $15\text{ MPa}$ , that was, when the crustal stress difference coefficient  $k$  was greater than  $0.25$ , the hydraulic fracture did not deflect during its propagation, and it continued to expand along the direction of the maximum horizontal principal stress until it communicated with the hole body. Therefore, when only holes exist, the greater the difference of horizontal crustal stress, that was, the greater the difference coefficient of

**Table 2.** Parameter setting of crustal stress in numerical simulation

No	Maximum horizontal principal stress/MPa	Minimum horizontal principal stress/MPa	Horizontal stress difference/MPa	Poisson's ratio	Elastic modulus/GPa	Biot coefficient
1	75	70	5	0.19	38.54	0.87
2		65	10			
3		60	15			
4		55	20			

horizontal crustal stress, the stronger the ability to overcome the stress concentration of the hole body, and the easier the fracture was to communicate with the hole body in the direction of the maximum horizontal principal stress.

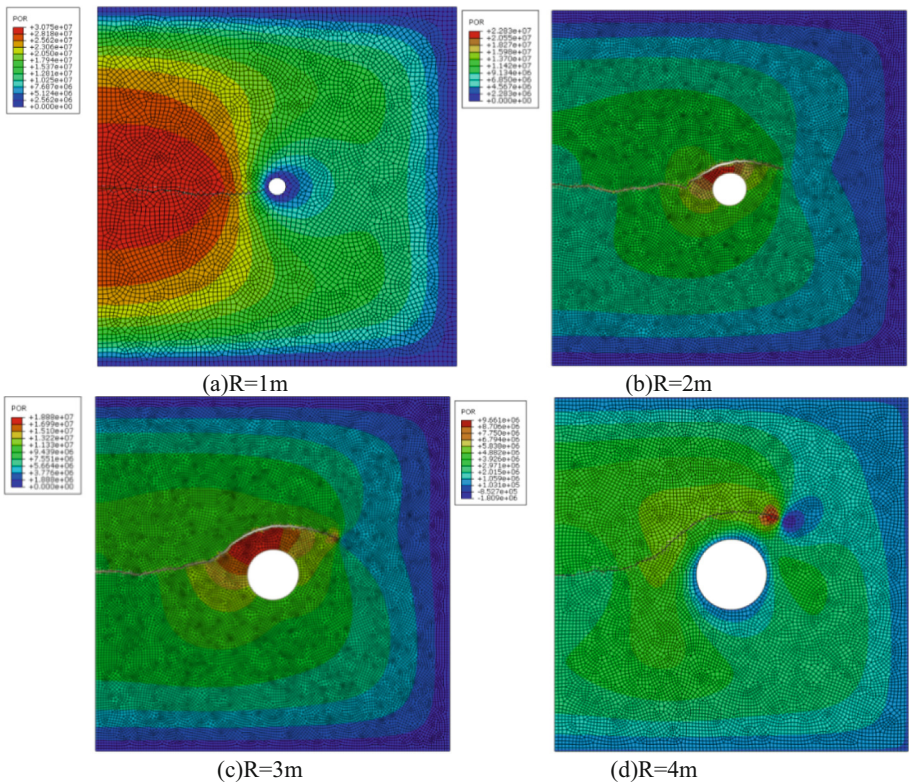


**Fig. 8.** Simulation effect diagram of corresponding fracture propagation under different crustal stress differences

## 4.2 The Influence of Pore Size on Hydraulic Fracture Propagation

The morphology and size of pores in carbonate reservoirs vary, which affect the expansion of hydraulic fractures. Set the angle between the initial fracture and the maximum horizontal principal stress direction to  $0^\circ$ , set the radius of the hole to 1 m, 2 m, 3 m, and 4 m, and set the pressure inside the hole to 50 MPa. The maximum horizontal principal stress was 75 MPa, and the minimum horizontal principal stress was 65 MPa. The distribution of fracture propagation stress was shown in Fig. 9. The simulation results indicated that there was significant stress concentration around the pore body, and as the pore size increased, the stress concentration area gradually increased, and the influence range on hydraulic fracture propagation also gradually increased. At the same time, it was observed that the direction of stress concentration for the same stress component tended to be consistent.

The propagation path of hydraulic fractures under different pore sizes was shown in Fig. 10. Except for the fracture trajectory did not deflect when the pore body  $R = 1$  m, fracture propagation underwent varying degrees of deflection under other conditions. When the size of the hole was small, the range of stress concentration generated by the hole was small, which had a smaller impact on the propagation path of hydraulic



**Fig. 9.** Fracture propagation characteristics corresponding to different pore sizes

cracks, resulting in a smaller deflection distance of hydraulic fractures along the y-axis. When the size of the hole was large, the stress concentration range generated by the hole increased, which had a greater impact on the propagation path of hydraulic fractures, the time for hydraulic fractures to deflect was advanced, and the distance of deflection in the y-axis direction increased. When the size of the hole was very small, such as  $R = 1$  m, the stress concentration phenomenon generated by the hole was not enough to overcome the influence of the difference in horizontal crustal stress, and the fracture propagation trajectory did not deflect, and it extended directly along the direction of the maximum horizontal principal stress until it communicated with the hole.

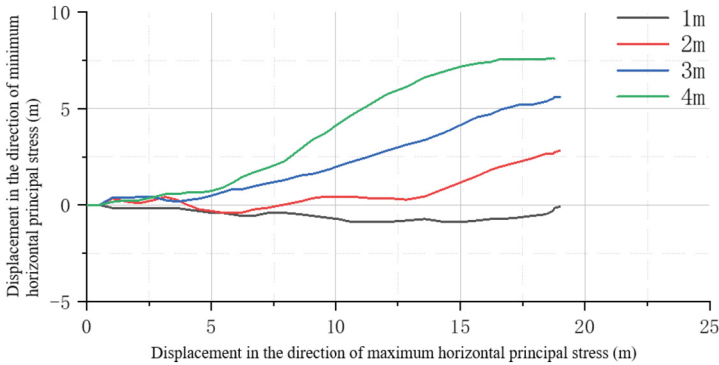


Fig. 10. Fracture propagation paths corresponding to different pore sizes

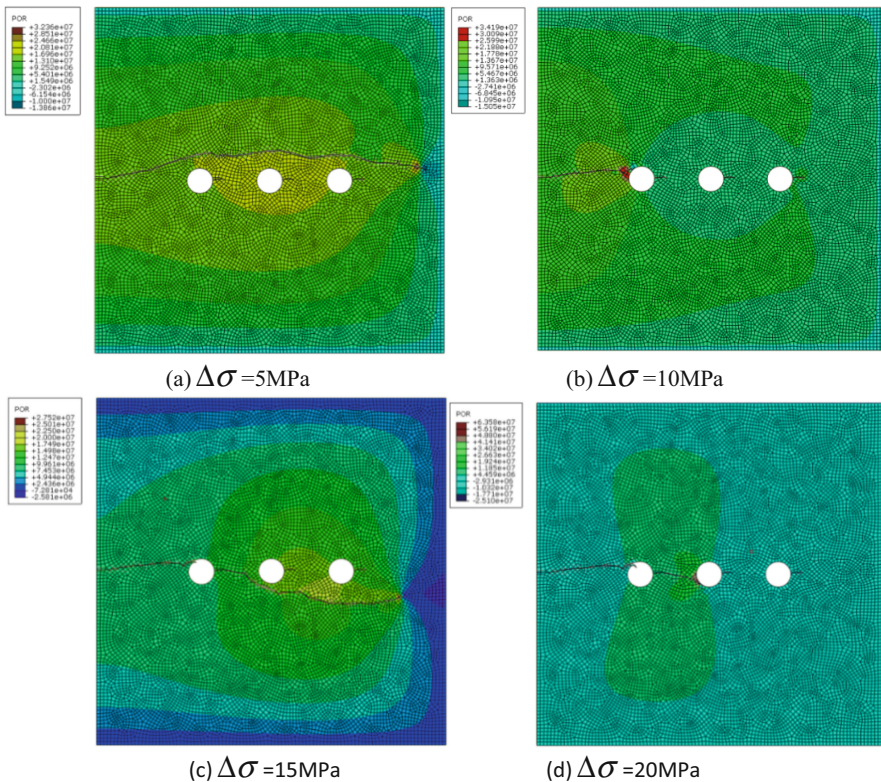
### 4.3 The Influence of Continuous Voids on Hydraulic Fracture Propagation

In actual carbonate reservoir, there were many holes continuously distributed. According to the simulation results of a single hole body, the hole size and the difference of horizontal crustal stress would affect the interaction mode between fractures and holes. When the hole body size was small or the difference of horizontal crustal stress was large, hydraulic fractures would be caught by the hole body or directly passed through the hole body. Horizontal crustal stress difference, as the main controlling factor of hydraulic fracture propagation, was also the primary influencing factor considered under the condition of continuous hole body distribution.

Established a continuous distribution model of holes. Crustal stress values were shown in Table 2. The hole radius was set to 1.5 m. The simulation results were shown in Fig. 11. By comparing the interaction between fractures and continuous holes under different crustal stress differences, it could be observed that the horizontal crustal stress difference was still the main controlling factor for fracture propagation. The smaller the difference of horizontal crustal stress ( $\Delta\sigma = 5$  MPa), the easier it was for the hydraulic fracture propagation deflect to the y-axis. The stress concentration area generated by a continuous cavity was also continuously distributed, so the fracture would continue to expand along the boundary of the stress concentration area after the first cavity was repelled and turned. With the increase of horizontal crustal stress difference, it could

overcome the stress concentration generated by the first hole. Hydraulic fractures and the first hole would have two interaction modes: trapped by the hole ( $\Delta\sigma = 10$  MPa) and passed through the hole ( $\Delta\sigma = 15$  MPa). The hydraulic fracture passing through the hole continued to expand along the direction of the maximum horizontal principal stress and entered the stress concentration area generated by the second hole. The interaction between the hydraulic fracture and the second hole also changed with the change of stress difference. There were three cases in total: bypassing the hole ( $\Delta\sigma = 15$  MPa), being trapped by the hole ( $\Delta\sigma = 20$  MPa), and passing through the hole ( $\Delta\sigma > 20$  MPa).

Due to the energy consumption when the hydraulic fracture passed through the hole body, under the same horizontal crustal stress difference, the fracture might not pass through the second hole after passing through the first hole. The distribution of continuous pores increased the influence area of stress concentration, and further multi factor analysis was needed to communicate the continuous pores.



**Fig. 11.** Fracture propagation characteristic diagram with continuous cavity distribution

## 5 Conclusion

Through the true triaxial hydraulic fracturing physical simulation experiment and numerical simulation research on the carbonate rock samples with simulation holes, the influence of horizontal crustal stress difference on the propagation path of artificial fractures with different hole characteristics was clarified. The main conclusions were as follows.

1. The existence of pore bodies directly affected the propagation morphology and path of main fracture. Under the condition of low horizontal crustal stress difference ( $k \leq 0.15$ ), the hydraulic fracture would expand non planar after encountering the hole body, and the smaller the horizontal crustal stress difference was, the greater the turning distance was, and the more complex the fracture morphology was after fracturing.
2. Under the condition of medium horizontal crustal stress difference ( $0.15 < k < 0.36$ ), the horizontal crustal stress difference would overcome the influence of stress concentration in the hole body to form a plane propagation hydraulic fracture, but it would be caught by the hole body after encountering it, and could not continue to expand through the hole body.
3. Under the condition of high horizontal crustal stress difference ( $k \geq 0.36$ ), the horizontal crustal stress difference would overcome the stress concentration of the hole body and expanded along the plane, and would directly pass through the hole body and continued to expand along the original path after encountering it. With the increase of horizontal crustal stress difference coefficient, the fracturing pressure corresponding to hydraulic fractures gradually decreased.
4. Affected by crustal stress conditions, hole body characteristics, etc., the artificial fracture expansion in carbonate reservoir was very complex. We can refer to the research ideas in this paper to further explore the fracture expansion law in carbonate reservoir under the conditions of different crustal stress characteristics, irregular holes, different acid fracturing construction parameters, etc., to provide a basis for dry hot rock fracturing design scheme, and provide a theoretical basis for achieving efficient development of dry hot rock.

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