Fracture Propagation Modes of Lower Cambrian Shale Filled with Different Quartz Contents under Seepage-Stress Coupling

Zhonghu Wu,1,2,3 Shuang Wang,4,5 Jun Chen,4,6 Huailei Song,3 Wentao Wang,3 Ruyue Wang,7 and Hao Liu8

1School of Qilu Transportation, Shandong University, Jinan 250002, China
2Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China
3College of Civil Engineering, Guizhou University, Guiyang, 550025 Guizhou, China
4College of Resources and Environmental Engineering, Guizhou University, Guiyang, 550025 Guizhou, China
5Key Laboratory of Karst Georesources and Environment, Ministry of Education, Guizhou University, Guiyang, 550025 Guizhou, China
6Guizhou Institute of Technology, Guiyang, 550003 Guizhou, China
7SINOPEC Petroleum Exploration and Production Research Institute, Beijing 100083, China
8College of Mining, Guizhou University, Guiyang, 550025 Guizhou, China

Correspondence should be addressed to Shuang Wang; 971540436@qq.com

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The content and spatial distribution of brittle minerals, such as quartz, are important factors in determining the fracture initiation mechanism induced by hydraulic fracturing in shale reservoirs. To further research the impact of quartz content in shales of the Lower Cambrian Niutitang Formation in northern Guizhou on the fracture expansion of its reservoir, 7 groups of randomly filling shale models with different quartz contents were established using rock failure process analysis (RFPA 2D-flow) code for numerical test studies under seepage-stress coupling, and 5 samples were also subjected to uniaxial compression tests using the INSTRON 1346 electrohydraulic servo-controlled material testing machine (200T). The results show that the average growth rate of the compressive strength and the fracture proportion for a quartz content of 50% to 65% are 4.22 and 1.15 times higher than those for 35% to 50%, respectively. Fractures sprout, expand, and breakdown in the shale matrix or at the junctions of the shale matrix and quartz grains. The mechanical properties and pattern of the fracture extension of the shale in the physical tests are similar to those in the numerical tests, indicating the reliability of the numerical simulations. The fractal dimension curves at different stress levels are divided into three stages: flattening, increasing, and surging, and the fractal dimension value for a quartz content of 50%~65% at a 100% stress level is 1.02 times higher than that for 35%~50%. The high degree of natural fracture development in high quartz content formations in shale gas reservoirs is of some reference value for logging data. The research results provide a reference value for the content and spatial distribution of brittle minerals for the initiation mechanism and fracture propagation of hydraulic fracturing in shale reservoirs.

1. Introduction

As one of the main unconventional natural gases, shale gas is freely stored in adsorbed and free forms in black shale with a high carbon content [1–4]. It is favored by countries worldwide for its clean and efficient characteristics, wide distribution, and large reserves, which are considered major strategic resource reserves [5–7]. Nevertheless, the small pores (nanoscale pores) and low permeability of shale gas reservoirs have led to low shale gas recovery and extraction efficiency [8–11]. Additionally, due to the apparent tectonic stress activity in multiple phases, the spatial distribution of mineral components is anisotropic and inhomogeneous. More than 90% of shale gas wells have to be artificially fractured to
create joints, or reservoir fracture modification has to be applied further to improve the extraction efficiency and recovery volume [12–14].

Hydraulic fracturing is considered one of the most effective fracking techniques for shale gas extraction today and has been widely recognized and applied in engineering [15–18]. Shale gas reservoirs are highly inhomogeneous and anisotropic, and reservoir-geomechanics-fracturing simulations are used to investigate the effect of subsequent parent well injection on interwell fracture disturbance and changes in induced stresses [19, 20]. Natural fractures are both shale gas storage spaces and transport channels [21]. Induced fractures under hydraulic fracturing connect natural fractures and laminae running through the shale gas reservoir, resulting in a complex network of fractures [22]. Because the existence of laminae makes shale distinctly anisotropic [23, 24], the mechanical characteristics and fracture expansion paths of shale under hydraulic fracturing vary from one lamina angle to another [25]. From a microscopic view, shale microfracture extension during hydraulic fracturing is caused by the concentration of tensile stresses in front of the fracture, and this microfracturing can increase permeability of shale gas reservoirs by connecting the pore spaces to the microfractures [26, 27]. Additionally, complex fractures are more likely

Figure 1: Regional tectonic geological map of the study area: (a) the location of the study area, (b) the main tectonic movement, and (c, d) the tectonic distribution of the study area.
to form in shales with high brittle mineral contents under hydraulic fracturing, and these generally extend along the boundaries between hard mineral grains and soft organic matter [28, 29]. The fracturing mechanism, fracture extension characteristics, and spatial distribution under hydraulic fracturing are investigated by a true triaxial fluid-solid coupling test system [30] and numerical tests [31-33], which lead to the conclusion that the induced fractures mainly extend along natural fractures and laminar surfaces [34, 35].

In recent years, many studies have performed and laid a solid cornerstone in the area of hydraulic fracture modification [36]. They mainly focus on the interrelationships and expansion patterns between laminated rock masses, natural fractures, pore structures, and hydraulic fracturing [37]. However, these studies are mainly based on the macroscopic mechanical damage and microscopic natural fracture expansion of rock masses. The influences of mineral content and inhomogeneity on cracking and damage patterns in shale are rarely reported. Additionally, the application and reference values of brittle mineral contents, such as quartz, with regard to logging techniques are rarely mentioned. Therefore, in this paper, a numerical experimental study is conducted on the seepage-stress coupling in randomly filled shales with different quartz contents using RFPA<sup>2D</sup>-flow to analyze the fracture process, the acoustic emission evolution characteristics, and the relationship between filling with different quartz contents and the fractal dimension, and a brief analysis of the influence of the content of brittle minerals, such as quartz, in shale reservoirs on the logging data, is also conducted. The research results provide reference value for exploring the mechanism of secondary fracture initiation in shale reservoirs by hydraulic cracking and enhancing the recovery of shale gas.

2. Geological Characteristics of the Area

In this study, the shale gas reservoir of the Lower Cambrian Niutitang Formation in northern Guizhou is used as the research object, and the research area is divided into the Yangtze platform area because of its consistency with the regional tectonic evolution of the Yangtze platform [38]. As shown in Figure 1, the research area is subject to the superposition of multiple phases of tectonic activity. Since the late Middle Age, the tectonic evolution of this research area has mainly been divided into three phases: the late Middle Age-Silurian development phase, the Devonian-Middle Late Triassic development phase, and the late part of the Late Triassic [39]. The tectonic activity frequency analysis shows that the research area was mainly influenced by the 380 Ma-80 Ma late Caledonian period and the 10 Ma-60 Ma Yanshan period (Figure 2), which formed a complex shale reservoir tectonic fracture mesh and allowed the storage and transport of shale gas. The folds in the research area are mainly “spaced trough” structures [39], with a series of NE- and NS-oriented compound anticline and compound syncline structures. The faults are mainly NE- and NNE-oriented compressional-torsional faults, with multiple strike faults cutting and overlapping each other. The NS tectonic zone is the earliest, followed by the NNS tectonic zone, and the NE tectonic zone was the last to be formed [40]. The nature of the faults can control the complexity of fracture development; generally speaking, the density of fracture development is higher for compressional-torsional faults. Moreover, the influence of the type of tectonics on the fracture development and the density and penetration of fracture development on the two flanks of the anticlines are lower than those of the axis.

3. Samples and Methods

3.1. Samples

3.1.1. Mineral Content of Samples. The whole-rock quantification and clay mineral analysis of 20 shale samples using X-ray diffraction technology illustrate that the quartz content is approximately 36%-92%, averaging 78%. The contents of pyrite, plagioclase, and clay minerals (kaolinite and illite) ranged from 2% to 25%, 3% to 23%, and 2% to 30%, respectively. The analysis of the mineral content data shows that the quartz content increases with increasing depth of shale burial, while the clay minerals decrease (Figure 3) [21]. The different mineral contents and characteristics also lead to different levels of fracture development, with fractures increasing with quartz content and decreasing with clay mineral content (Figure 4).

3.1.2. Physical Test Specimens. An analysis of the mineral composition of 5 samples using X-ray diffraction shows that all 5 samples contain more than 50% quartz, with a maximum of 81.3% (Figures 5 and 6) [41]. These 5 samples are tested under uniaxial compression using an INSTRON 1346 electrohydraulic servo-controlled material testing machine with a loading rate of 0.01 mm/min (Figure 7). The results of the uniaxial compression tests in Table 1 [41, 42] show that the modulus of elasticity increases with increasing quartz content, and the highest modulus of elasticity and the most complex fracture extensions occur when the quartz content is at its maximum, indicating that quartz...
Figure 3: Proportional distribution of mineral content: (a, b) the mineral compositions and proportions of the 20 samples, respectively.

Figure 4: Relationship between mineral properties, content, and fracture density: (a) the relationship between quartz content and natural fracture density and (b) the correlation between clay mineral content and natural fracture density.
is one of the main factors controlling the mechanical properties of shale.

3.2. Methods

3.2.1. PCAS Software. The PCAS software can be used to not only quantify and analyze fracture-related data but also store the relevant data [43, 44]. To concretely represent the fracture rupture of shales filled with different quartz contents under seepage-stress coupling, the fracture quantification output is performed as follows: (1) the acoustic emission map is set to a 600 × 600-pixel size and imported into the PCAS software, automatic image segmentation is performed, and the binary map is obtained; (2) the binary mapping map is smoothed, and the noise is removed to obtain the fracture skeleton map; (3) the fracture skeleton data is analyzed to derive the fracture parameters.

3.2.2. Fractal Theory. Fractal theory differs from traditional Euclidean geometry in that it considers that diverse spatial dimensions can be either continuous or discrete and is often used to characterize objects that are widely irregular and morphologically complex in nature, quantifying the self-similar characteristics in fractals by their fractal dimensions [45, 46]. Fractal dimensions vary considerably for different object representations and are divided into the information dimension $D_i$, the correlation dimension $D_c$, the Lyapunov dimension $D_l$, and the box-counting dimension $D_b$. In this investigation, the box-counting dimension is used to analyze the fractal characteristics of shale (Equation (1)) [47, 48]. The whole calculation process is carried out in the MATLAB software platform in the following steps: (1) the shale acoustic emission map is processed into a 600 × 600-pixel size image; (2) the image is imported for image greyscaling, binarization preprocessing, and storing the correlation numbers; (3) the binary map is overlayed in the second step with square boxes of side length $r$, the number of square boxes $N(r)$ in the damaged area is calculated, and the correlation data are stored at the same time; (4) data processing is performed, and double logarithmic axes for $1/r$ and $N(r)$ are obtained for regression analysis.

$$D_s = \lim_{r \to 0} \frac{\log N(r)}{\log r},$$ (1)

where $D_s$ is the self-similar fractal dimension of the shale damage zone, $r$ is the side length of the square box, and $N(r)$ is the total number of boxes covering the entire shale damage zone with square boxes of side length $r$.

3.2.3. Seepage-Stress Coupling Equation. The shale has a large proportion of fragile minerals similar to quartz and calcite, which are significantly brittle and have high moduli of elasticity. Under stress loading, the shale exhibits mainly elastic characteristics, the length of which depends mainly on the degree of hardness of the rock, i.e., the magnitude of the modulus of elasticity. Therefore, the mechanical characteristics of shale mineral unit particles can be
characterized using the constitutive relationship of elastic damage mechanics.

Equations of balance

$$\frac{\partial \sigma_{ij}}{\partial x_{ij}} + \rho X_j = 0 \quad (i, j = 1, 2, 3).$$  \hfill (2)

Geometric equations

$$\varepsilon_{ij} = \frac{1}{2} (\mu_{ij} + \mu_{ji}) \varepsilon = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}. \quad (3)$$

Constitutive equations

$$\sigma_{ij}' = \sigma_{ij} - \alpha p \delta_{ij} = \lambda \delta_{ij} \varepsilon + 2G \varepsilon_{ij}. \quad (4)$$

Flow equation

$$k \nabla^2 p = 0. \quad (5)$$

Coupling equation

$$k(\sigma, p) = \xi k_0 e^{-\beta (\sigma_{ij} - \alpha p)} \quad (6)$$

where (2)–(5) are from Biot’s theory of consolidation [49] and (6) represents the relationship between stress and penetrability. $\sigma_{ij}$ and $\rho$ represent the total stress and body density, respectively; $\varepsilon_{ij}$ and $\mu_{ij}$ represent the total strain and displacement curves, respectively; $\sigma_{ij}'$, $\alpha$, and $p$ represent the effective stress, pore water pressure coefficient, and pore water pressure, respectively; $\delta$, $G$, and $\lambda$ represent the Kronecker coefficient, shear modulus, and Lamé coefficient, respectively; $k$ and $k_0$ represent the penetrability coefficient and initial penetrability coefficient, respectively; $\nabla^2$ and $\beta$ represent the pull-down operator and coupling coefficient, respectively; $\xi$ ($\xi \geq 1.0$) represents the sudden jump multiplier of the penetrability coefficient, which increases with unit damage. $\xi = 5$ can be assumed to be the unit damage $0 < D < 1$ and $\xi = 100$ to be the variation over the range of unit damage $D = 1$ [50], as shown below [51, 52].

3.2.4. Constitutive Equations for Damage in Shale Units from a Mesoscopic View. Once the stress or strain in the shale unit reaches a given damage threshold, damage to the unit starts to occur. The constitutive relationships of the shale mesoscopic unit minerals are shown in Figure 8 [53–55].

$$E = (1 - \omega)E_0, \quad (7)$$

where $\omega$ represents the damage parameter and $E$ and $E_0$ are the elastic moduli of the damaged and undamaged parts, respectively.

The damage parameters of the unit under uniaxial tension can be expressed as [56]

$$D = \begin{cases} 0 & \varepsilon > \varepsilon_{t0}, \\ 1 - \frac{\lambda \varepsilon_{t0}}{\varepsilon} & \varepsilon_{tu} < \varepsilon \leq \varepsilon_{t0}, \\ 1 & \varepsilon \leq \varepsilon_{tu}, \end{cases} \quad (8)$$

where $\lambda$ is the residual tensile strength factor and $f_{t0} = \lambda f_{t0}$ is assigned as shown in Figure 8. The threshold strain $\varepsilon_{t0}$ characterizes the magnitude of the elastic maximum tensile strain, and $\varepsilon_{tu}$ is the maximum tensile strain at which the unit wastes its tensile load carrying volume. The maximum
The tensile strain of the unit can be expressed as $\varepsilon_{tu} = \eta\varepsilon_{t0}$, where $\eta$ is the maximum strain coefficient of the unit.

The unit damage variables are shown in the following equations for uniaxial compression conditions [52, 57]:

$$D = \begin{cases} 0 & \varepsilon < \varepsilon_{c0}, \\ 1 - \frac{\lambda\varepsilon_{c0}}{\varepsilon} & \varepsilon \geq \varepsilon_{c0}, \end{cases} \quad (9)$$

where $\varepsilon_{c0}$ is the unit compressive strain at the elastic restraint and $\lambda$ is the residual strength coefficient. The assumption $f_{cr}/f_{c0} = f_{tr}/f_{t0} = \lambda$ is correct when the unit is under uniaxial compression or tension.

### 4. Numerical Tests

**4.1. RFPA Software.** RFPA2D is a realistic simulation of the fracture process and damage mode of brittle materials based on finite unit theory, dividing different mineral compositions into unit bodies with different characteristics and forming a unit grid by four-node isoparametric units, which is fully validated in rock fracture damage simulations. The mechanical parameters of rock, such as the elastic modulus, strength, and Poisson’s ratio, are heterogeneous and assumed to conform to the Weibull distribution. The mesoscopic element is assumed to be homogeneous and isotropic, and its damage evolution conforms to the specific elastic damage constitutive law [54, 58, 59].

Figure 9 shows the distribution of mineral grains obtained under polarized light microscopy in a shale sample from the Lower Cambrian Niutitang Formation in northern Guizhou, with bright white quartz grains, bright black shale matrix, and calcite of veins running throughout the shale sample. It is assumed that the mechanical parameters of the mesoscopic material quartz and shale matrix obey Weibull’s random distribution in this model [58, 60, 61], thus characterizing the heterogeneity of the shale (Equation (10)) [58, 62].

$$f(a) = \frac{m}{a_0} \left( \frac{a}{a_0} \right)^{m-1} \exp \left[ -a \left( \frac{a}{a_0} \right)^m \right], \quad (10)$$
Table 2: Shale mesomaterial unit parameters.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Elastic modulus (GPa)</th>
<th>Compressive strength (MPa)</th>
<th>Poisson’s ratio</th>
<th>Pressure rabbi</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>51.6</td>
<td>145</td>
<td>0.22</td>
<td>14</td>
<td>35</td>
</tr>
<tr>
<td>Quartz</td>
<td>96.0</td>
<td>375</td>
<td>0.08</td>
<td>15</td>
<td>60</td>
</tr>
</tbody>
</table>

Figure 9: Spatial distribution of mineral particles.

Figure 10: Numerical model of quartz-filled shale with different contents.

Figure 11: Schematic diagram of stress loading and grid element division.
where $\alpha$ represents the material parameters of the meso-unit in shale, $a_0$ represents the mean material parameters of the meso-unit in shale, and $m$ represents the uniformity of the material in shale.

In triaxial stress loading tests, the magnitude of the confining pressure has a strong relationship with the damage model of the rock, as follows: (1) at negative confining pressure or low confining pressure, or when the surface of the rock sample easily slides with the pressurized plate, the rock is broken in tension; (2) as the surrounding pressure continues to rise, the rock gradually undergoes shear damage; (3) when the surrounding pressure is large or rises to a fixed value (generally approximately 150 MN/m$^2$), the rock is broken in plasticity. However, the final damage of the rock can be represented by not only a single damage model but also often a composite damage model. In the RFPA, it is assumed that the strength failure criterion for shales obeys the Mohr-Coulomb criterion, as shown in Equation (11) [63].

$$\tau = c + \sigma \tan \varphi,$$

where $\tau$ is the shear strength of the shale, $\sigma$ is the maximum principal stress acting on the surface of the shale, $\varphi$ is the
angle of internal friction of the shale, and \( c \) is the cohesion between mineral particles in the shale.

### 4.2. Numerical Model.

The unit strengths of rocks at the mesoscopic scale satisfy a specific principle of normal statistical distribution, and the underlying cause of the macroscopic nonlinear rupture of quasi-brittle mineral materials results from the mesoscopic scale heterogeneity of the rock [64]. To adequately represent the heterogeneity of mineral grains in shale, the Monte Carlo standard was used to assess the mineral units in RFPA\(^{2D} \). The initial mechanical parameters of the mineral units need to be set when building the numerical model, as shown in Table 2.

In physical tests, the random distribution of minerals, the filling content, and the organic combination of seepage-stress coupling cannot be fully reflected. However, it is possible to set different unit mechanical parameters representing different mineral characteristics and unit filling ratios in RFPA\(^{2D} \)-flow to establish a coupled seepage-stress model to simulate the whole process of shale rupture; to better reflect the heterogeneity of shale, each group of models randomly fills the shale. The model was built as a 50 mm \( \times \) 50 mm square and divided into 200 \( \times \) 200 units. The quartz content was set to an initial value of 35% with an increment of 5%, creating a total of 7 groups of models with quartz contents of 35%, 40%, 45%, 50%, 55%, 60%, and 65%, as shown in Figure 10. Displacement loading was used with a loading speed of \( \Delta S = 0.0003 \) mm and a fixed confining pressure \( P = 12 \) MPa in the model and a fixed seepage pressure difference \( \Delta P = P_1 - P_2 \) with \( P_1 = 8 \) MPa and \( P_2 = 0 \) MPa, as shown in Figure 11. Water is considered a fluid medium in RFPA\(^{2D} \)-flow, while the upper and lower percolation boundaries are set in the pattern to create a penetration pressure difference, thus allowing the medium to percolate and expand in the model. Figure 11 shows the numerical model of shale created by RFPA\(^{2D} \)-flow. The brightness of the units in the model represents the difference in the modulus of elasticity of the different materials. The

<table>
<thead>
<tr>
<th>Quartz content (%)</th>
<th>The fracture area</th>
<th>Percentage of fractures (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>52253</td>
<td>14.51</td>
</tr>
<tr>
<td>40</td>
<td>50277</td>
<td>13.97</td>
</tr>
<tr>
<td>45</td>
<td>44546</td>
<td>12.37</td>
</tr>
<tr>
<td>50</td>
<td>48779</td>
<td>13.55</td>
</tr>
<tr>
<td>55</td>
<td>62350</td>
<td>17.32</td>
</tr>
<tr>
<td>60</td>
<td>53597</td>
<td>14.89</td>
</tr>
<tr>
<td>65</td>
<td>61362</td>
<td>17.04</td>
</tr>
</tbody>
</table>

Table 4: Total amount and proportion of fractures in shale with different quartz contents.

![Figure 14: Schematic diagram of the fracture process, acoustic emission, and fracture skeleton of shale with different quartz contents.](image1)

![Figure 15: Percentage of fractured infilled shales with different quartz contents.](image2)
bright grey units represent the quartz mineral material, which has a higher modulus of elasticity, while the grey-black units represent the shale matrix, which has a lower modulus of elasticity.

5. Results

5.1. Characteristics of Shale Mechanical Properties. Figure 12 shows the trend of stress-strain curves for shales filled with different quartz contents under seepage-stress coupling. This is analogous to the stress-strain curve of the rock under triaxial tests, both of which show the destruction of the rock after the peak strength with the continuous loading of stress, but there are small differences in the trend of the curves at different stress loading stages. Table 3 indicates the compressive strength and modulus of elasticity of the seven categories of shale samples. Figure 13 shows the trends in the modulus of elasticity and compressive strength for the different quartz-filled shales. Both the compressive strength and elastic modulus rise with increasing quartz content, while the trends differ significantly in that the elastic modulus increases nearly linearly with increasing quartz content, similar to the results of the uniaxial compression test above. Conversely, the compressive strength rises in a stepwise manner with quartz content. When the quartz content is 35%, the compressive strength of the shale is the lowest, 87.18 MPa. When the quartz content is 40%–50%, the compressive strength curve tends to level off. When the quartz content is greater than 50%, the compressive strength grows at a high rate with the quartz content, and the average growth rate at 50%–65% is 4.22 times higher than that at 35%–50%. The compressive strength reached a maximum of 105.33 MPa at a quartz content of 65%. This is because the shale matrix accounts for a significant proportion of shale, the quartz has less control over the mechanical characteristics of the shale, and the shale matrix is damaged before the quartz under stress loading. Additionally, it indicates that the shale matrix and quartz are weakly cemented, and water pressure has a softening effect on them. Hydraulic fractures preferentially extend along the shale matrix destruction path during the hydraulic fracturing extraction process and where the shale matrix is cemented to quartz.

Table 5: Fractal dimension values of stress levels under different quartz contents.

<table>
<thead>
<tr>
<th>Stress level</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>35%</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>40%</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>45%</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>50%</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>55%</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>60%</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>65%</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
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<td>0.00000</td>
<td>0.00000</td>
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</table>

Figure 16: Schematic diagram of quartz content and fracture density: (a) the relationship between quartz content and fracture density and (b) the correlation between shale gas reservoir properties and hydraulic fracturing.
When the fractures in all directions converge to form macroscopic penetrating fractures, they contribute to the rapid transport of hydrocarbons, thereby increasing recovery.

5.2. Fracture Prolongation and Acoustic Emission Characteristics. It shows a schematic diagram of the fracture process, acoustic emission, and fracture skeleton of shales filled with different quartz contents (Figure 14). It is clear from the figure that the fracture development process varies considerably between the different quartz-filled shales and is summarized in three stages: initial fracture initiation, fracture prolongation, and destruction. In summary, regardless of the changes in the quartz content and fracture expansion path, the sprouting, expansion, and destruction of fractures are sprouted and expanded at the junction of the shale matrix or quartz and shale matrix because the mechanical characteristics of quartz particles are much larger than those of the shale matrix. In the process of continuous stress loading, fracture expansion turns at quartz, and the shale matrix is damaged or even destroyed first. Moreover, in the process of shale deposition, quartz particles are randomly distributed and unevenly arranged in space, and there is weak cementation between the shale matrix and quartz particles. Additionally, under the action of penetrability pressure, the cohesive force is weakened, and the mechanical characteristics of quartz particles are reduced, resulting in easier damage. When the quartz content <50%, the initial sprouting of fractures is all at the boundary of shale; when the quartz content > 50%, the sprouting of fractures shifts to the middle of shale; when the quartz content is 50%, the initial fractures occur at both the boundary and the middle, indicating that a quartz content of 50% is the vital node influencing the mechanical characteristics of the shale, because the quartz content plays a controlling role with regard to the mechanical characteristics of shale.

The different colors represent different damage characteristics in the acoustic emission diagram, with red representing tensile damage, yellow representing shear damage, and black representing complete damage. From the acoustic emission diagrams, it may be considered that at various quartz contents, the shale is mainly damaged in tension with shear damage. This is because the fractures expand in the shale matrix or at the cementation of the shale matrix with the quartz under low confining pressure axial compressive stresses. At this point, they expand into branching fractures as the tangential tensile stresses continue to concentrate at the end of the fracture, followed by the branching fractures gradually turning parallel to the orientation of the greatest
main compressive stress. As the main compressive stress continues to load, when the multicomponent branch fractures turn parallel to the greatest main compressive stress, they tend to form penetrating fractures, which are eventually accompanied by shear damage, which is the reason why tensile damage (compressive tension fracturing) is accompanied by shear damage under compressive stress and demonstrates the mechanical nature of shale to resist compression but not tension. The expansion of fractures is similar to Griffith’s strength theory, which states that first, stresses are constantly concentrated at the ends of microfractures and microporosities. When the stresses exceed the maximum strength, damage occurs, which is then concentrated at the next weakest point, leading to damage at the next weakest point, and by analogy, each one breaks down, eventually forming macroscopic fractures. Water plays two main roles in this process: it weakens the cementation strength between the shale matrix and the quartz particles, making it easier for the fractures to expand, and the penetrability pressure forces the fractures to expand in all directions, forming macroscopic penetrating complex fractures.

The fracture percentage is a quantitative evaluation of the fracturing of a sample, and the size is equal to the percentage of the fracture area to the sample area. Corresponding data, such as the fracture area of the seven groups of processed samples are shown in Table 4. To further reflect the trend of fracture expansion in the different quartz-filled shales, the fracture ratios in Table 4 are plotted in Figure 15. It is clear from Figure 15 that the fracture ratios are greatest for a quartz content of 55%, the corresponding fracture areas are also the largest, and the acoustic emission and fracture skeleton plots are the most complex. The average fracture ratio for a quartz content of 50%–65% is 1.15 times higher than that for 35%–50%, which can indicate that the quartz content has a further effect on fracture expansion, and the larger the quartz content is, the more difficult the fracture geometry mesh, the greater the drainage area and the larger the extraction volume. It is further concluded that the brittle mineral content directly affects the shale fracturing effect and shale gas recovery during hydraulic fracturing, similar to the findings of [51], as demonstrated in Figure 16.

5.3 Fractal Characteristics of Fracture Processes in Shale from a Mesoscopic View. Table 5 shows the fractal dimensions for different stress levels and different quartz-filled shales, and Figure 17 shows the damage fractal characteristics fitted to the shale at a stress level of 100% and quartz content c = 65%.

It demonstrates the relationship between the stress level and fractal dimension for various quartz contents in the shale (Figure 18). As we have seen from the graph, the fractal dimension curve changes at different stress levels in three stages: flattening, increasing, and surging. The fractal dimension remains zero until the stress level is lower than 50%, and the fractal dimension curve becomes flat, indicating that no damage occurs in the shale at this stage, i.e., the acoustic emission number is zero. This stage also corresponds to the elastic deformation phase of the stress-strain curve. The length of the elastic deformation process depends mainly on the strength of the rock material, and the long smoothing phenomenon in Figure 15 indicates that the quartz content is one of the significant reasons for determining the mechanical characteristics of the shale. When the stress level reaches 50%, the fractal dimension starts to show a near-linear increase, indicating that the rupture development stage has begun and damage begins to occur within the shale. After the stress level reaches 90%, there is a high angular surge in the fractal dimension, and at 100%, the shale is devastated, and the fractal dimension reaches its maximum. The fractal dimension of quartz-filled shales with 50% to 65% at a 100% stress level is 1.02 times higher than that of 35% to 50%, and the fractal dimension of quartz-filled shales with 65% is the highest at 1.44, the corresponding fracture paths are also quite complex, indicating that the higher the
quartz-filled shales are, the more brittle they are, and the more likely they are to break suddenly when they reach their peak strength. Therefore, in shales with high quartz contents, hydraulic fracturing is more likely to induce the formation of fractures and increase the oil and gas drainage area, thus increasing the amount of oil and gas recovery.

**Figure 21:** Relationship between the natural gamma curve and mineral composition of shale: (a) well CY-1 and (b) well TX-1.
It shows the relationship between the quartz content and fractal dimension at various stress levels (Figure 19). As shown in the graph, the fractal dimension values at a stress level of 100% differ from those at 90%, which is due to the step-in-step loading used in the test, which maximally selects the fractal dimension values at the destruction of the peak-strength shale to better characterize the fracture of the shale. The fractal dimension curve increases and then decreases with increasing quartz content up to a 90% stress level, because when the quartz content is small, the shale matrix is more prone to damage relative to the quartz grains. When the quartz content is greater than the shale matrix, the quartz is stronger than the shale matrix, so it is difficult to damage the shale internally, and the amount of damage is small, resulting in the fractal dimension decreasing as the quartz content increases. However, when the stress reaches 100%, the fractal dimension curve shows an overall increase with increasing quartz content due to the shale’s mechanical characteristics. The higher the quartz content is, the more pronounced the brittle characteristics of the shale and the more complex the damage, thus indicating that the quartz content has great control over the mechanical characteristics of the shale and that hydraulic fracturing is more effective in areas with high quartz contents in the shale.

It shows a three-dimensional surface plot of the relationship between the quartz content, stress level, and fractal dimension (Figure 20). The three-dimensional surface is similar to a waterfall, showing three distinct phases: straight dipping, slowing down, and lying flat. This phenomenon indicates that at the beginning of the stress loading, the shale has a high modulus of elasticity and is in the elastic deformation phase for a long time, with no change in the fractal dimension. At the slowing down phase, the shale enters the rupture development phase, and damage occurs internally, but this process is short, and the surface soon enters the straight dipping phase. The greater the quartz content is, the more obvious this phase becomes, indicating that the shale shows prominent brittle characteristics. Therefore, the fractal dimension can be used to characterize the fracture development of the rock, and the mechanical characteristics of the rock can be analyzed more effectively.

5.4. Relationship between Quartz Content and Logging Evaluation. Shale gas reservoir logging evaluations should be based on the characteristics of self-generating and self-storing shale gas reservoirs. In addition to evaluating the same basic characteristics of conventional reservoirs, such as lithology and physical properties, shale gas reservoirs should also be evaluated in terms of gas-bearing properties and later extraction value, taking into account geological needs. The main technologies involved are the following: (1) shale mineral composition determination and processing technology, (2) shale gas parameter modelling technology, (3) brittleness evaluation and fracturing prediction technology, and (4) reservoir effectiveness evaluation technology. In this study, the influence of quartz mineral content in shale reservoirs on logging data is briefly analyzed in terms of both shale mineral composition determination and brittleness evaluation.

A popular topic of research related to this has been reported in previous studies [40, 65–69], where the dynamic rock modulus of elasticity and Poisson’s ratio were obtained from array acoustic logging, combined with static rock mechanics parameters and the statistical analysis of longitudinal core fractures. The results show that the fracture density is higher at sites with high moduli of elasticity and low Poisson’s ratios [68]. The presence of quartz as a major mineral component in shale reservoirs is critical. Quartz is a typical brittle mineral with distinct brittle characteristics, a high modulus of elasticity, and a low Poisson’s ratio. Thus, it also indirectly indicates that quartz content is a good guide for logging techniques. Although the relationship between logging and quartz content is not explicitly stated in Sun et al.’s study [38], the organic carbon content calculated from the logs correlates well with the quartz content, and their location in the formation fits perfectly (Figure 21) [40], which suggests that the quartz content in shale reservoirs is informative for logging techniques.

6. Conclusions

(1) The modulus of elasticity and compressive strength increase nearly linearly and increase in a stepwise manner with increasing quartz content, respectively. The average growth rates of the compressive strength and fracture proportion for quartz contents of 50% to 65% are 4.22 and 1.15 times higher than those for 35% to 50%, respectively. The mechanical properties and pattern of fracture extension of the shale in the physical tests are similar to those in the numerical tests, indicating the reliability of the numerical simulations.

(2) The fractal dimension curve changes at different stress levels in three stages: flattening, increasing, and surging. The fractal dimension value for a quartz content of 50% to 65% at a 100% stress level is 1.02 times higher than that for 35% to 50%, the fractal dimension of quartz-filled shales with \( c = 65\% \) is the highest at 1.44, and the corresponding fracture paths are also quite complex.

(3) The fracture density is higher in areas with high moduli of elasticity and low Poisson’s ratios. Additionally, the organic carbon content calculated from the log correlates well with the quartz content, and their location in the formation fits perfectly. Therefore, the quartz content is of some reference value for the logging data.

Data Availability

The data used to support the research is available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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References


