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Research Article

Keywords: Deep drilling, Borehole wall stability, Thermo-Hydro-Mechanical coupling, Discrete element method, Fracture evolution mechanism

Posted Date: August 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10249335/v1>

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Additional Declarations: No competing interests reported.

Fracture development mechanism of borehole walls in deep drilling

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Acknowledgements

This research is partially supported by the National Natural Science Foundation of China (Grant No. 52104112), the Natural Science Foundation of Hunan Province, China Grant No. (2025JJ20030), and the Science and Technology Program of Changsha of China (Grant No. kh2401026).

Abstract: Deep drilling is essential for accessing deep Earth resources and data, but its development is constrained by borehole wall instability and core fracturing, with the key scientific challenge being the mechanism of fracture evolution. Using granite as a representative case, this study integrates the discrete element method (DEM), thermo–hydro–mechanical (THM) coupling theory, laboratory tests, and elastic analysis to investigate fracture development under high temperature, high in-situ stress, and drilling fluid column pressure. The main findings are as follows: (1) Thermal damage-induced fractures in granite primarily originate from the differential thermal expansion between quartz and plagioclase grain boundaries, with elevated temperature significantly accelerating fracture propagation; (2) Horizontal in-situ stress predominantly governs the secondary development of shear fractures, which are most densely distributed in the direction of the minimum horizontal principal stress; (3) Drilling fluid column pressure markedly influences fracture morphology—when lower than the in-situ stress, fractures are predominantly circumferential with a “V”-shaped profile, whereas when higher than the in-situ stress, they tend to extend radially. This study provides an important theoretical basis for borehole wall stability evaluation and the optimization of drilling fluid loss prevention and plugging technologies in deep drilling.

Key words: Deep drilling; Borehole wall stability; Thermo-Hydro-Mechanical coupling; Discrete element method; Fracture evolution mechanism

1 Introduction

The increasing demand for mineral resources, underground space utilization, and energy development has intensified the need for exploration, drilling, and resource extraction in deep geological formations (Xie et al., 2015). As the primary technical means for deep resource exploitation, the safety and stability of deep drilling directly determine the feasibility and economic benefits of engineering projects. However, under complex conditions involving high temperature, large in situ stress, and great pore water pressure, deep drilling operations are frequently affected by borehole wall instability issues such as collapse, lost circulation, and borehole enlargement, which are closely related to the rapid development and heterogeneous evolution of fractures (He et al., 2005; Xie et al., 2015). This problem is particularly evident in crystalline formations such as granite, where thermo-hydro-mechanical (THM) coupling significantly accelerates fracture propagation and structural failure

(Wang et al., 2019), ultimately inducing borehole wall instability. Therefore, it is essential to systematically investigate the mechanisms that govern fracture initiation and evolution in deep crystalline formations, and to elucidate their influences on borehole stability. Such work has substantial theoretical significance and practical value for enhancing drilling safety and optimizing borehole design and reinforcement strategies in deep drilling.

Over the past decades, with a focus on the mechanical properties of rocks and borehole wall stability mechanisms in deep drilling environments, numerous studies have been conducted on granite, including theoretical analyses, experimental investigations, and numerical simulations. In terms of theoretical analysis, Westergaard (1939) applied a mechanical model to analyze the plastic state of surrounding rock mass in borehole wall stability studies. Subsequently, Bradley (1979) extended the borehole stress calculation methods based on Fairhurst (1964)'s work. Aadnoy et al. (1987) and Guz (2003) established borehole mechanical models based on the elastoplastic theory and analyzed borehole instability through stress field assessment. Yew et al. (1992) employed the Drucker-Prager criterion along with Mohr-Coulomb failure envelopes derived from experiments to determine the critical conditions for borehole breakdown pressure and proposed methods to enhance the stability of extended-reach boreholes. Jin et al. (1999) converted the in-situ principal stresses to the borehole coordinate system by a two-step rotation involving the azimuthal difference β and borehole inclination α , and then expressed the transformed stresses in cylindrical coordinates for wellbore stress and stability analysis. Based on statistical analyses of borehole breakout orientations, some researchers hypothesized that the breakout direction generally aligns with the minimum horizontal principal stress (Carr, 1974; Bell and Gough, 1983), which was validated in subsequent simulated drilling experiments (Mastin, 1984; Haimson and Herrick, 1986). Under large in situ stress conditions, borehole walls tend to fail in tension along the minimum principal stress direction, forming “dog-ear” or “spiral” fracture patterns (Lee and Haimson, 1993; Song, 1998; Meier et al., 2013).

From an experimental perspective, many researchers have systematically studied the changes in mechanical parameters and microcrack distribution patterns of granite under high temperatures, using uniaxial/triaxial compression tests, thermal treatment, Brazilian splitting, acoustic emission monitoring, and scanning electron microscopy (Liu et al., 2001; Wan et al., 2008). Results show that when the temperature exceeds 300 °C–400 °C, the compressive strength and elastic modulus of granite decrease markedly, entering a stage dominated by thermal damage (Du et al., 2004; Zhao et al., 2008a). Vishal et al. (2011) and Xu et al. (2014) independently reported that the tensile strength of granite exhibits a nonlinear relationship with temperature, showing inflection points around 100 °C and 400 °C. Numerous studies on thermal fracturing and thermal damage analyzed the mechanisms and patterns of crack formation and propagation, and concluded that the mismatch in thermal expansion coefficients among mineral grains under high temperature and pressure is the primary cause of thermal damage, predominantly leading to shear failure (Xie and Zhao, 2017). Shang et al. (1999) examined the entire process from crack initiation to coalescence using electron microscopy, and revealed the intrinsic relationship between microcrack formation and rock structural characteristics, thereby deepening the micro-mechanical understanding of thermal fracturing behavior.

Although high-temperature rock mechanics experiments provide useful insights into thermally induced rock weakening and borehole stability, they cannot continuously monitor and characterize mesoscale changes within rocks, making it difficult to fully capture the mechanisms of borehole wall failure. Consequently, research has increasingly turned to numerical simulation approaches for investigating the fracture evolution. Using the particle flow code (PFC), researchers have developed a series of models for fracture evolution in granite under high-temperature or triaxial conditions, validating the effectiveness of discrete element method (DEM) in simulating thermal fracturing (Hofmann et al., 2016; Potyondy and Cundall, 2004). Huang et al. (2000) and Tang et al. (2006) simulated thermally induced fracture propagation by assigning different thermal expansion coefficients to constituent minerals, and confirmed that mineral thermal properties have a decisive impact on fracture patterns. Zhao et al. (2018) calibrated the uniaxial compressive and tensile strengths by adjusting particle size and bond strength, and provided a methodology for aligning DEM simulations with laboratory test results. Ali et al. (2010) further investigated the thermal fracturing using PFC, and demonstrated that the particle size and thermal expansion parameters significantly influence simulation results. Wang et al. (2009) established a triaxial

loading model for granite, and revealed that fracture evolution initially proceeds via tensile failure, thereby elucidating the underlying damage mechanisms during loading.

Nevertheless, a systematic understanding of THM coupling mechanisms in deep granite environments remains insufficient, and only limited numerical studies have incorporated hydraulic coupling under such conditions. This study develops a DEM-based THM coupling numerical framework to reveal the spatial distribution and evolutionary patterns of borehole wall fractures, with the goal of predicting and mitigating instability risks during drilling.

2 Model establishment

2.1 Calibration of particle parameters and experimental comparison

To ensure that the model could accurately reproduce the actual mechanical behavior of granite, the microscopic parameters should be calibrated. Because mineral composition strongly affects the thermophysical properties of granite, the granite samples from Zhangzhou, Fujian Province, China are selected for mineralogical analysis. The mineralogical composition of the granite specimens is characterized using optical thin-section observations combined with X-ray diffraction (XRD) analysis. The specimens are composed of approximately 33% plagioclase, 25% quartz, 15% potassium feldspar, and 27% biotite and other minor accessory minerals (Fig. 1). Based on magnification calibration under the microscope, the particle size of the various mineral phases is determined to be approximately 0.3-0.5 mm, with feldspar exhibiting a wider size range, while quartz and sericite particles are comparatively smaller.

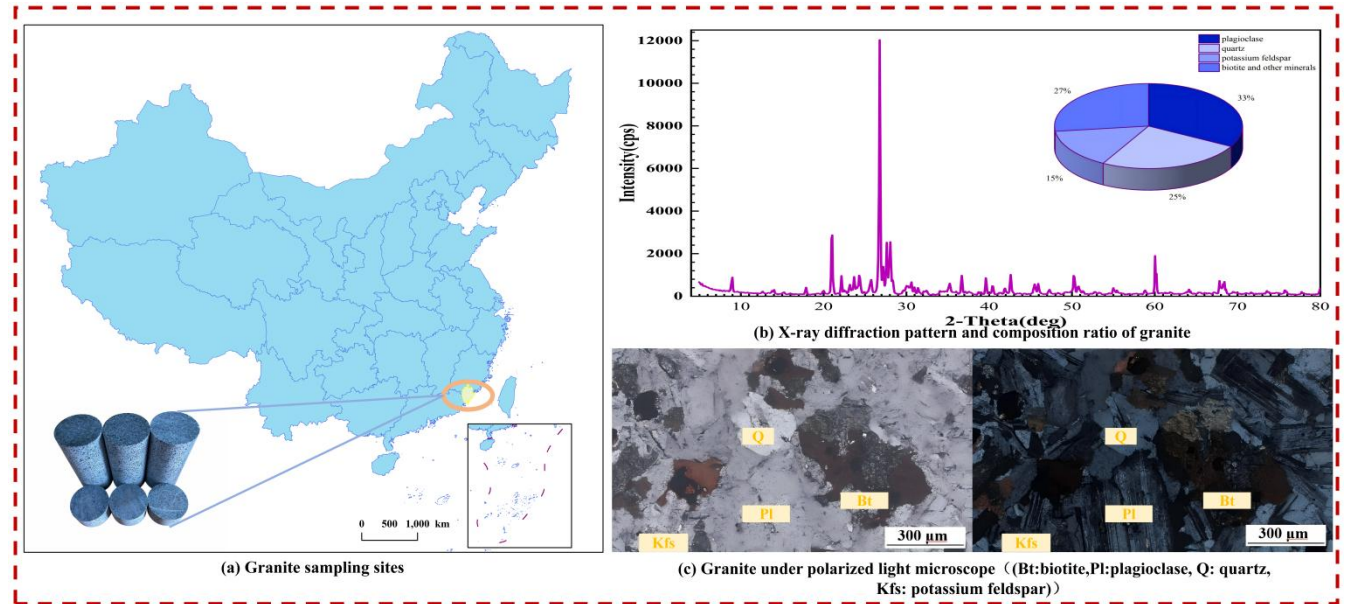


Fig. 1. Analysis of mineral composition of granite.

With reference to the typical failure patterns of granite reported in Huang et al. (2016), three specimens exhibiting a representative “X”-shaped fracture mode are selected as representative samples. The average UCS of these specimens is 91.06 MPa, and the corresponding latic modulus is 33.50 GPa. In addition, the tensile strength of three granite specimens is measured using the Brazilian splitting test, yielding an average tensile strength of 10.48 MPa.

In PFC, the construction of the DEM model involves three steps: particle assembly generation, bonded contact definition, and servo-controlled loading. The primary parameters for particle generation include porosity, particle radius, and ratio of maximum to minimum particle radius ($R_{\max}/R_{\min}$), with particles also assigned a

specified density. Based on existing experience in DEM modeling of granite (Wu et al., 2018; Zhang et al., 2026b) and parameter adjustment strategies (Guo et al., 2016), the physical parameters of the particle assembly are determined. A combination of the linear model and the linear parallel bond model is adopted. Referring to mesoscale parameters of granite obtained in previous simulation studies using PFC (Zhang et al., 2014; Tian, 2020), the initial mesoscale parameters are specified, and the servo-controlled loading system is implemented using Fish language and callback functions.

In the uniaxial compression simulation, a rectangular specimen with dimensions of $\phi 50 \text{ mm} \times 100 \text{ mm}$ is constructed. Random particle sizes are assigned, and axial displacement-controlled loading is applied. By iteratively adjusting key parameters, including the normal-to-shear stiffness ratio between particles, bond strength, and friction coefficient, the simulated stress–strain curve is aligned with experimental results in terms of peak strength, elastic modulus, and failure pattern. Subsequently, a Brazilian splitting simulation is conducted to calibrate the tensile strength. A disc model with a diameter of 50 mm is generated, with loading applied at the top and bottom to produce a lateral tensile stress field. The particle bond strength and tensile limit are adjusted until the simulated peak splitting strength matches the measured value. After extensive trial-and-error simulations and optimizations, the final calibrated model produces deviations from the laboratory data of 0.57%-3.12%, all below 5%. These results confirm the validity of the constructed DEM model in reproducing macroscopic mechanical responses (Table 1), providing a reliable mechanical foundation for subsequent simulations.

Table 1. Macroscopic mechanical parameters of the calibration model.

Macroscopic Parameter	Laboratory Test	Simulated Value	Difference
Compressive Strength	91.06 MPa	93.90 MPa	3.12%
Elastic Modulus	33.50 GPa	34.46 GPa	2.87%
Tensile Strength	10.48 MPa	10.42 MPa	0.57%

2.2 Establishment of thermal damage and borehole mechanical models

Using the calibrated parameters, a thermal damage DEM model for granite is established for thermo-mechanical coupling simulations. Subsequently, the borehole models for deep drilling are constructed using both elastic theory and DEM, and the two approaches are cross-validated.

2.2.1. Establishment of thermal damage model and verification of thermo-mechanical coupling

Following the International Society for Rock Mechanics (ISRM) recommended methodology and based on the measured mineral composition together with related studies (Xu et al., 2018; Zhang et al., 2018), the DEM model of granite is established using four major minerals, i.e. plagioclase (33%), biotite (27%), quartz (25%), and K-feldspar (15%). The calibrated mesoscale parameters are combined with mineral-specific thermal properties, including specific heat and thermal expansion coefficient (Table 2), for each particle type, according to the PFC particle-generation rules. A $100 \text{ mm} \times 100 \text{ mm}$ square particle assembly is then generated to represent the granite specimen, and the particles are classified by mineral type (Fig. 2). To further characterize fracture development during thermo-mechanical loading, a DFN-based contact fracture network is introduced to identify bond-break events and monitor the evolution of tensile and shear cracks.

Table 2. Final calibrated micromechanical parameters and mineral thermophysical parameters.

Parameter	Symbol	Unit	Value
Stiffness ratio	Kratio		2.0
Friction coefficient	Firc		0.5
Parallel-bond effective modulus	Pb_emod	GPa	31.5
Parallel-bond normal strength	Pb_ten	MPa	74
Parallel-bond shear strength	Pb_coh	MPa	105

Parallel-bond internal friction angle	Pb_fa	°	20
Specific heat capacity	c	J·kg ⁻¹ ·°C ⁻¹	1015
Thermal expansion coefficient of biotite		10 ⁻⁶ ·°C ⁻¹	3.0
Thermal expansion coefficient of quartz		10 ⁻⁶ ·°C ⁻¹	24.3
Thermal expansion coefficient of plagioclase		10 ⁻⁶ ·°C ⁻¹	14.1
Thermal expansion coefficient of K-feldspar		10 ⁻⁶ ·°C ⁻¹	8.7

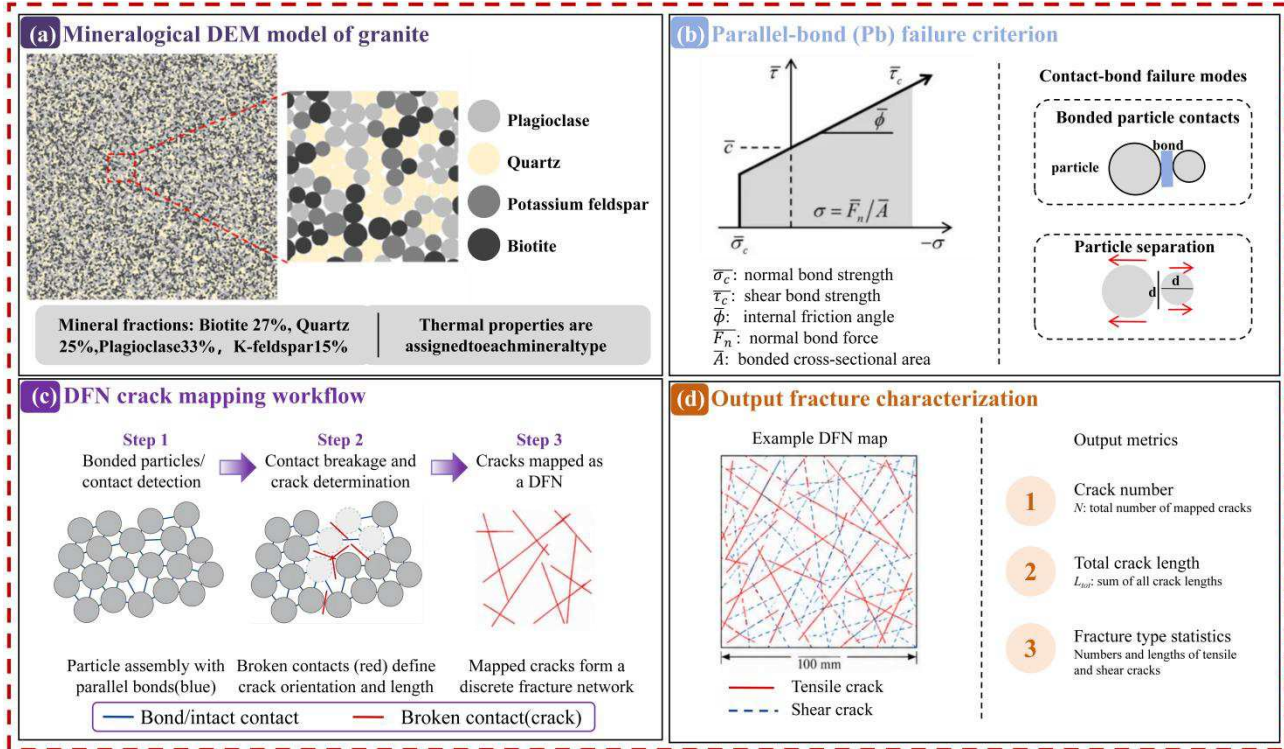


Fig. 2. Construction of the mineralogical DEM model and DFN-based fracture characterization workflow.

The `deltemp` command is used to heat the particle assembly to the specified temperature, with the initial temperature set to 25 °C, and the prescribed temperature boundary conditions are set to 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, and 600 °C, respectively. An outward-expanding temperature field configuration is adopted in the model to simulate the non-uniform temperature diffusion characteristics of natural heating processes. To capture the particle contact state during the thermal damage process, the built-in plot function in PFC is employed to generate force chain diagrams representing the distribution of contact force magnitudes, where concentrated force chains represent large variations in particle contact forces. The simulation results show that under different temperature conditions, the model predominantly develops tensile thermal damage cracks (black lines), whose distribution coincides with the locations of concentrated force chains, as illustrated in Fig. 3.

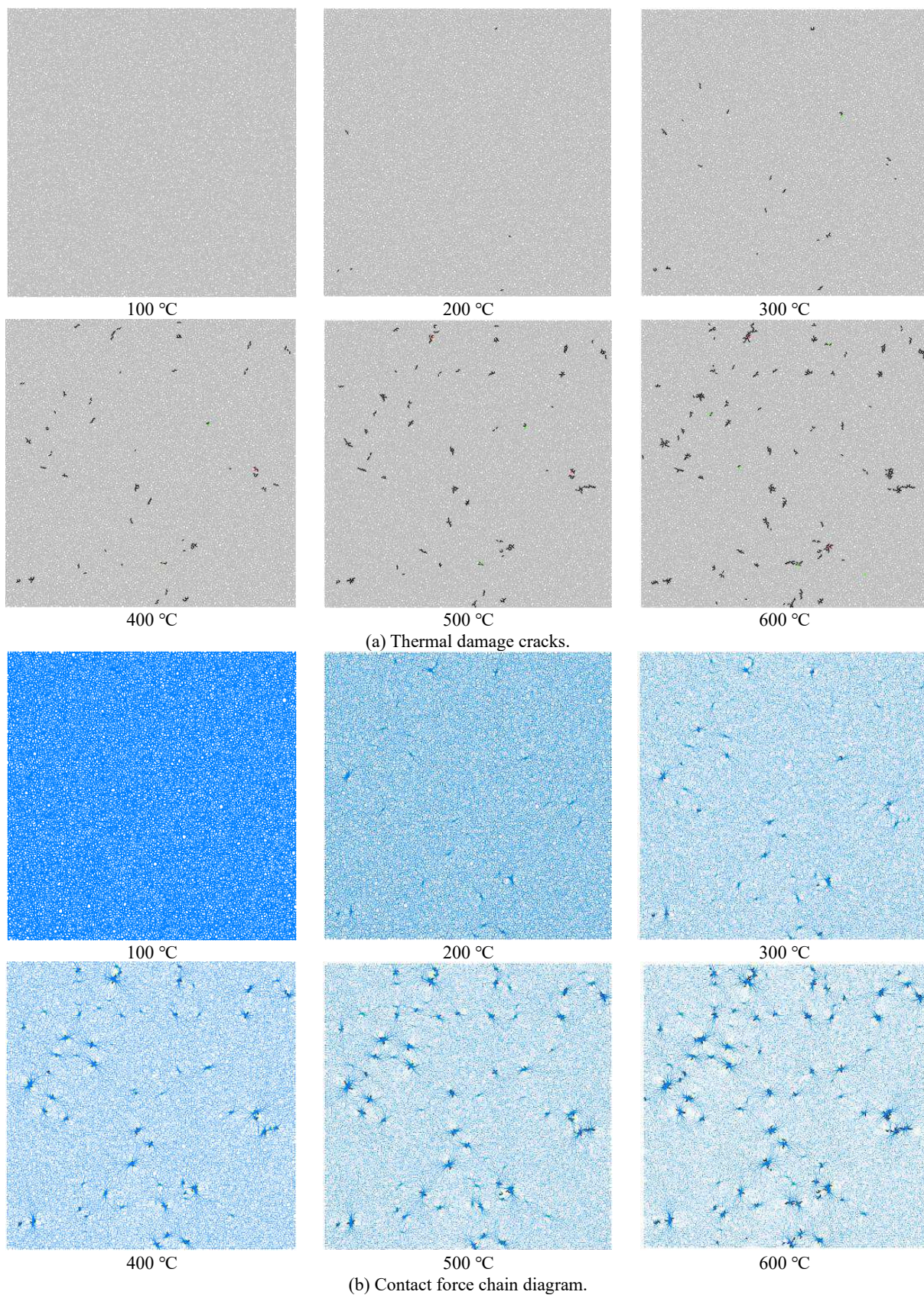


Fig. 3. Thermal damage-induced fractures and contact force chains at different temperatures (force-chain concentration indicates large contact-force variations).

The developed DEM model for thermally damaged granite effectively reproduces the fracture morphology and spatial distribution characteristics. The thermally induced fractures are mainly distributed around quartz and plagioclase particles with relatively large thermal expansion coefficients. Their overall distribution shows no obvious geometric regularity, and the orientations of individual fractures are relatively random, showing a strong agreement with the results reported by Gao (2018). In that study, a Nano Voxel-2000 high-resolution CT system was used to scan granite specimens subjected to thermal treatment at 600 °C, and the comparison demonstrated that the model is reliable for characterizing thermal damage evolution in granite (Fig. 4).

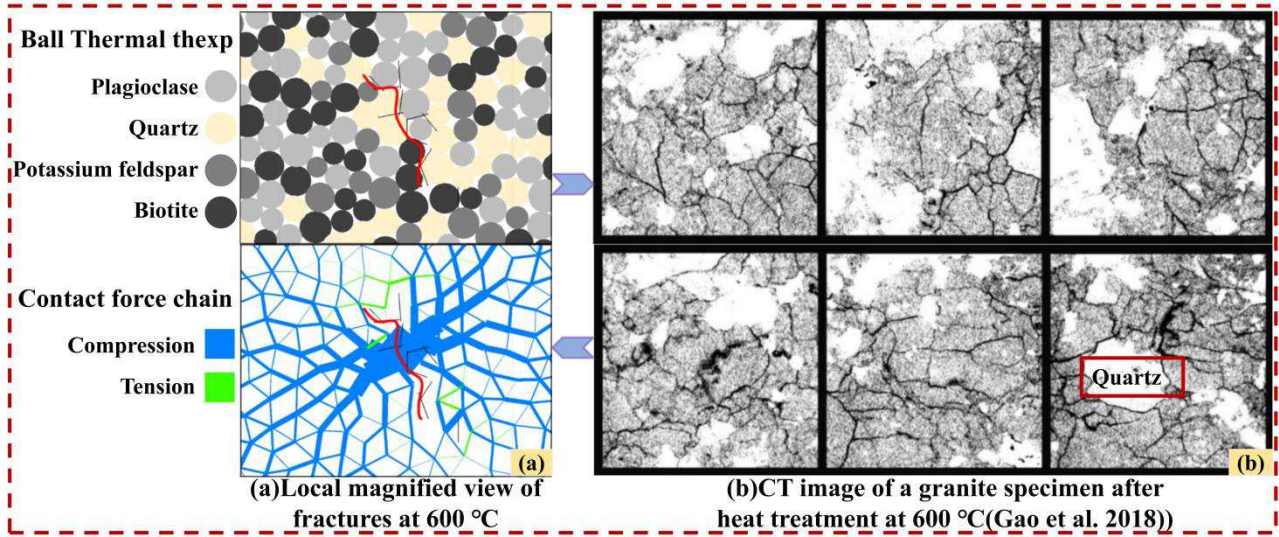


Fig. 4. Thermal damage evolution in granite.

The granite is simplified as a two-dimensional (2D) plane model, the stress conditions around the borehole are characterized by the vertical principal stress (σ_v), maximum horizontal principal stress (σ_H), minimum horizontal principal stress (σ_h), wellbore fluid column pressure (P_b), and pore pressure (P_p). Based on the field measurements obtained by Chang et al. (2011) at a depth of 7000 m in the northeastern Sichuan Basin, and considering the relationship between horizontal in situ stress and pore pressure as well as the principal stress state at any point within the formation, the relevant stress parameters are determined, as summarized in Table 3. In this study, the vertical stress σ_v is taken as a fixed value of 168 MPa. The stress state at any point in the formation can generally be classified into three typical cases, in which σ_v corresponds to the maximum, intermediate, or minimum principal stress. The fracture distribution in the DEM model after the application of confining pressure is shown in Fig. 5.

Table 3. Values of horizontal stress (MPa) under different geostress conditions.

$\sigma_v > \sigma_H > \sigma_h$ ($\sigma_H / \sigma_h = 1.1$)		$\sigma_H > \sigma_v > \sigma_h$ ($\sigma_H / \sigma_h = 1.18$)		$\sigma_H > \sigma_h > \sigma_v$ ($\sigma_H / \sigma_h = 1.08$)	
σ_H	σ_h	σ_H	σ_h	σ_H	σ_h
154	140	182	154	196	182

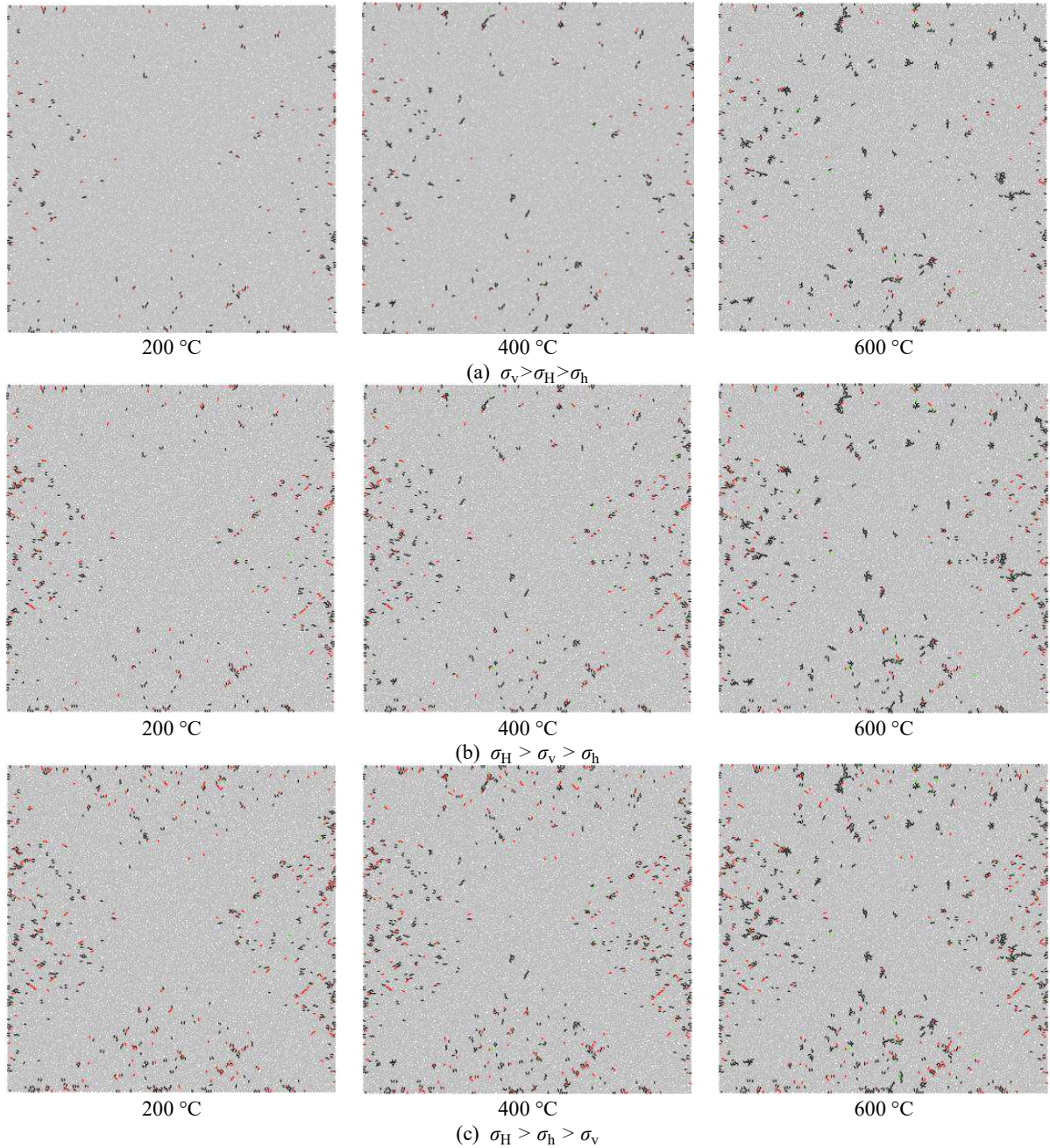


Fig. 5. Development of granite fractures under different in situ stress conditions (black color represents the tensile fracture, and red color denotes the compressive shear fracture).

The results are consistent with the findings of Zhang et al. (2018) regarding the evolution of thermal damage-induced fractures in granite under compression. Compressive–shear fractures are distributed around tensile fracture zones and exhibited secondary initiation along their tangential directions. Moreover, the distribution of thermally induced fractures is associated with mineral grains, while the compression–shear fractures induced after confining pressure is applied (red lines) are generally distributed in an “X”-shaped pattern along the boundaries of the granite model (Fig. 6). The sequence of fracture development, the orientation of the main fractures, and the failure stages show a good consistency, aligning with the formation mechanisms of thermal damage-induced fractures. This indicates that the developed DEM model can effectively characterize the evolution of thermal damage-induced fractures in granite under high-temperature conditions.

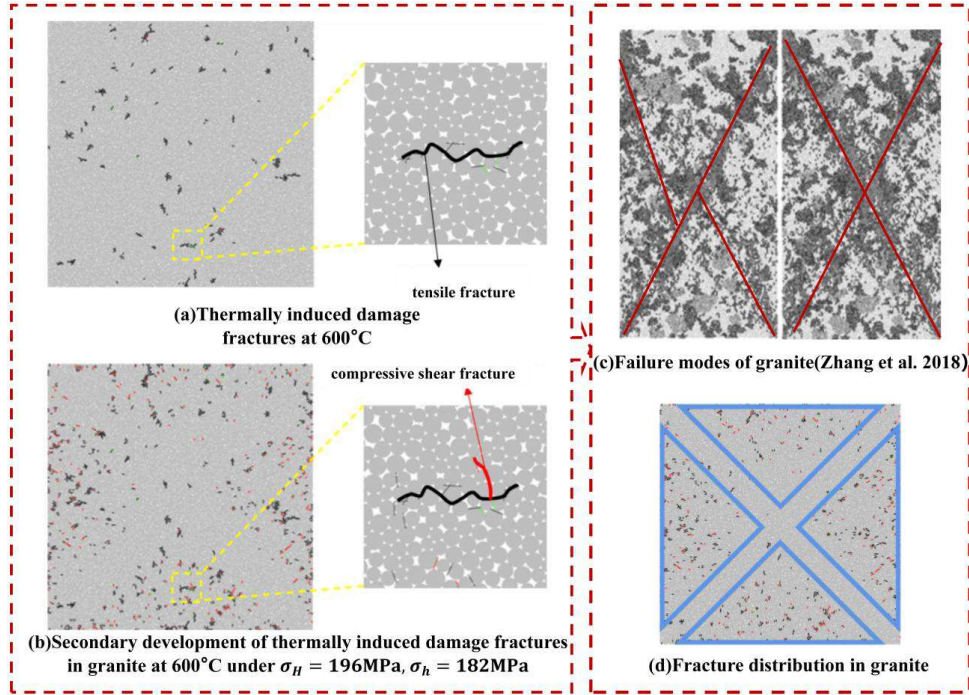


Fig. 6. Distribution of thermally induced fractures in granite.

2.2.2. Establishment of borehole mechanical model

By analyzing the stress distribution around the borehole, a THM coupling model is established from the perspectives of temperature, drilling fluid column pressure, and in situ stress. Borehole mechanical models for deep drilling are constructed using both elastic theory and DEM. Comparative analysis between the two approaches is performed to enhance result reliability and improve the explanatory capability regarding underlying mechanisms.

(1) Borehole mechanical model based on elastic theory

The horizontal in situ stress is decomposed into the maximum and minimum principal stress components, and the effect of drilling fluid column pressure P_w is incorporated. Assuming that the borehole is located in an infinite plane, with the surrounding rock mass and borehole wall modeled as isotropic linear elastic media, the stresses at any point around the borehole can be decomposed into radial stress σ_{rr} , tangential stress $\sigma_{\theta\theta}$, and shear stress $\tau_{r\theta}$ in polar coordinates, as shown in Fig. 7.

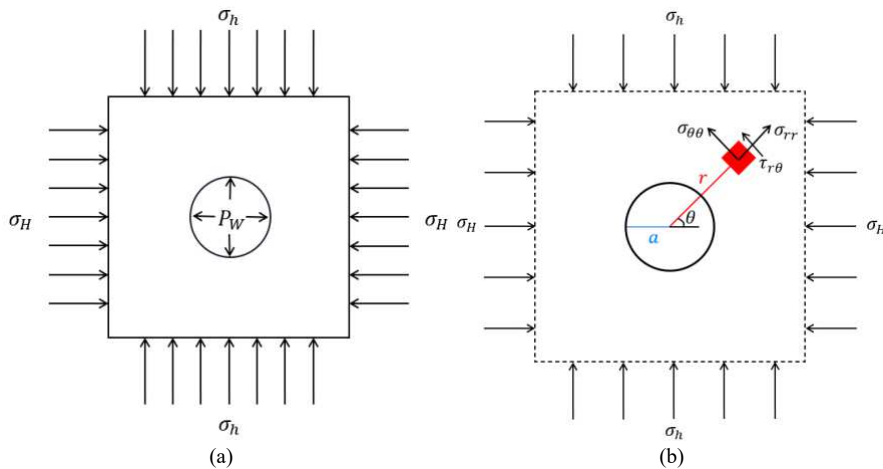


Fig. 7. Stress distribution (a) and internal stress decomposition (b) of borehole model.

According to the Kirsch solution for borehole wall stability, when only the horizontal in situ stresses acting on the rocks are considered, the stress distribution at each point within the borehole model can be obtained. It is further assumed that the pore water pressure and drilling fluid column pressure, as hydrostatic pressures, are uniformly applied to the borehole wall and transmitted into the model as a linear elastic medium. To incorporate hydraulic effects, the superposition method is employed to modify the stress state. Based on thermoelastic theory (Yan et al., 2014), and accounting for the additional stresses induced by temperature, the resulting additional stress field is expressed as follows:

$$\begin{cases} \sigma_{rr} = \frac{\sigma_H + \sigma_h}{2} \left(1 - \frac{a^2}{r^2}\right) + \frac{\sigma_H - \sigma_h}{2} \left[1 - 4\frac{a^2}{r^2} + 3\left(\frac{a^2}{r^2}\right)^2\right] \cos(2\theta) + \Delta P \frac{a^2}{r^2} + \sigma_{rT} \\ \sigma_{\theta\theta} = \frac{\sigma_H + \sigma_h}{2} \left(1 + \frac{a^2}{r^2}\right) - \frac{\sigma_H - \sigma_h}{2} \left[1 + 3\left(\frac{a^2}{r^2}\right)^2\right] \cos(2\theta) - \Delta P \frac{a^2}{r^2} + \sigma_{\theta T} \\ \tau_{r\theta} = \frac{\sigma_H - \sigma_h}{2} \left[1 + 2\frac{a^2}{r^2} - 3\left(\frac{a^2}{r^2}\right)^2\right] \sin(2\theta) \end{cases} \quad (1)$$

where a is the borehole radius (m); r is the distance from the borehole center (m); θ is the borehole circumferential angle, defined as the angle between the line connecting the point of interest to the borehole center and the direction of the maximum horizontal in situ stress ($^\circ$); and ΔP is the difference between the fluid pressure in the borehole and the pore fluid pressure within the formation rock (Pa).

From Eq. (1), it can be observed that the shear stress is independent of both the drilling fluid column pressure and the additional thermal stress. If the pore water pressure in the rock is neglected, ΔP represents the drilling fluid column pressure P_w continuously applied to the borehole wall. Substituting $a = r$ and $\Delta P = P_w$ into Eq. (1), the 2D plane-stress state of the borehole wall, considering horizontal in situ stress, fluid pressure, and thermal effects, can be expressed as follows (Baohua et al., 2013):

$$\begin{cases} \sigma_{rr} = P_w \\ \sigma_{\theta\theta} = (\sigma_H + \sigma_h) - 2(\sigma_H - \sigma_h) \cos(2\theta) - P_w \\ \tau_{r\theta} = 0 \end{cases} \quad (2)$$

where T_b is the borehole wall temperature ($^\circ\text{C}$).

This indicates that the borehole wall stress state is primarily influenced by drilling fluid column pressure, horizontal in situ stress, and the temperature difference between the borehole wall and the surrounding rocks. Among these factors, drilling fluid column pressure plays a dominant role in controlling radial stress σ_{rr} , while the shear stress $\tau_{r\theta}$ at the borehole wall remains 0.

Based on the borehole wall stress field distribution, the Hoek-Brown strength criterion is applied to evaluate the borehole wall stability. Compared with the Mohr-Coulomb and maximum principal stress criteria, the Hoek-Brown criterion is better suited to representing the strength behavior of rocks under combined tensile and shear failure, particularly for deep rock masses that exhibit pronounced nonlinear failure characteristics.

(2) DEM model of borehole based on DEM

On the basis of the previously developed thermal damage particle model, a “borehole excavation” procedure is applied to construct the borehole structure. A fluid grid is embedded within the borehole domain to simulate the process of drilling fluid seeping into the borehole interior, diffusing into the pore spaces of the surrounding rock particles, and exerting pressure on the borehole wall, thereby representing the effect of drilling fluid column pressure (Fig. 8). During each fluid time step Δt , the change in fluid pressure within the domain can be obtained from Eq. (3). By integrating the temperature field and horizontal in situ stress field, a THM coupling model for deep drilling is established.

$$\Delta P = \frac{K_f}{V_d} (\sum q \Delta t - \Delta V_d) \quad (3)$$

where K_f is the fluid bulk modulus (Pa), V_d is the apparent volume of the fluid domain (m^3), and ΔV_d is the volume change of the fluid domain (m^3).

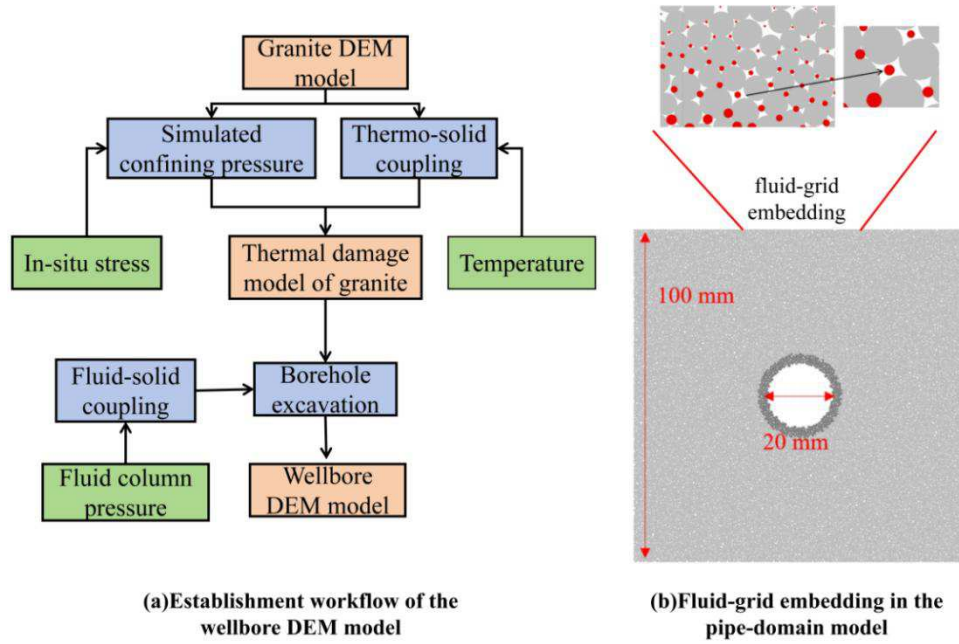


Fig. 8. Establishment of THM coupling model of borehole based on DEM.

In the DEM model of borehole, stress measurement circles with a radius of $R = 2.5$ mm are uniformly arranged (a total of 396) to record the normal stresses in the x and y directions, as well as the shear stresses, at each monitoring point. A customized PFC script is used to extract the stress monitoring data from the model, which are then processed and visualized using Surfer software. The Kriging interpolation is applied to plot the principal stress datasets as planar contour maps matching the size of the original model, thereby providing an intuitive representation of the principal stress distribution.

3 Results and analysis

In deep geological conditions, the combined action of in situ stress and drilling fluid column pressure significantly alters the stress distribution around the borehole wall and can even directly trigger structural failure. Based on the developed numerical model, the effects of temperature, in situ stress state, and drilling fluid column pressure are systematically investigated to study the fracture development patterns in the borehole wall, with emphasis on fracture quantity, spatial distribution characteristics, morphological evolution, and dominant influencing factors.

3.1 Effect of temperature on in situ stress in surrounding rocks

Under conditions of $\sigma_H = 182$ MPa, $\sigma_h = 154$ MPa, and drilling fluid column pressure of 105 MPa, the numerical simulations are performed with temperatures of 200 °C, 400 °C, and 600 °C. As temperature increases, the overall stress distribution changes slightly, whereas the peak value (absolute magnitude) of minimum principal stress exhibits a slight increase, reaching 210 MPa at 200 °C and 220 MPa at 600 °C. Taking 600 °C, where thermal stress concentration is most pronounced, as an example, the distributions of thermal damage-induced fractures at $\sigma_H = 182$ MPa and $\sigma_h = 154$ MPa are compared with the contour maps of the maximum and minimum principal stresses of a model with the same in situ stress state and a fluid column pressure of 105 MPa, as shown in Fig. 9.

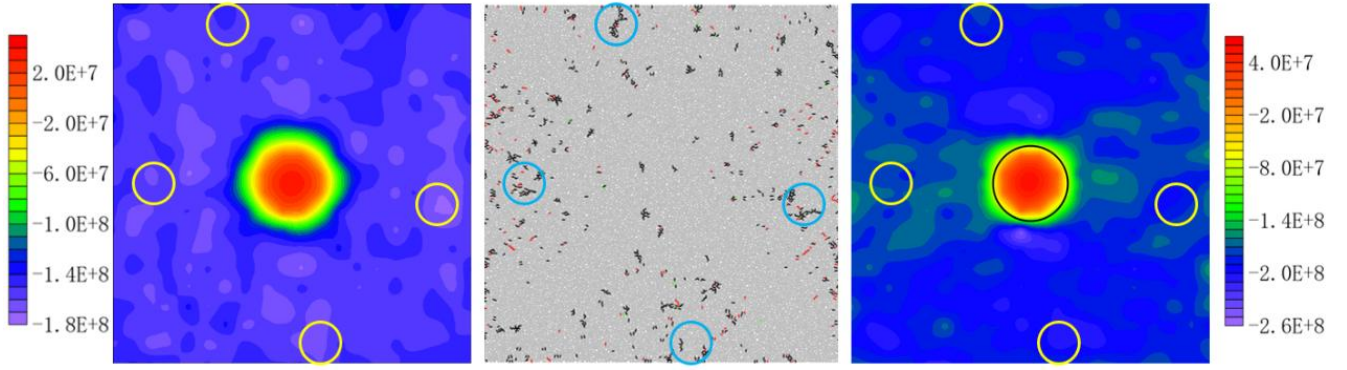
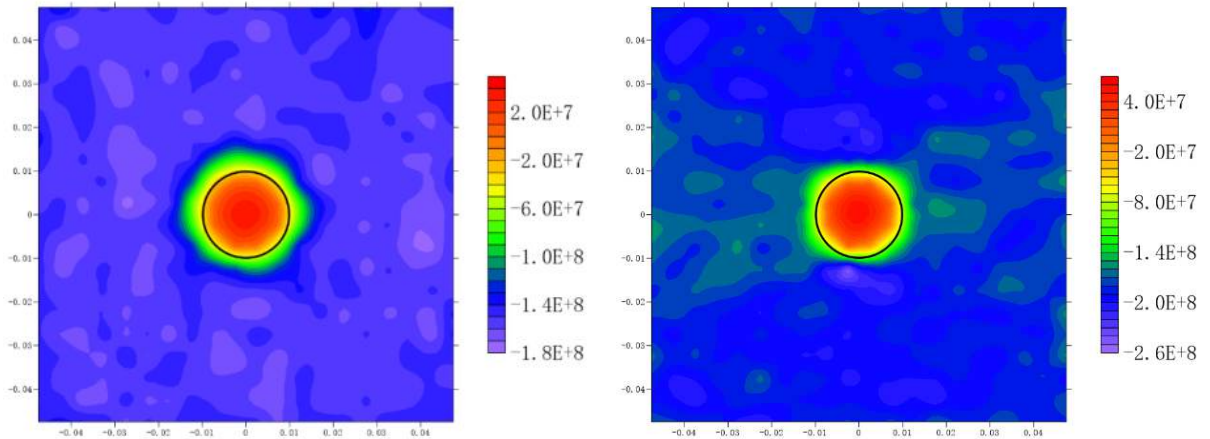


Fig. 9. Relationship between thermal damage-induced fracture and stress distribution at 600 °C (left panel shows the minimum principal stress diagram, and right panel shows the maximum principal stress diagram).

The stress concentration regions in the model partially overlap with the zones where thermal damage-induced fractures are concentrated, consistent with the definition that thermal damage-induced fractures are caused by stress concentration. This indicates that the thermal properties of different minerals within the granite, together with temperature, primarily influence the stress distribution and thermal damage-induced fracture development in the DEM model. Overall, temperature mainly affects the in situ stress concentration in the surrounding rocks and promotes the formation of thermal damage-induced fractures. Compared with in situ stress and drilling fluid column pressure, a constant temperature has a relatively minor impact on the peak stress values.

3.2 Influence of in situ stress conditions on internal stress and borehole deformation

At a temperature of 200 °C and a drilling fluid column pressure of 105 MPa, three combinations of maximum and minimum horizontal in situ stresses are applied: $\sigma_H = 182$ MPa, $\sigma_h = 154$ MPa; $\sigma_H = \sigma_h = 154$ MPa; and $\sigma_H = 154$ MPa, $\sigma_h = 140$ MPa. The numerical simulation is performed for each case, and the corresponding stress contour maps are generated.



(a) $\sigma_H=182$ MPa, $\sigma_h=154$ MPa

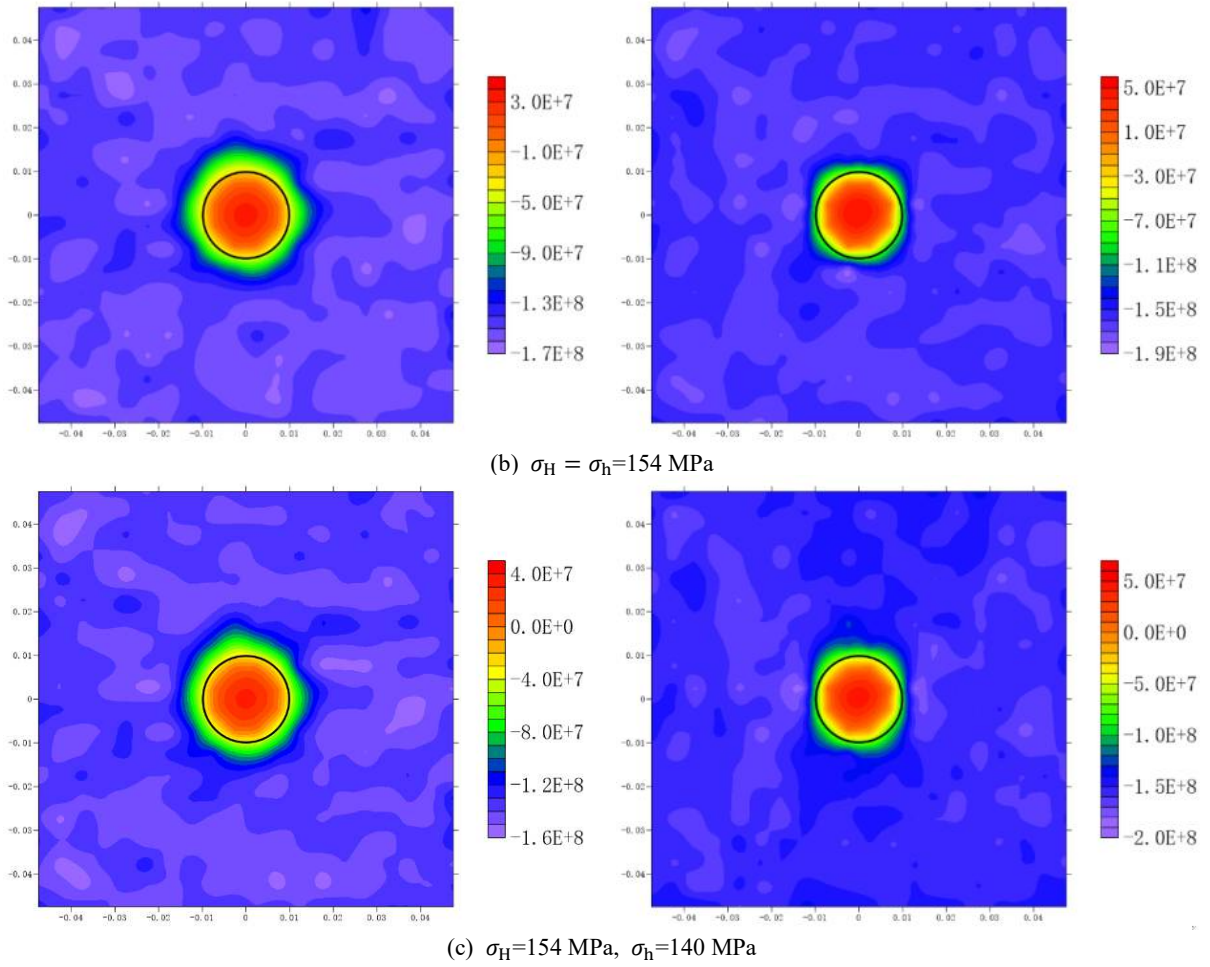


Fig. 10. Contour maps of principal stress (Pa) under different in situ stress conditions (left panel shows the contour maps of the maximum principal stress, and right panel shows the contour maps of the minimum principal stress).

As shown in Fig. 10, the peak value of stress concentration decreases as the average horizontal in situ stress decreases. The distribution of minimum principal stress depends on the in situ stress state, i.e. its absolute value is larger in the direction of the maximum horizontal in situ stress and smaller in the direction of the minimum horizontal in situ stress. This effect becomes more pronounced as the ratio of maximum to minimum horizontal in situ stress increases.

After the numerical simulation, particles are grouped and color-coded based on the magnitude of their displacement vectors during simulation to generate displacement contour maps. Combined with the fracture networks obtained using the DFN approach, the deformation trends of the borehole are visually assessed. As shown in Fig. 11, when the maximum and minimum horizontal in situ stresses are unequal, fractures concentrate in the direction of the minimum horizontal in situ stress. This concentration aligns with the direction of smaller particle displacements, indicating that the borehole undergoes compression along the maximum in situ stress direction and tension along the minimum in situ stress direction. Consequently, the borehole deformation direction changes in response to variations in the horizontal in situ stress distribution.

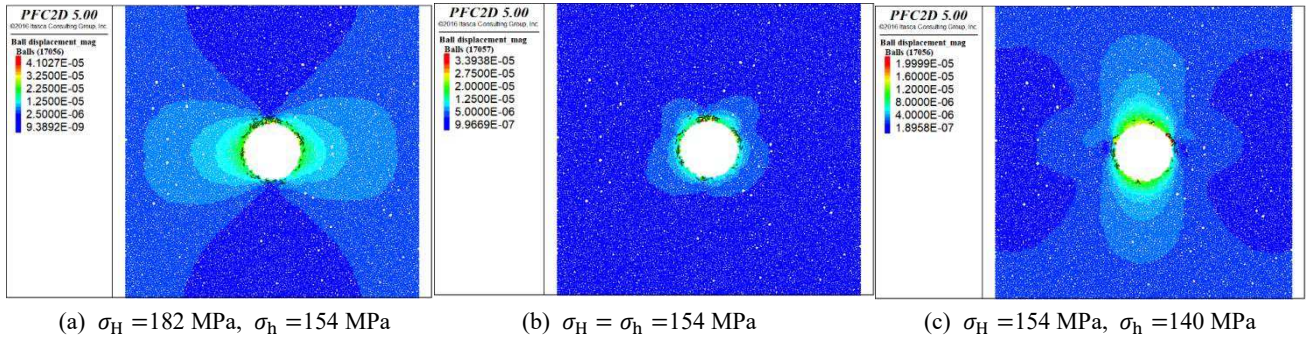


Fig. 11. Contour maps of fracture development and particle displacement under different in situ stress conditions (m).

The borehole failure orientations obtained from the DEM model are generally consistent with the observations from numerous actual drilling cases (Carr, 1974), as well as with the simulated drilling tests on granite conducted by Lee (1993), Song and Haimson (1997), and Song (1998). Through optical microscopy observations, Haimson (2007) summarized the experimental results and correlated them with the directions of the maximum and minimum principal stresses under confining pressure, as illustrated in Fig. 12.

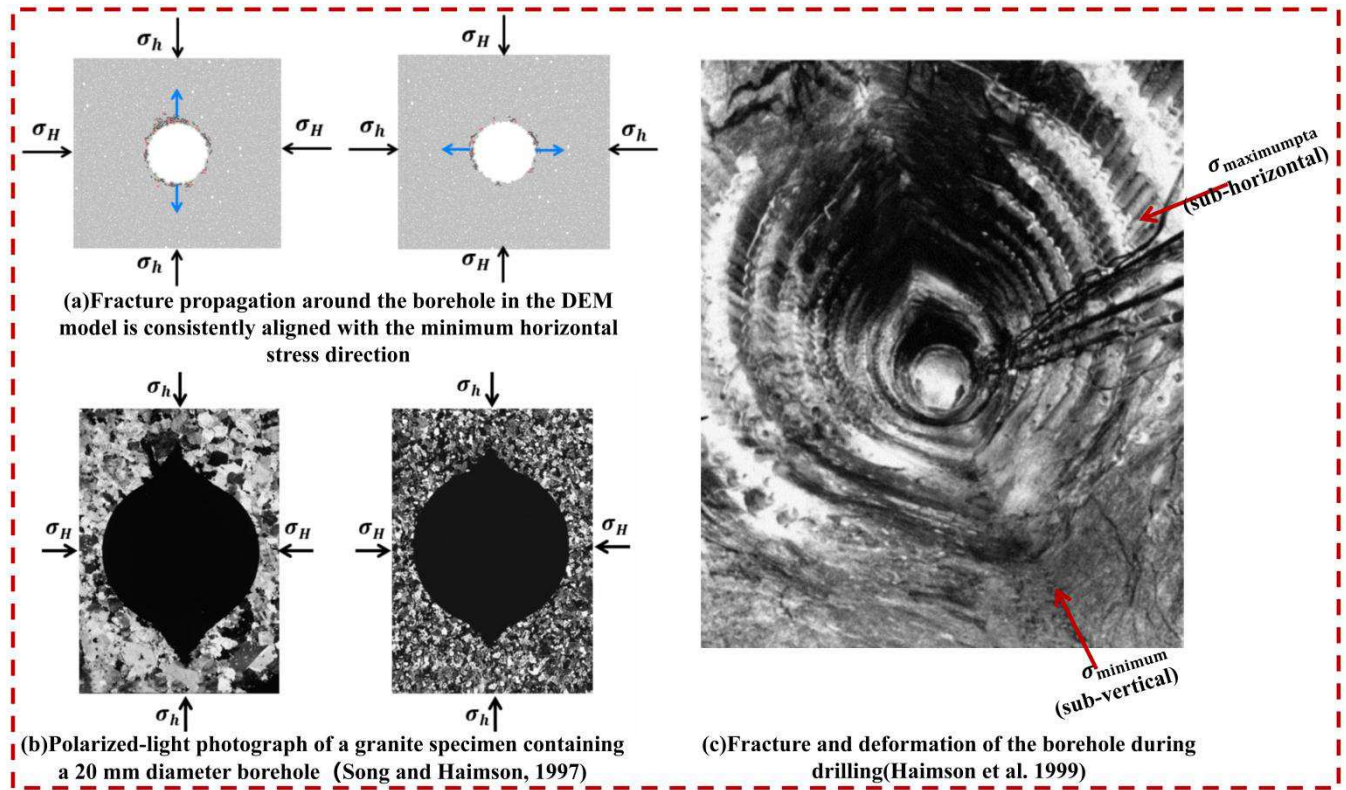
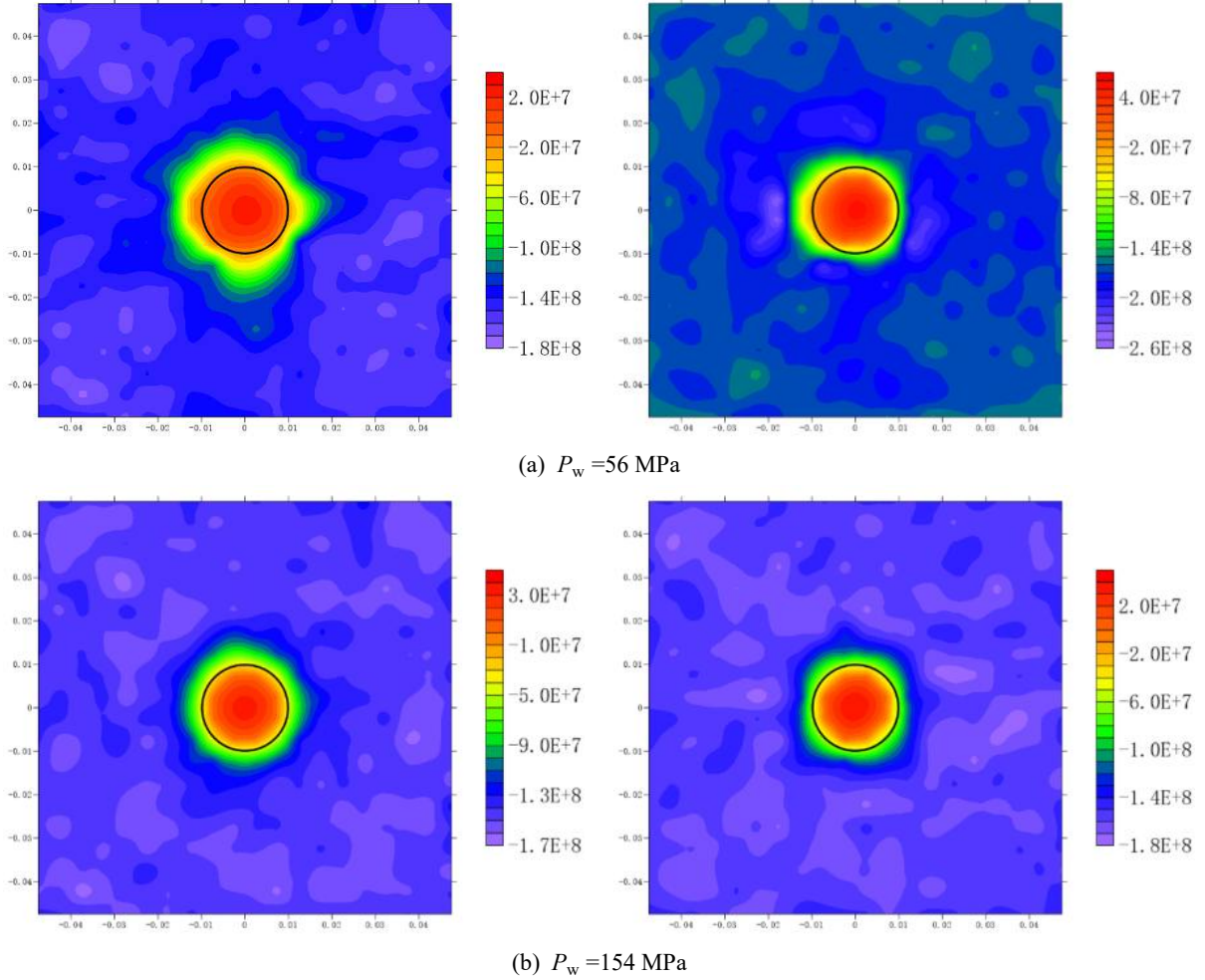


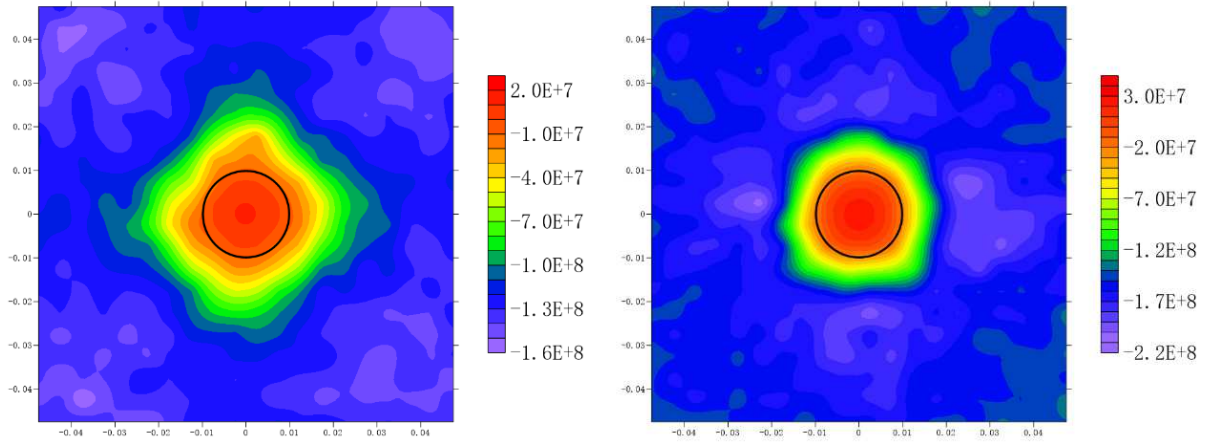
Fig. 12. Fracture development characteristics of the borehole wall.

The laboratory test results also show a good consistency with field drilling observations. Compared with the borehole failure photographs taken by Haimson (1999) in a Lac du Bonnet granite borehole at a depth of 420 m and a diameter of 3 m in the Canadian Underground Research Laboratory (Fig. 12), it is evident that the failure orientation aligns with the direction of the minimum horizontal principal stress. This further validates the reliability of both the laboratory tests and numerical simulations in predicting fracture orientations.

3.3 Effect of drilling fluid column pressure on stress distribution and borehole fractures

Under the conditions of 200 °C and $\sigma_H = \sigma_h = 154$ MPa, different drilling fluid column pressures of 56 MPa, 154 MPa and 252 MPa are applied to the DEM model of borehole. As shown in Fig. 13, the maximum and minimum principal stresses within the model are redistributed in response to the change in drilling fluid column pressure. When the drilling fluid column pressure is equal to the maximum and minimum horizontal in situ stresses, the stress distribution within the model is relatively uniform. In contrast, at $P_w = 56$ MPa and 252 MPa, the minimum principal stress becomes concentrated around the borehole wall, and its peak values at the borehole wall are significantly larger than those observed at $P_w = 154$ MPa.





(c) $P_w = 252$ MPa

Fig. 13. Contour maps of stress under different drilling fluid column pressures (left panel shows the maximum principal stress, and right panel shows the minimum principal stress) (Pa)

Using the DFN network, the contour maps of particle displacement are generated for different drilling fluid column pressures (Fig. 14). As the drilling fluid column pressure increases, the particle displacement at the borehole wall first decreases and then increases, while the number of borehole wall fractures also decreases initially and then increases. At $P_w = 56$ MPa, the particle displacement at the borehole wall is relatively large, whereas the displacement of the surrounding rocks is smaller; fractures around the borehole wall are densely developed with relatively disordered orientations. At $P_w = 154$ MPa, most particles in the model exhibit smaller displacements, while particles in the outer ring of the borehole wall show larger displacements. At $P_w = 252$ MPa, the particle displacement within the borehole model is small and relatively uniform, the extent of fracture development along the borehole wall is limited, and the fractures tend to propagate outward in the directions roughly aligned with the borehole radius.

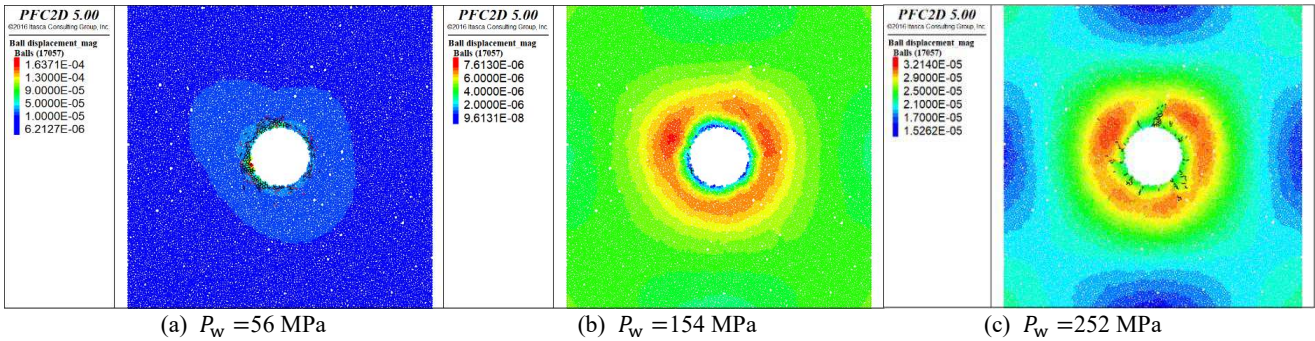


Fig. 14. Contour maps of fracture development and particle displacement under different drilling fluid column pressures (m).

When $\sigma_H = \sigma_h$, the distribution of borehole wall fractures does not exhibit a pronounced concentration at any specific angle. As P_w increases, the borehole stress transitions from $\sigma_{\theta\theta} > \sigma_{rr}$ to $\sigma_{\theta\theta} < \sigma_{rr}$, and the fracture pattern shifts from a circumferential “V”-shaped distribution to a radial distribution aligning with the borehole radius. This indicates that under $\sigma_H = \sigma_h$ conditions, the orientation of the maximum principal stress—affected by drilling fluid column pressure—has a significant influence on the fracture distribution pattern.

As shown in Fig. 15a, at the initial stage of fracture formation at the borehole wall, fractures are predominantly circumferential. As the simulation progresses, the number of radial fractures gradually increases, and the circumferential fractures between particles become interconnected (Fig. 15b). This causes the fracture

distribution to evolve from being uniformly developed around the borehole wall to becoming locally concentrated and extending outward, ultimately forming a “V”-shaped pattern (Fig. 15c). The development process of the “V”-shaped fractures in the DEM model closely matches that observed by Haimson (1999) through optical microscopy in the borehole fractures of Lac du Bonnet granite after simulated drilling, where the rapid increase in circumferential fractures leads to particle splitting at the borehole wall, and the interconnection of circumferential fractures causes the detachment of borehole wall particles (Fig. 15d). When $P_w = 154$ MPa, the borehole wall predominantly develops radial fractures (Fig. 15e). The fracture patterns in the model are similar to those observed by Li et al (2021) using CT imaging (Fig. 15f), where hydraulic fracturing of granite boreholes is conducted under confining pressures of 3-6 MPa and unconfined conditions, respectively, with either a constant flow rate of water or a constant water pressure of 12.6 MPa. In both cases, the resulting fractures are primarily single fractures with almost no branching. This indicates that when the drilling fluid column pressure exceeds the confining pressure, the fracture behavior at the mesoscopic particle contacts in the DEM model closely matches the fracture patterns observed in laboratory hydraulic fracturing tests, thereby supporting the reliability of the DEM model under large drilling fluid column pressure conditions.

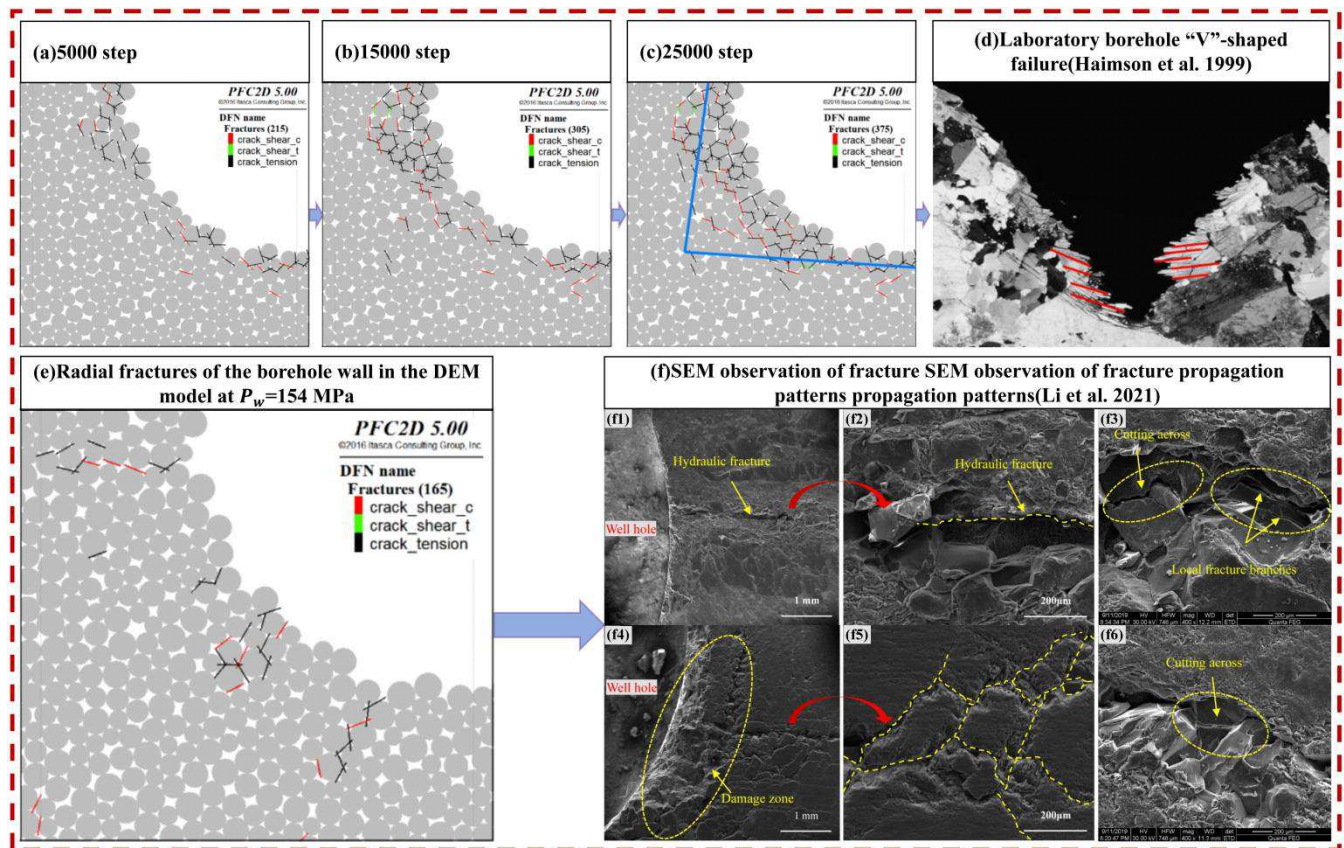


Fig. 15. Development process of “V”-shaped fractures and radial distribution of fractures.

According to the Hoek-Brown strength criterion, smaller values of σ_3 and larger values of σ_1 make the rock more susceptible to tensile and shear failure. As shown in Table 4, with increasing drilling fluid column pressure, the number of fractures in the borehole wall first decreases and then increases. At $P_w = 154$ MPa (equal to the horizontal in situ stress), both tensile and shear fractures reach their minimum numbers.

Table 4. Relationship between liquid pressure P_w and number of fractures.

Type of crack	Number of fractures		
	$P_w = 56$ MPa	$P_w = 154$ MPa	$P_w = 252$ MPa
Stretch	279	8	116
Tensile fracture	6	0	1
compression–shear fracture	90	5	48

4 Discussion

4.1 Comparative validation of elastic theory and DEM

This study employs both elastic theory and PFC software to develop a THM coupling borehole mechanical model and a DEM model. To verify the reliability of the model results, a comparative analysis of the two approaches is conducted. In the borehole mechanical model, the stress state at any point can be determined from Eq. (4). Correspondingly, in the DEM model of borehole, the σ_x , σ_y , and τ_{xy} values at each point obtained from the stress measurement circles can be converted, based on the borehole circumferential angle, into the radial stress, tangential stress, and shear stress acting on the borehole wall and surrounding rocks using a polar coordinate transformation.

$$\begin{cases} \sigma_{rr} = \sigma_x \cos^2 \theta + \sigma_y \sin^2 \theta + 2\tau_{xy} \sin \theta \cos \theta \\ \sigma_{\theta\theta} = \sigma_x \sin^2 \theta + \sigma_y \cos^2 \theta - 2\tau_{xy} \sin \theta \cos \theta \\ \tau_{r\theta} = (\sigma_y - \sigma_x) \sin \theta \cos \theta + \tau_{xy}(\cos^2 \theta - \sin^2 \theta) \end{cases} \quad (4)$$

Due to significant variations in stress of the borehole model under different drilling fluid column pressures, the stress states and distributions of the borehole mechanical model and the DEM model are compared at a temperature of 200 °C, $\sigma_H = \sigma_h = 154$ MPa, and drilling fluid column pressures P_w of 56 MPa, 154 MPa, and 252 MPa. To compare the stress distributions obtained by the two methods, a polar coordinate reference system is adopted, and two directions are selected for analysis: variation with the borehole circumferential angle θ (circumferential direction) and variation with the distance r from the borehole center (radial direction), as illustrated in Fig. 16:

- (1) Circumferential direction: The borehole circumferential angle θ varies from $\arctan 0.2$ to $2\pi - \arcsin 0.2$, while the distance r from the measurement circle to the borehole center remains constant.
- (2) Radial direction: For convenience of analysis, two adjacent rows of measurement circles located approximately along the x axis in the positive direction (where the borehole circumferential angle is close to 0°) are selected. The average values of σ_x , σ_y and τ_{xy} are taken for each row. The distance r from the measurement circles to the borehole center varies from 12.5 mm to 47.5 mm.

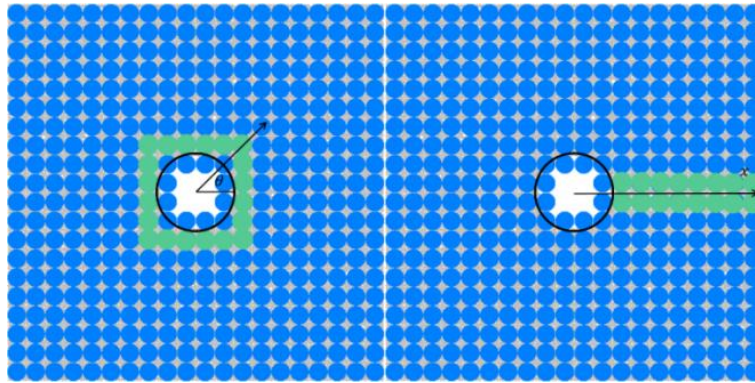


Fig. 16. Measurement circle (left panel shows the circumferential direction, and right panel shows the radial direction).

The comparison between the analytical solution from the elastic theory and the DEM solution for the borehole is shown in Fig. 17.

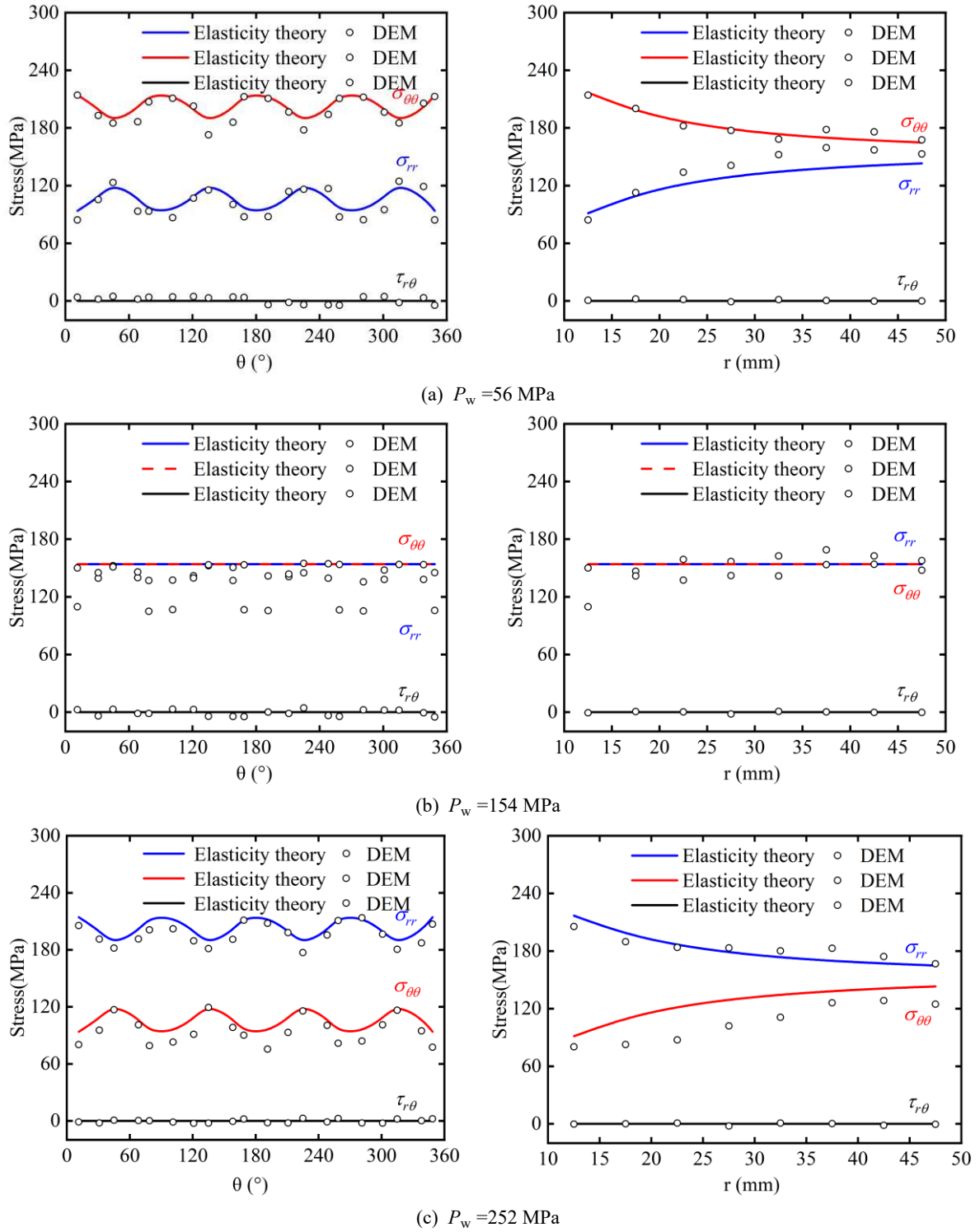


Fig. 17. Stress state of borehole model under different drilling fluid column pressures (left panel shows the circumferential stress distribution, and right panel shows the radial stress distribution).

Because the measurement circles at $\theta = 0^\circ, 90^\circ, 180^\circ$ and 270° are located close to the borehole wall, the size effect of the measurement circles is more pronounced. As a result, in the circumferential direction (θ -variation), the DEM model solutions show larger deviations from the analytical solutions of elastic theory. Under different drilling fluid column pressures, the difference between the DEM and analytical solutions for radial stress σ_{rr} is greater than those for tangential stress $\sigma_{\theta\theta}$ and shear stress $\tau_{r\theta}$, with the largest discrepancy observed at $P_w = 154$ MPa. The smallest deviation occurs in shear stress $\tau_{r\theta}$, indicating that the error of radial stress σ_{rr} in the DEM model of borehole is relatively large, while the error of shear stress $\tau_{r\theta}$ is relatively small. For radial stress σ_{rr} and tangential stress $\sigma_{\theta\theta}$, which have a greater influence on the borehole wall, the DEM solutions generally fluctuate slightly below the analytical solutions of elastic theory. At $P_w = 252$ MPa, the DEM solutions show a larger deviation from the analytical solutions, suggesting that the internal stresses predicted by the DEM model are relatively conservative. Under larger drilling fluid column pressures, the DEM model exhibits greater errors compared to the theoretical mechanical model. Overall, the THM coupling simulation results for borehole wall fracture development, after measurement and transformation into polar coordinates, are generally consistent with the analytical solutions from elastic theory in the polar coordinate system.

4.2 Influence of THM coupling on in situ stress and fracture development in high-temperature deep boreholes

High-temperature conditions provide the initial thermal damage background for fracture development in borehole wall rocks and exert a pronounced influence on the redistribution of in situ stress. As the temperature increases, differences in thermal expansion coefficient, elastic modulus, and grain size among granite-forming minerals generate localized stress concentrations along grain boundaries. These stress concentrations induce incompatible deformation among adjacent mineral grains and promote the formation of intergranular cracks, particularly tensile-dominated fractures along quartz–plagioclase boundaries (Dong et al., 2024). Biotite also plays an important role in crack-path evolution. Although its fracture toughness is relatively low under comparable stress conditions, making it prone to cracking, its high plasticity can significantly affect crack propagation. At the microscopic scale, cracks are less likely to penetrate biotite crystals directly and are more likely to deflect and propagate along biotite boundaries (Zhou et al., 2025). The thermal effect on granite is not simply monotonic (Wu et al., 2025). At relatively low to moderate temperatures, especially below approximately 200 °C, thermal expansion has the potential to promote the closure of pre-existing pores and microcracks, producing a thermal densification effect and temporarily increasing compressive strength and elastic modulus. However, at the temperature of approximately 300 °C, the phenomenon of thermal damage becomes dominant. The mismatch in thermal expansion among quartz, feldspar, biotite, and other minerals weakens intergranular bonding, promotes fracture initiation and propagation, and causes a marked reduction in macroscopic strength and stiffness (Ma et al., 2025; Qin et al., 2025).

At the mineral scale, quartz plays a particularly important role in thermally induced fracture development. Owing to its relatively large elastic modulus and thermal expansion coefficient, quartz can generate intense local thermal stress at interfaces with adjacent minerals. As the temperature increases, the aforementioned stress concentration promotes both intergranular cracking along mineral boundaries and transgranular cracking around or through quartz grains. It is therefore evident that the propagation of transgranular fractures around quartz is a key microscopic mechanism that controls the degradation of the macroscopic mechanical properties of thermally treated granite (Qiu and Lin, 2006; Zhao et al., 2008a, 2010; Chen et al., 2016). Furthermore, experimental investigations involving high-temperature uniaxial and triaxial tests have demonstrated a substantial increase in the number of thermal cracks with rising temperature. Additionally, crack propagation accelerates markedly once the temperature exceeds 300 °C, displaying a highly heterogeneous spatial distribution (Wang et al., 2025). During the 300 °C–600 °C stage, fractures continue to propagate, the total fracture length generally increases, and the fracture network gradually becomes more complex. In particular, fracture development

accelerates markedly within the 500 °C-600 °C interval, which is associated with the $\alpha \rightarrow \beta$ phase transition of quartz at approximately 573 °C. This quartz phase transition induces lattice changes and volumetric effects, thereby promoting the extension of pre-existing fractures and increasing both fracture aperture and network complexity (Xie et al., 2026; Zhang et al., 2026a).

High temperature weakens the rock matrix and promotes thermal cracking. Thermally induced cracks caused by mineral-scale incompatible deformation usually develop without a pronounced directional preference (David et al., 1999). Under this condition, the redistributed in situ stress field around the borehole becomes the dominant factor that controls fracture orientation and morphology. Nonuniform stress fields around the borehole can easily induce shear failure, particularly in regions where the difference between the maximum and minimum horizontal principal stresses is large. Moreover, the intermediate principal stress can significantly affect crack initiation stress, dilatancy threshold, peak strength, failure plane orientation, brittleness, and permeability evolution (Xie et al., 2022). When the circumferential stress exceeds the compressive strength of the rocks, fractures tend to propagate along the direction of the minimum horizontal principal stress, producing elliptical borehole deformation and directionally oriented fracture patterns (Springer, 1987; Wang et al., 2021). With increasing in situ stress, shear fractures become more likely to occur, and the dominant fracture type may shift from tensile-controlled to shear-controlled pattern. As the stress difference further increases, fractures tend to cluster into localized damage zones, forming highly connected shear fracture bands. These bands may extend into other directions as fracture length increases, ultimately leading to borehole wall instability (Feng et al., 2025).

Drilling fluid column pressure further modifies this stress-controlled fracture evolution. Its variation alters the radial, circumferential, and axial stress distributions around the borehole wall and thereby determines the mode of fracture initiation and the propagation path. When the drilling fluid column pressure is lower than the in situ stress, the borehole wall is primarily compressed, which favors the development of circumferential fractures. Conversely, when the drilling fluid column pressure exceeds the in situ stress, radial fractures may form under tensile-dominated conditions. However, fracture formation does not necessarily indicate immediate instability. Morita et al. (1996) indicated that when drilling fluids containing solid particles are used, even if fractures have formed, they may remain stable and may not immediately propagate to instability if their length is below a critical threshold of 0.76-7.62 cm. Once a fracture becomes fully connected, drilling fluid infiltration can trigger a “dilation–propagation” mechanism, leading to progressive instability. Increasing drilling fluid density may provide greater support pressure for the borehole wall, but it may also induce shear failure at fracture sites (Wei et al., 2024). Therefore, variations in drilling fluid column pressure not only change the spatial distribution of fractures but also affect their connectivity and propagation rate. In addition to modifying the macroscopic stress distribution around the borehole, pore pressure can also influence fracture evolution at the mesoscale. THM coupling simulations of granite show that increasing pore pressure can promote the opening of pre-existing defects, enhance pore-aperture evolution, and induce microcrack initiation along mineral grain boundaries, especially at quartz/feldspar-related interfaces (Li et al., 2025). Under coupled thermal and hydraulic conditions, these microcracks may evolve into connected seepage pathways, thereby accelerating the transition from isolated damage to throughgoing fracture networks.

4.3 Current limitations and future work

On the basis of elastic theory and DEM, this study develops a THM coupling numerical model tailored for analyzing borehole wall stability in deep drilling. The model is applied to simulate and quantitatively analyze fracture evolution patterns under various representative working conditions, including temperature gradients, in situ stress states, and changes in drilling fluid column pressure. Nevertheless, the present DEM model is based on several assumptions and idealized conditions and therefore has inherent limitations. Variations in rock mineral composition can lead to differences in thermophysical and mechanical properties, influencing thermal conductivity and fracture evolution patterns. The proposed model also faces challenges in fully simulating the intersection, penetration, and spatially asymmetric propagation behaviors within complex three-dimensional (3D) fracture networks. Moreover, it does not adequately account for the role of pre-existing fracture systems, nor for their evolution under initial damage states in the coupled action of temperature and seepage fields. These factors

may have coupled impacts on the borehole wall failure mechanism, affecting the accuracy of instability predictions.

Future research should further integrate high-resolution 3D modeling techniques into the existing framework, combining microscale mechanical parameters with macroscale field data for unified multi-scale modeling. Field data and fracture imaging should also be incorporated to effectively calibrate simulation parameters, thereby enhancing the physical fidelity and applicability of the model. It is worth emphasizing that the developed THM coupling model not only elucidates, at the theoretical level, the key mechanisms of thermally induced fracture evolution and borehole wall instability in deep rock masses, but also holds significant practical value for stability assessment of site-scale borehole wall.

5 Conclusions

Focusing on granite, a common lithology in deep drilling, and addressing the complex conditions of high temperature, large in situ stress, and great pore pressure in deep boreholes, this study investigates the meso-mechanisms and coupled response patterns of borehole wall fracture development. Laboratory testing, DEM, elastic theory, and THM coupling theory are integrated to establish a visualized, traceable, and quantitative full-process simulation framework for borehole wall fracture development. The main conclusions are drawn as follows:

- (1) Through uniaxial compression and Brazilian splitting tests, combined with meso-parameter sensitivity analysis and calibration methods, a representative granite DEM model is established. The deviations of the model from experimental results in elastic modulus, compressive strength, and tensile strength are all less than 5%, demonstrating that the model could accurately reflect the macroscopic properties of rocks such as elastic modulus and compressive/tensile strength.
- (2) The micro-mechanism of thermal damage-induced fracture formation in granite is clarified. Differences in mineral's thermal expansion drive the development of thermal damage-induced fractures, with tensile fractures mainly occurring at the boundaries of high-expansion-coefficient particles such as quartz and plagioclase. Crack propagation is disordered, and the locations of stress chain concentration coincide closely with fracture growth zones. The results agree with high-resolution CT scan observations, confirming that thermally induced heterogeneous expansion is a key mechanism for early-stage fracture initiation in deep boreholes.
- (3) The controlling laws of fracture development under THM coupling in deep boreholes are clarified, and the relationships between coupled fields and fracture types are established. Temperature influences fracture activation by regulating stress concentration in the surrounding rocks. Fractures preferentially grow along the direction of the minimum principal stress. The difference between drilling fluid column pressure and in situ stress determines fracture morphology; the circumferential fractures dominate when the drilling fluid column pressure is lower, whereas the radial fractures dominate when it is larger. The constructed THM simulation framework enables quantitative characterization of borehole wall fracture development under multi-field coupling conditions.

Competing 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.

Author contributions

Lichang Wang: original draft, writing—review and editing, conceptualization, formal analysis, methodology, investigation, and supervision. Qinfu Qian: original draft, writing—review and editing, formal analysis, data curation, methodology, software, visualization, and validation. Longjun Dong, Wei Long: original draft, writing—review and editing, methodology, resources, supervision, validation, and funding acquisition. Hanyang

Zhu, Lu Wang: conceptualization, writing—review and editing, methodology, and software. Wenxiang Peng: writing—review and editing, data curation, resources, and validation. Jian Zhou: writing—review and editing and investigation. All authors have read and agreed to the published version of the manuscript.

References

- Aadnoy B, Chenevert M 1987. Stability of highly inclined boreholes. *SPE Drilling Engineering*, 2 (4): 364–374.
- Ali A Y, Bradshaw S 2010. Bonded-particle modelling of microwave-induced damage in ore particles. *Minerals Engineering*, 23: 780-790.
- Baohua Y, Chuanliang Y, Qianga T, Et Al. 2013. Wellbore stability in high temperature and highly-depleted reservoir. *Electronic Journal of Geotechnical Engineering*, 18: 909-922.
- Bell J, Gough D 1983. The use of borehole breakouts in the study of crustal stress. *Hydraulic Fracturing Stress Measurements* 201: 209.
- Bradley W B 1979. Failure of inclined boreholes. *Journal of Energy Resources Technology*, 101(4): 232-239.
- Carr W J 1974. Summary of tectonic and structural evidence for stress orientation at the Nevada test site. *US Geological Survey*.
- David C, Menéndez B, Darot M 1999. Influence of stress-induced and thermal cracking on physical properties and microstructure of La Peyratte granite. *International Journal of Rock Mechanics and Mining Sciences*, 36: 433-448.
- Chang D Y, Li G S, Shen Z H, et al. 2011. The stress field of bottom hole in deep and ultra-deep wells. *Acta Petrolei Sinica*, 32: 697-703.
- Dong L, Zhang Y, Wang L, et al. 2024. Temperature dependence of mechanical properties and damage evolution of hot dry rocks under rapid cooling. *Journal of Rock Mechanics and Geotechnical Engineering*, 16: 645-660.
- Du S, Liu H, Zhi H, et al. 2004. Testing study on mechanical properties of post-high-temperature granite. *Chinese Journal of Rock Mechanics and Engineering*, 23: 2359-2364.
- Fairhurst C 1964. Measurement of in-situ rock stresses. With particular reference to hydraulic fracturing. *Rock Mechanics*, 2.
- Feng Y, Wei Y, Tan Z, et al. 2025. Wellbore breakouts in heavily fractured rocks: A coupled discrete fracture network-distinct element method analysis. *Journal of Rock Mechanics and Geotechnical Engineering*, 17: 1685-1699.
- Gao J. 2018. Study on thermal effect of mesoscopic characteristics of granite based on X-ray Ct technology. *Beijing University of Technology*.
- Guo W, Zhu J, Xu J, Et Al. 2016. A method to determine the porosity and friction coefficient of coarse-grained soil in the model of PFC3D. *Chinese Journal of Underground Space and Engineering*, 12: 157-162.
- Guz A N 2003. Establishing the fundamentals of the theory of stability of mine workings. *International Applied Mechanics*, 39: 20-48.
- Haimson B 1999. Six hydraulic fracturing campaigns at the URL, Manitoba. In: *ISRM Congress*.
- Haimson B 2007. Micromechanisms of borehole instability leading to breakouts in rocks. *International Journal of Rock Mechanics and Mining Sciences*, 44: 157-173.

- Haimson H, Herrick C 1986. Borehole breakouts-a new tool for estimating in situ stress? In: ISRM International Symposium.
- He M-C, Xie H-P, Peng S-P, Et Al. 2005. Study on rock mechanics in deep mining engineering. *Chinese Journal of Rock Mechanics and Engineering*, 24: 2803-2813.
- Hofmann H, Blöcher G, Milsch H, Et Al. 2016. Transmissivity of aligned and displaced tensile fractures in granitic rocks during cyclic loading. *International Journal of Rock Mechanics and Mining Sciences*, 87: 69-84.
- Huang M, Tang C, Zhu W 2000. Numerical simulation on failure process of rock. *Chinese Journal of Rock Mechanics and Engineering*, 19: 468-471.
- Huang Y-H, Yang S-Q, Zeng W 2016. Experimental and numerical study on loading rate effects of rock-like material specimens containing two unparallel fissures. *Journal of Central South University*, 23: 1474-1485.
- Jin Y, Chen M, Liu G 1999. Wellbore stability analysis of extended reach wells. *Journal of Geomechanics*, 5: 11-15.
- Lee M, Haimson B 1993. Laboratory study of borehole breakouts in Lac Du Bonnet granite: A case of extensile failure mechanism. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 30 (7): 1039-1045.
- Li M, Li M, Zhang F, et al. 2025. Assessing the contribution of mineral composition to meso-macro progressive failure in granite under thermo-hydro-mechanical (THM) conditions: Inspiration for hydraulic fracturing in enhanced geothermal systems (EGS). *International Journal of Rock Mechanics and Mining Sciences*, 194: 106238.
- Li N, Zhang S, Wang H, et al. 2021. Effect of thermal shock on laboratory hydraulic fracturing in Laizhou granite: An experimental study. *Engineering Fracture Mechanics*, 248: 107741.
- Liu Q, Xu X, Yamaguchi T, et al. 2001. Testing study on mechanical properties of the Three Gorges granite concerning temperature and time. *Chinese Journal of Rock Mechanics and Engineering*, 20: 715-719.
- Ma Q, Liu X, Wang E, et al. 2025. Micromechanical behavior of granite under high temperature with enhanced Mori-Tanaka model. *Journal of Rock Mechanics and Geotechnical Engineering*, 17 (12), 7628-7638.
- Mastin L G 1984. The development of borehole breakouts in sandstone. Stanford University, California.
- Meier T, Rybacki E, Reinicke A, et al. 2013. Influence of borehole diameter on the formation of borehole breakouts in black shale. *International Journal of Rock Mechanics and Mining Sciences*, 62: 74-85.
- Morita N, Black A, Fuh G-F 1996. Borehole breakdown pressure with drilling fluids—I. Empirical results. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 1996: 39-51.
- Potyondy D O, Cundall P A 2004. A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, 41: 1329-1364.
- Qin W, Zhao Y, Jin A, Et Al. 2025. Analysis of precursor and failure mechanisms of granite under high temperature: based on acoustic emission and 3D-DIC perspectives. *Construction and Building Materials*, 473: 141049.
- Qiu Y-P, Lin Z-Y 2006. Testing study on damage of granite samples after high temperature. *Rock and Soil Mechanics*, 27: 1005-1010.
- Zhang S Q, Yan W D, Li D P, et al. 2018. Characteristics of geothermal geology of the Qiabuqia HDR in Gonghe Basin, Qinghai Province. *Geology in China*, 45: 1087-1102.
- Shang J, Kong C, Li T, et al. 1999. Observation and study on meso-damage and failure of rocks. *Journal of Experimental Mechanics*, 14: 373-383.

- Chen, S.W., Yang, C.H., Liu, P.J., Wang, G.B., 2016. Laboratory simulation test of thermal cracking of beishan granite. *Rock and Soil Mechanics*, 37: 547-556.
- Tang S B, Tang C A, Zhu W C 2006. Numerical investigation on rock failure process induced by thermal stress. *Chinese Journal of Rock Mechanics and Engineering*, 25: 2071-2078.
- Song I, 1998. Borehole breakouts and core diskings in westerly granite: mechanisms of formation and relationship to in situ stress. The University Of Wisconsin-Madison.
- Song I, Haimson B C 1997. Polyaxial strength criteria and their use in estimating in situ stress magnitudes from borehole breakout dimensions. *International Journal of Rock Mechanics and Mining Sciences*, 34: 116.
- Springer J E 1987. Stress orientations from well bore breakouts in the coalinga region. *Tectonics*, 6: 667-676.
- Tian W 2020. Study on the mechanical behavior and damage mechanism of granite after high temperature treatment. *Case Studies in Thermal Engineering*, 61, 104910.
- Vishal V, Pradhan S P, Singh T 2011. Tensile strength of rock under elevated temperatures. *Geotechnical and Geological Engineering*, 29: 1127-1133.
- Wan Z, Zhao Y, Dong F, et al. 2008. Experimental study on mechanical characteristics of granite under high temperatures and triaxial stresses. *Chinese Journal of Rock Mechanics and Engineering*, 27: 72-77.
- Wang L, Dong L, Wang L, et al. 2025. Experimental high-temperature heat treatment of crystalline rocks and analysis of crack development characteristics. *Chinese Journal of Nonferrous Metals*, 35: 1005-1016.
- Wang L, Zhu Z, Lei J, et al. 2021. Mechanical responses to wellbore instability of crystalline rocks in scientific deep well during thermo-mechano coupling. *J. Cent. South Univ. (Sci. Technol.)*, 52: 465-477.
- Wang L, Wang C, Zhang J. 2019 Mechanism analysis and method research of scientific deep well borehole stability. *Geological Equipment*, 20: 25-28.
- Wang Y, Tonon F 2009. Modeling Lac Du Bonnet granite using a discrete element model. *International Journal of Rock Mechanics and Mining Sciences*, 46: 1124-1135.
- Wei Y, Feng Y, Tan Z, et al. 2024. Borehole stability in naturally fractured rocks with drilling mud intrusion and associated fracture strength weakening: A coupled DFN-DEM approach. *Journal of Rock Mechanics and Geotechnical Engineering*, 16: 1565-1581.
- Westergaard H M 1939. Plastic state of stress around a deep well. Harvard University.
- Wu S, Guo P, Zhang S, Et Al. 2018. Study on thermal damage of granite based on Brazilian splitting test. *Chinese Journal of Rock Mechanics and Engineering*, 37: 3805-3816.
- Wu Z, Zhang D, Liang Y, et al. 2025. Mechanical and microstructural properties of Gonghe granite for enhanced geothermal systems: Thermal effects and energy evolution. *Journal of Rock Mechanics and Geotechnical Engineering*, 18 (5), 3512-3525.
- Xu X L, Gao F, Zhang Z Z 2014. Research on triaxial compression test of granite after high temperatures. *Rock and Soil Mechanics*, 35: 3177-3183.
- Xie H, Gao F, Ju Y 2015. Research and development of rock mechanics in deep ground engineering. *Chinese Journal of Rock Mechanics and Engineering*, 34: 2161-2178.
- Xie H, Lu J, Li C, et al. 2022. Experimental study on the mechanical and failure behaviors of deep rock subjected to true triaxial stress: A review. *International Journal of Mining Science and Technology*, 32: 915-950.
- Xie J, Xi B-P, He S-X, et al. 2026. Mesoscopic fracture evolution of granite under different thermal disturbances. *Journal of Central South University*, 33: 767-782.
- Xie J, Zhao Y 2017. Meso-mechanism of permeability decrease or fluctuation of coal and rock with the temperature increase. *Chinese Journal of Rock Mechanics and Engineering*, 36: 543-551.

- Xu Z, Li T, Chen G, et al. 2018. The grain-based model numerical simulation of unconfined compressive strength experiment under thermal-mechanical coupling effect. *KSCE Journal of Civil Engineering*, 22: 2764-2775.
- Yan C, Deng J, Yu B, et al. 2014. Borehole stability in high-temperature formations. *Rock Mechanics and Rock Engineering*, 47: 2199-2209.
- Yang Z, Lipeng L, Bin Z, et al. 2018. Numerical experimental study on biaxial compression of granite based on digital image. *Journal of Hunan University*, 45: 52-57.
- Yew C, Liu G 1992. Pore fluid and wellbore stabilities. SPE International Oil and Gas Conference and Exhibition in China. SPE; Spe-22381-Ms.
- Zhang X, Gong H, Luo Y, et al. 2026a. Effects of high-temperature cooling on the dynamic fracture toughness, fracture energy, and fractal characteristics of granite. *Theoretical and Applied Fracture Mechanics*, 143 (2): 105522.
- Zhang X, Wang G, Jiang Y, et al. 2014. Simulation research on granite compression test based on particle discrete element model. *Rock and Soil Mechanics*, 35: 99-105.
- Zhang Y, Zou M, Zhang Z, et al. 2026b. Thermal cracking properties of granite considering mineral heterogeneity based on a thermo-mechanical grain-based model. *Journal of Earth Science*, 37: 882-889.
- Zhao Y-S, Wan Z-J, Zhang Y, et al. 2010. Experimental study of related laws of rock thermal cracking and permeability. *Chinese Journal of Rock Mechanics and Engineering*, 29: 1970-1976.
- Zhao Y, Meng Q, Kang T, et al. 2008b. Micro-CT experimental technology and meso-investigation on thermal fracturing characteristics of granite. *Chinese Journal of Rock Mechanics and Engineering*, 27: 28-34.
- Zhao Y, Wan Z, Zhang Y, Et Al. 2008a. Research and development of 20 MN servo-controlled rock triaxial testing system with high temperature and high pressure. *Chinese Journal of Rock Mechanics and Engineering*, 27: 1-8.
- Zhao Z, Liu Z, Pu H, Et Al. 2018. Effect of thermal treatment on brazilian tensile strength of granites with different grain size distributions. *Rock Mechanics and Rock Engineering*, 51: 1293-1303.
- Zhou P, Li C, Xie H 2025. Micromechanical properties of granite with insights into mineral interface mechanics. *International Journal of Mining Science and Technology*, 35 (9): 1419-1437.