Hydraulic Fracturing in a Confined Space System: Stress State, Fracture Space, and Production Enhancement Mechanism

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Abstract: Existing mechanical models for hydraulic fracturing technology are established based on open space systems, assuming fractures are primarily formed through tensile failure. However, the source mechanism of newly created fracture space under confined space conditions with constant total volume remains unclear. This study develops a mechanical model for hydraulic fracturing in confined space systems based on fundamental principles including volume conservation, pore volume redistribution, Newton's third law, and Pascal's law. The research demonstrates that: the formation of artificial fractures and accommodation space for proppants originates from the adjustment and redistribution of existing pore space; compressive differential deformation provides the mechanical basis for shear fracture formation; rock deformation and failure follow an evolutionary sequence of "compression (generating fracture space) → tension (controlling fracture propagation direction) → differential deformation (forming shear fractures)."Based on the newly established mechanical model and Biot's poroelastic coupling theory, a novel fracturing production enhancement mechanism is proposed. This mechanism can provide theoretical guidance for well placement, wellbore trajectory design, and hydraulic fracturing target optimization, contributing to improved reservoir utilization and recovery rates, while offering new theoretical foundations for reservoir development numerical simulation..

Highlights

(1)The artificial fractures and proppant-accommodating spaces formed in a confined space system are the result of the adjustment and redistribution of the existing pore space.

(2)The increase in reservoir fluid pressure and fracture space are the controlling factors of fracturing production increase.

(3)The compaction of the formation after reservoir formation, the secondary enlargement of diagenetic minerals, and the expansion of clay minerals can all increase the pressure of the reservoir fluid.

(4)The three-dimensional distribution of porosity and the reservoir fluid pressure parameters after fracturing can be used to quantitatively evaluate the effect of hydraulic fracturing and predict production.

Keywords: Confined space system; Pore volume redistribution; Fracture space; Biot's poroelastic coupling theory; Oil enhancement mechanism

1. Introduction

Hydraulic fracturing has long been regarded as a key stimulation technique for enhancing the recovery of low-permeability oil and gas reservoirs. Since the 1950s, when Hubbert and Willis proposed the classical linear elastic fracture model (Hubbert and Willis, 1957)[8], it has been assumed that fractures form in an infinite or semi-infinite homogeneous elastic medium in a tensile mode. Subsequently, the PKN and KGD[1][11] models were developed by Perkins and Kern (1961) [13]and Geertsma and de Klerk (1969), respectively, to describe the planar propagation characteristics of fractures (Perkins and Kern, 1961; Geertsma and de Klerk, 1969)[4][5][6]. In recent years, models such as the Finite Element Method (FEM), Discrete Fracture Network (DFN) (Berkowitz, 2002, Olson, J.E., & Dahi-Taleghani, A. 2010) [2,12], and phase-field fracture models(Miehe et al., 2010)[7] have significantly advanced our understanding of fracture propagation, stress redistribution, and fracture conductivity. However, these conventional models commonly assume that fracture propagation occurs in an open or semi-infinite elastic medium, neglecting the spatial confinement of real geological formations. Moreover, they diverge significantly from the complex fracture networks (including shear fractures) observed in modern volume fracturing through microseismic monitoring(Fisher, M.K., & Warpinski, N.R. 2012 , Warpinski et al.,Warpinski et al., 2009)[5][16]. This fundamental assumption is now facing serious challenges in the context of widespread application of modern volume fracturing technologies.

With the rise of shale gas and tight oil development, massive volume fracturing technology has been widely applied. Unlike traditional small-scale fracturing, volume fracturing involves massive injection volumes—typically millions of pounds of proppant and tens of thousands of cubic meters of fracturing fluid. This high-intensity, large-volume operation creates a complex multi-stage fracture network around the wellbore, significantly enhancing the reservoir’s flow capacity (Economides and Nolte, 2000)[4] and enabling overall optimization of reservoir stimulation (Mayerhofer et al., 2010)[9].However, this large-scale injection of fluids and solids raises a fundamental and critical question: where does the internal space within the formation come from to accommodate such a vast volume of injected materials? Traditional theories have primarily focused on fracture opening and conductivity, assuming that as long as failure criteria are met, sufficient fracture space will naturally be generated. Yet, they largely overlook the fundamental physical issue of spatial availability. Prior to the work presented in this paper, there has been virtually no systematic research addressing this “volume constraint” problem—how exactly the formation accommodates these injected materials within a confined underground space remains an underappreciated and insufficiently understood issue.

To address this fundamental issue, this study proposes a new mechanical model for hydraulic fracturing under confined space constraints. Within this framework, fracture formation is no longer viewed as a purely tensile failure process, but rather as a volume reconfiguration process driven by compressive deformation, pore collapse, and localized shear failure. This model introduces the fundamental principles of rock volume conservation and pore space redistribution, and draws upon Biot’s theory of poroelasticity in porous media (Biot, 1941)[3]. It emphasizes that the creation of any new fracture space must be accompanied by a reduction in existing pore volume. This perspective breaks away from the traditional assumption that “fracture propagation equals space creation,” and also rejects the notion of “volume expansion” as a valid explanation. Instead, it redefines the mechanical essence of fracture formation under realistic geological constraints.

Building upon this new model, the paper further reveals an enabling mechanism for production enhancement through hydraulic fracturing: the process not only improves flow conditions by creating high-conductivity fractures, but more importantly, the compressive deformation during fracturing significantly reduces the original pore volume, resulting in an increase in the internal fluid pressure of the reservoir. This elevated pressure not only enhances the mechanical driving force for hydrocarbon migration toward the wellbore but also partially overcomes the confining effect of surrounding rock, thereby mobilizing more reservoir fluids and potentially converting isolated pores into interconnected ones. Therefore, the essence of production enhancement lies not only in creating new flow pathways, but also in mechanically empowering and pressure-activating the reservoir system. This novel perspective not only broadens the scope of conventional fracturing theory but also provides new insights for fracturing design and production forecasting.

In addition, this new model holds significant practical value in reservoir stimulation, production enhancement design, and economic evaluation. By introducing the concept of pore space redistribution, it enables more accurate prediction of effective proppant placement efficiency, thereby optimizing fracture space design and improving proppant utilization. Moreover, based on the newly proposed mechanism of reservoir pressure elevation, the model facilitates more effective selection of injection pressure and fluid volume, enhancing the efficiency of fracturing fluid usage and reducing operational costs. Furthermore, the model allows for more precise assessment of stimulation effectiveness, offering theoretical support for the optimization of reservoir development strategies. Overall, it demonstrates strong potential for impactful engineering applications in unconventional reservoir development.

The remainder of this paper is organized as follows: Section 2 presents the theoretical foundation of the confined-space mechanical model in detail, including stress analysis, boundary conditions, volume balance equations, and fracture criteria. Section 3 validates the proposed model based on the characteristics of microseismic activity. Section 4 discusses the origin of fracture space, the production enhancement mechanism, fracture conductivity, and new perspectives for numerical simulation. Section 5 elaborates on the new mechanism of production enhancement and its implications for fracturing design and reservoir development strategies.

2. Stress Field in a Confined Space System

2.1 Key Conceptual Definitions

2.1.1Confined Space System

A confined space system refers to a relatively closed domain filled with both fluid and rock, within which the rock cannot move freely. According to Newton’s Third Law, the presence of high-pressure fluid in such a system necessarily implies a reactive force exerted by the surrounding rock, thus forming a pair of action and reaction forces.

When large-scale hydraulic fracturing is considered within a confined space system, both total volume (rock volume + pore volume before fracturing) and pore volume are subject to conservation principles. The space required for the formation of new fractures during fracturing is obtained through the adjustment and redistribution of pre-existing pore space, which simultaneously serves as the accommodation space for a large amount of proppant. While the total volume remains constant, its composition changes to: rock volume + pore volume (after fracturing) + proppant volume.

2.1.2 Stress State

In conventional models, which assume an open-space system (with unlimited and freely expandable volume), tensile stress is not opposed by any reactive force, resulting in a non-compressive environment that allows free tensile opening. The stress condition can be expressed as: fluid pressure > minimum principal stress + tensile strength → fracture opening (tension-dominated).

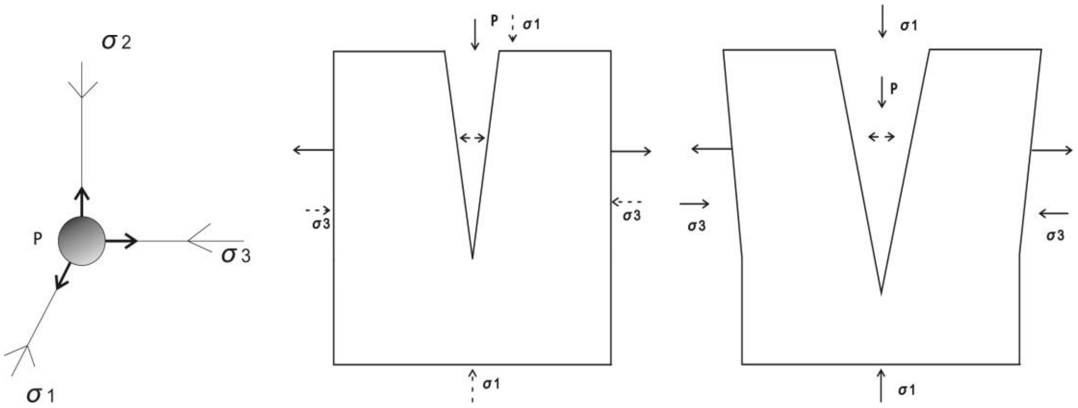

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Fig. 1 Stress state and 2D fracture propagation model under an open-space system

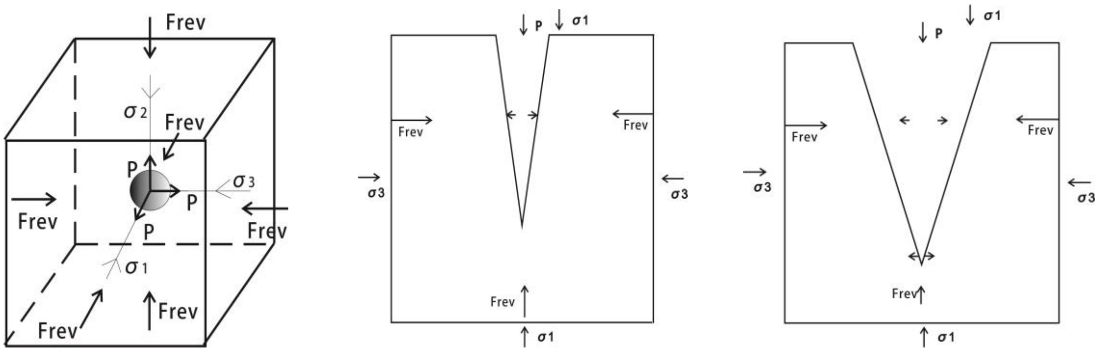

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Fig. 2 Stress state and 2D fracture propagation model under a confined-space system

In the new model, the system is a confined space system, where the target formation is surrounded by a relatively closed boundary and no free tensile expansion space exists. The high-pressure fluid and its reactive force together create a compressive environment. The stress condition follows the sequence: fluid pressure → compressive stress on rock → adjustment and redistribution of existing pore space into fracture space (compression- and shear-dominated) → crack tip opening (tension-dominated) → control of fracture propagation direction.

The core of this transition lies in changing the system from an open space to a confined space, where fluid pressure shifts from being the main driver for tensile fracturing to the driving force for compressing the rock. Consequently, the stress state changes from free tensile deformation to compression.

2.2 Mechanical Model

2.2.1 Force Analysis, Boundary Conditions, and Stress State under Confined Space

Boundary Conditions: Triaxially confined (rock formation boundaries exist in X, Y, and Z directions), with no free volumetric expansion allowed.

Loading Mode: Pressure is transmitted to pores and weak planes through fluid conduction; loading is slow and continuous, with gradual pressure variation.

Stress State: A coupled stress field dominated by compressive and shear stresses is formed, supplemented by tensile failure at fracture tips and pore volume compression.

Fracture Criterion: Based on the Mohr-Coulomb failure criterion.

Fracture Path: Governed mainly by differential stress, distribution of structural weak planes, and pore space redistribution; macroscopically, fracture propagation remains constrained by the minimum principal stress direction.

Fracture Width Origin: Formed by compaction-driven reconfiguration rather than simple tensile "opening."

Constraints: Conservation of total volume, conservation of pore space volume, Newton's third law, and Pascal's law.

2.2.2 Rock Stress State under Confined Space

2. 2. 2. 1 **Definition of Key Variables**

P: External high-pressure fluid pressure

σ3: Minimum principal stress

σ1 : Maximum principal stress

Sc : Compressive strength

Ss : Shear strength

St: Tensile strength

ϕ: Rock porosity (affects strength parameters)

Frc: Reactive force in compression direction

Frs: Reactive force in shear direction

Frt: Reactive force in tensile direction

Vpre : Pore volume before fracturing

Vpro : Pore volume after fracturing

Vfra: Volume of new fracture space

Vpr : Proppant volume

2. 2. 2. 2 **Stress State and Analysis under Confined Space Constraints**

Force analysis in minimum principal stress direction:

Resultant force $\sigma = P - \sigma 3$ (1)

Force analysis in maximum principal stress direction:

Resultant force $\sigma = \sigma 1 - P$ (2)

Compression direction:

Reactive force equals external high-pressure fluid pressure

$Frc = P$ (3)

Location of shear failure:

The magnitude of the reaction force is determined by the magnitude of the external high-pressure fluid.

Location of tensile failure:

The magnitude of the reaction force is determined by the magnitude of the external high-pressure fluid.

Volume conservation:

Total volume before fracturing equals rock matrix plus pore volume

$Vpre = Vrock + Vpre$ (4)

Total volume after fracturing equals matrix volume plus post-fracture pore volume plus proppant volume:

$Vpro = Vrock + Vpro + Vpr$ (5)

Pore volume conservation:

Post-fracture pore volume equals pre-fracture pore volume minus new fracture volume

$Vpro = Vpre - Vfra$ (6)

Proppant volume approximately equals new fracture space volume:

$Vpr \approx Vfra$ (7)

For porous rocks, the compressive strength, shear strength, and tensile strength are all closely related to porosity, and this relationship must be taken into account in the model.

In a confined space system, the total pore volume remains conserved (note that after fracturing, part of the pore space is occupied by proppant, and this must be considered when establishing the equations). The amount of solid material increases (due to the addition of proppant), while fluid can flow unidirectionally—typically, high-pressure fluid enters the formation, generating local high-pressure zones that displace the original formation fluids toward lower-pressure regions.

2.2.3 Fracture Initiation Conditions

In an open-space system, fracture initiation does not require overcoming reactive forces. However, in a confined space system, the rock can only fracture after overcoming the reactive forces and disrupting the existing mechanical equilibrium.

To determine whether rock failure occurs, the following criteria can be used:

① Compressive Fracture: P> Frc (8)

② Tensile Fracture: Pf> Frt

③ Shear Fracture:

In confined systems, the reactive force FrsF_{rs}Frs must be incorporated as a correction term: τ>(σn+Frs)tanϕ (9)

2.3 Feasibility Analysis of the New Model

2.3.1 Mechanical Implications of Different Spatial Types

In an open-space system, a unidirectional force source can independently produce deformation effects. The pressure exerted by high-pressure fluid on the formation rock is not constrained by any opposing force from the surrounding rock, allowing the rock to move freely (see Fig. 1c).

In a confined-space system, however, the rock cannot move freely. The externally applied pressure is met with a reactive force from the surrounding formation, together forming a compressive interaction (see Fig. 2b).

Conventional perspective: Fluid pressure PPP applies stress directly on the fracture walls (see Figs. 1b and 1c), but lacks a counteracting force, allowing free tensile opening.

New perspective: In a confined-space system, the presence of boundary constraints means that fluid pressure PPP, together with its reactive force, applies compressive stress on the rock and fracture surfaces, manifesting as a compression-dominated process (see Figs. 2b and 2c).

2.3.2 Changes in Pore Volume Within Rock

The space generated when rock is subjected to compression consists of two components: (1) elastic deformation of the rock matrix, and(2) redistribution of space from the compression of pre-existing pores.

Under subsurface compressive stress conditions, the rock is already in a state of elastic deformation. Any additional pressure beyond this state will exceed the elastic limit and result in rock failure. Therefore, it is unnecessary to attribute the creation of proppant-accommodating space to elastic volume reduction. Instead, both the fracture space and the space for proppant placement originate from the adjustment and redistribution of pre-existing pore space

2.3.3 Formation of Fracture Space under Compression

Under a compressive stress environment, fracture formation is no longer a pure opening mode (Mode I), but rather involves compression-induced localized deformation. Rocks between regions of high-pressure fluid are under strong compression, causing collapse of various pore types within the rock. The space released from this collapse, after redistribution, becomes the space available for proppant placement. Differential compressive deformation can also induce shear slip (Mode II or III), leading to the formation of secondary fractures intersecting with the main fracture, characterized as shear fractures (see Fig. 3b).

2.3.4 Increase in Reservoir Pressure after Fracturing

In a reservoir system, pore space exists prior to the establishment of fluid pressure within those pores. The pressure in the pores is determined by the degree of fluid filling, not by burial depth. For an isolated pore, the internal pressure is independent of depth and is solely a function of its fluid saturation. Therefore, reduction of pore volume is the key factor leading to an increase in reservoir pressure, a concept that aligns with Biot's poroelastic theory of fluid-solid coupling in porous media.

3. Validation of the New Theory by Microseismic Observations

Conventional theory holds that the dominant fractures generated during hydraulic fracturing are of tensile nature. However, monitoring results from massive volume hydraulic fracturing operations have revealed a significant number of shear fractures, which are often interpreted as the result of shear slip along pre-existing faults or fractures. Even if such shear slip occurs, it presupposes the existence of available space for displacement—yet conventional models do not explain where this physical space comes from during the slip process.

The new mechanical model under the confined-space system proposes that differential compressive deformation of the rock is the key factor responsible for shear fracture formation. Vavrycuk et al. (2008)[14] noted that the non-double-couple components observed in seismic moment tensors during fluid injection at the German KTB super-deep borehole were most likely caused by rock anisotropy, rather than tensile opening.Vavrycuk. Their conclusion was based on the presence of negative CLVD components, which are inconsistent with tensile fracturing. Furthermore, these seismic events were triggered at fluid pressures far below the fracturing gradient (Zoback and Harjes, 1997)[18][19], making tensile failure unlikely. Notably, this phenomenon is also observed in microseismic events associated with hydraulic fracturing in unconventional reservoirs. These events occur in highly anisotropic formations, and are triggered by fluid pressures well below the fracture gradient. From this, it can be concluded that: under the same fluid pressure, rock anisotropy can result in differential compressive deformation, supporting the core mechanism proposed in the new model.

3.1 Validation from Microseismic Spatial Distribution

Zhang et al. (2018) [17]reported the presence of dense clusters of microseismic events during multi-stage fracturing operations, with event magnitudes decreasing from the center outward. While this phenomenon was previously attributed to fracture complexity, our model suggests it is a natural result of compressive stress redistribution under confined-space constraints.Zhang.

As the compressive stress front propagates outward, the availability of pore space decreases, and the rock becomes increasingly compacted, leading to smaller-magnitude microseismic events in the peripheral areas.

Energy dissipation becomes more dispersed and lower in intensity, which corresponds to the observed decrease in seismic magnitude.

Thus, the attenuation of magnitudes from center to edge is not merely a function of fracture complexity, but a predictable outcome of stress redistribution under confined spatial conditions.

This pattern reflects both the consumption of compressible pore space and the diminishing capacity of the system to accommodate slip or fracture growth as it seeks a new equilibrium under pressure.

3.2 Validation of Shear-Dominated Microseismic Mechanisms

In the study by Wang et al. (2021)[15], over 70% of microseismic events exhibited shear-dominated mechanisms. This aligns with our theoretical prediction: under constrained conditions, shear fractures are generated due to differential compressive deformation.

In hydraulic fracturing, the target formation is surrounded by rock layers that mechanically constrain deformation of the pressurized volume. These confined-space conditions prevent free expansion in all directions, especially in horizontal planes where adjacent rock masses remain stationary. Therefore, any volume increase due to fluid injection must be accommodated via internal reconfiguration.

As fluid enters the formation, pressure radially displaces rock material. However, lateral displacement is restricted by spatial boundaries, leading to the accumulation of horizontal compressive stress. Unless critical thresholds are reached, these stresses are insufficient to initiate new tensile fractures—but they do promote shear failure along pre-existing or stress-induced weak planes.

Mechanism Preference under Constraints: Under such stress conditions, Coulomb failure (which governs shear activation) is more likely to occur than tensile failure (which controls Mode I opening). Shear fractures require less net displacement and are more compatible with spatial confinement, giving them a mechanical advantage. Therefore, the high proportion of shear-dominated events is a natural outcome of the system seeking low-energy deformation pathways within a restricted environment.

Implications for Fracture Interpretation: The observed dominance of shear mechanisms reflects the primary stress paths in laterally constrained compressive environments. It also indicates that fracture propagation is not solely pressure-driven, but is strongly controlled by the degrees of freedom available in the surrounding medium.

3.3 Evolutionary Trends in Microseismic Magnitude

The microseismic clustering and magnitude attenuation observed by Maghsoudi et al. (2016)[8] can be reinterpreted within the framework of the confined-space stress model. In this framework, spatially limited pore spaces are progressively compressed under injection-induced stress. Initially, large amounts of energy are released through shear or compressive failure. As the available compressible space is gradually exhausted, the system transitions into a redistribution phase, during which microseismic activity continues, but with decreasing event magnitudes and increasing spatial dispersion.

In a closed or confined system, energy release must occur through progressive compression and shear-slipping transitions. The power-law characteristics of the observed magnitude distribution reflect the system’s inability to sustain continued fracture extension due to spatial constraints. Instead, energy is released through localized slip and shear deformation, with the energy released per event diminishing over time, forming a power-law distribution of event scales.

During the initial stage of fracturing, injected fluids rapidly enter natural pores or pre-existing weak planes, which are relatively easy to compress. In a confined space, the compressive stress field induced by fluid injection becomes concentrated in these localized regions. As a result, microseismic events are clustered within these "compression-shear-prone zones," forming what is known as non-uniform clustering.

4. Discussion

4.1 The Stress Field Responsible for New Fracture Formation Is Compressional in Nature

Traditional theories are based on mechanical models developed under open-space system assumptions, which implicitly presume that the formation is an open system—unconstrained by the surrounding rock and able to provide unlimited space for fracture propagation. Under the action of high-pressure fluid, it is assumed that the minimum principal stress is reversed from compression to tension, thereby inducing fracture opening—i.e., a tensile-dominated stress regime.

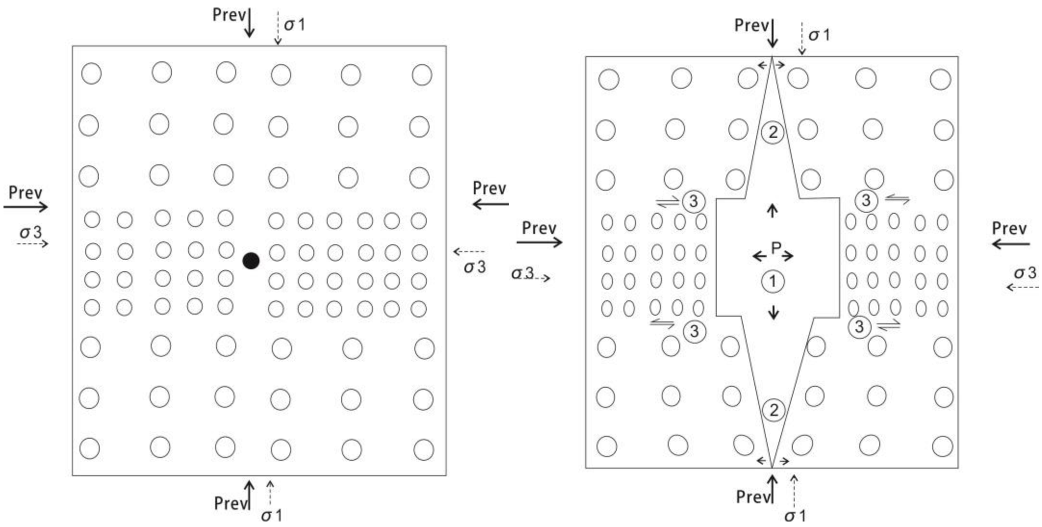

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Fig. 3 Pore compression and rock failure stages in a confined-space system

In reality, the subsurface within a confined domain is completely filled with rock, and any fracture propagation requires additional space. The surrounding rocks within this finite domain are subject to confinement forces from adjacent formations.

In such a confined environment, even if the high-pressure fluid alters the direction of the minimum principal stress, Newton's Third Law dictates that the reactive force (resulting from both compressive and shear strength) counters the fluid pressure, forming a force-reaction pair. This means the formation of new fractures is driven by compression of the existing pore space by the high-pressure fluid, thereby creating space for new fractures. In other words, it is compressive and shear actions that generate new fractures—indicating that the stress field is fundamentally compressional.

The fracture width is a result of this compressive action. It not only provides space for proppant placement but also serves as a critical flow conduit for hydrocarbons within the reservoir. Furthermore, it is a key factor contributing to increased reservoir pore pressure and enhanced hydrocarbon production.

Fracture extension, on the other hand, is the result of tensile action caused by bulk rock displacement. As more high-pressure fluid is injected into the confined space, the distance between the walls of the main fracture increases, leading to bulk movement of the rock on both sides of the fracture. The driving force comes from overcoming the shear strength, creating tensile conditions at the fracture tip, allowing the main fracture to propagate in tandem with increasing fracture width.

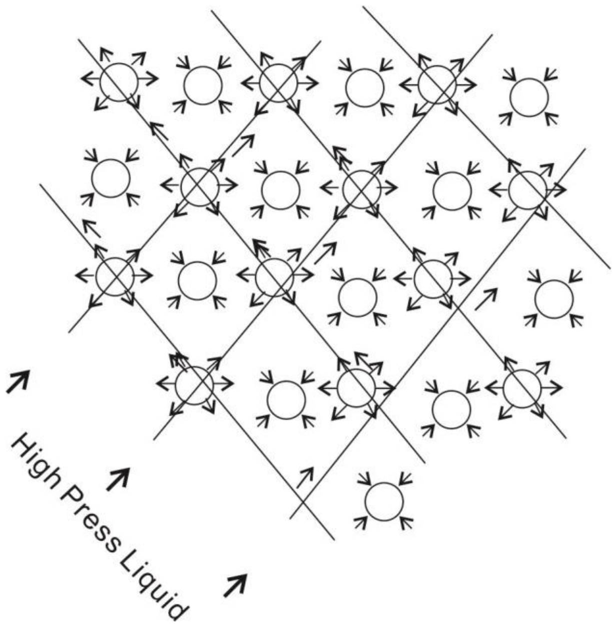

Fig. 4 Schematic diagram of the stress state after high-pressure fluid enters the rock along the optimal pathway

It is essential to clarify: without new space generated by compression, there is no mechanical basis for tensile action at the fracture tip.

Shear fractures are the result of differential compressive deformation. When such deformation becomes significant, it induces shear stress conditions between adjacent rock blocks. If the strain is large enough, shear fractures form (see Fig. 3b).

Under the traditional open-space model, shear fractures are often attributed to slip along pre-existing natural fractures. However, in reality, subsurface rock is subjected to triaxial compressive stress, and there is insufficient free space to accommodate such slip behavior.

Proppant accommodation space arises from adjustment and redistribution of existing pore space. Once high-pressure fluid enters pre-existing spaces (including structural weaknesses), the rock becomes enveloped by the pressurized fluid, including its isolated pores. Under compression, pore volume decreases, and the rock undergoes bulk displacement in the direction opposite to existing voids, thereby forming the fracture width—which also serves as the space for proppant.

Thus, under the new mechanical model, the sequential development of fractures is as follows: Compressive deformation creates new space for fracture width; Tensile action occurs at stress-concentrated zones in existing pores, determining the fracture propagation direction; Shear fractures form on both sides of the main fracture due to differential compression (see Fig. 3b).

4.2 Reservoir Fluid Pressure Increase as a Key Control Factor in Fracturing-Based Production Enhancement

Conventional hydraulic fracturing theories attribute production enhancement primarily to the creation of high-conductivity fractures. In these models, reservoir pressure increase during fracturing is explained by displacement effects. However, this explanation fails to account for the long-term maintenance of elevated reservoir pressure observed after fracturing.

In contrast, the new mechanical model under a confined-space system posits that enhanced hydrocarbon productivity after hydraulic fracturing is not primarily due to the creation of new fractures or increased permeability. Rather, it originates from the compression and redistribution of existing pore space (Fig. 3b), which leads to non-uniform increases in pore fluid pressure within the reservoir. A portion of the original hydrocarbon-bearing pore volume is irreversibly transformed into proppant-filled fracture space. This dual mechanism—stress-induced pressure amplification and irreversible pore volume transformation—offers a novel explanation for the sustained productivity observed after large-scale fracturing operations. This insight stems from the application of Biot’s poroelastic theory of coupled fluid-solid behavior in porous media.

Under confined-space conditions, massive hydraulic fracturing generates not only new fractures but also leads to reduction of existing pore volumes. As high-pressure fluids follow preferential flow paths into pre-existing pores and flow channels, pressure in these zones rises first. Some fluids are displaced, while pressure in isolated pores increases without displacement. As pore volume gradually decreases, fluid pressure continues to rise. In the case of isolated pores, calculations show that a 1% reduction in pore volume can lead to a pressure increase exceeding 20 MPa (for non-gaseous fluids). When the fluid pressure exceeds the rock’s compressive, shear, or tensile strength, fracture occurs—transforming an isolated pore into a connected flow pathway, thereby improving reservoir connectivity, mobilization, and ultimate recovery (Fig. 4).

Displaced fluids move into nearby pores or channels with lower fluid pressure, increasing the local fluid saturation and raising pore pressure. After external high-pressure injection is stopped, the presence of proppant maintains the deformed rock structure and sustains the elevated pore pressure, thereby providing additional driving energy for production. Thus, the role of proppant extends beyond flow conductivity—it also enhances reservoir energy via pressure retention. Therefore, it can be considered that massive fracturing is a coupled process of pore space redistribution and new fracture generation, which results in two key effects: an increase in reservoir fluid pressure and enhanced flow capacity.

The post-fracturing reservoir fluid pressure can be used to estimate daily oil production, providing a new foundation for optimizing production strategies.

The significance of this perspective lies in:

Elevating the concept of “fracture-stimulated productivity” from a geometric interpretation (fracture shape) to one of energy and volume conservation, shifting the focus from “fracture conductivity” to a combined mechanism of fracture conductivity + reservoir energy activation;

Providing a more physically consistent explanation for the phenomenon of long-term stable production, reframing the traditional model of “production = increased permeability × unchanged pressure differential” to “production = flow conduits (fractures) + enhanced driving force (pore compression increasing fluid pressure)”;

Establishing a new conceptual bridge between fracturing operations and resulting production behavior;

Offering guidance for future fracturing design in low-porosity, pressure-sensitive reservoirs.

Misconceptions in the understanding of fracturing mechanisms have led to misaligned objectives in stimulation design. Traditional models view the number of fractures as the sole determinant of productivity, thus making fracture count the primary design target.

In contrast, the confined-space model redefines fractures as fluid transport conduits, and emphasizes that compression of existing pores increases fluid pressure, effectively boosting reservoir drive energy—this is the true key to production enhancement. Consequently, expanding the volume of rock subjected to compression should also be a primary objective in fracturing-based stimulation.

4.3 Early Fracture Surface Permeability Determines the Productive Value of Natural Fractures

In hydraulic fracturing, not all reactivated natural fractures contribute equally to oil and gas production. A critical but often overlooked factor is the surface flow capacity of the fracture, which refers to the ability of fluids within the rock matrix to migrate across the fracture surface and enter the fracture network. This concept emphasizes the importance of connectivity between the matrix and the fracture surface.

Even if a fracture is physically reopened, its contribution to production depends on whether hydrocarbons can effectively flow into the fracture. In many sedimentary formations, natural fracture surfaces or bedding planes are lined with low-permeability minerals, such as calcite films, thin chert layers, or mica sheets. These mineral layers can severely hinder—or even completely block—flow pathways between the porous matrix and the fracture. As a result, even though such fractures may be mechanically open, they remain functionally isolated from the reservoir.

This understanding challenges the common assumption that reactivating natural fractures inherently improves production. Instead, it underscores that only fractures with sufficient surface permeability can effectively drain hydrocarbons from the matrix and enhance well performance. Therefore, pre-fracturing treatments targeting mineral barriers on fracture surfaces may improve their surface permeability. For instance, moderate acid fracturing may be used to dissolve calcite films, and CO_2 dissolved in water can also partially dissolve calcite layers on early fracture surfaces.

4.4 A New Perspective on Fracture Numerical Simulation

When the mechanical model is updated and the mechanism of fracture generation and evolution is redefined, numerical modeling software and algorithms must also be adjusted accordingly. First and foremost, the origin of fracture space must be incorporated, followed by modeling the initiation and propagation of fractures, and ultimately the transport range of proppants.

As of the writing of this paper, a review of representative literature reveals that understanding of the stress field associated with hydraulic fracturing still largely relies on the mechanical framework proposed by Hubbert and Willis (1957)[7]. This includes the assumption that the main fracture is tensile in nature and that the medium is a homogeneous elastic body. There remains a lack of detailed studies describing the progressive development of fractures, leading to fundamental flaws in current numerical simulation approaches for fracture modeling.

4.5 Deficiencies in Fracture Toughness Testing Methods

In Chapter 3 (page 3-20) of the third edition of *Reservoir Stimulation*[4] the experimental method for determining fracture toughness involves applying tensile force. However, this approach does not reflect actual subsurface conditions, and the fracture toughness values obtained are likely underestimated. As a result, the fracture initiation pressures used in fracturing design are too low, which directly compromises fracturing performance.

Under the confined-space model, high-pressure fluid should be injected through a central borehole, and the sample should be held under constraint. Such a testing environment would more accurately simulate the realistic in-situ stress conditions encountered underground

5. Understanding and Significance

5.1 New Insights

5.1.1 The Influence of Confined Space on the Fracturing Process

Under the constraint of a confined space, the stress state of the rock during fracturing undergoes significant changes. Fracture width is mainly determined by the degree of compressive deformation, while differential deformation induces shear. Fracture tip propagation depends on tensile forces generated by the overall displacement of the rock mass. This fundamentally differs from the "volume expansion" concept in traditional open-space models and emphasizes the limiting role of surrounding rock on fracture growth—representing a compressive stress field rather than a tensile one.

5.1.2 A New Perspective on Production Enhancement Mechanism

The primary contributor to enhanced production in large-volume hydraulic fracturing is not solely the conductivity of newly created fractures. More critically, it is the significant increase in reservoir fluid pressure after fracturing. As fracturing fluid enters the formation, the existing pore space is compressed, raising the fluid pressure and thereby increasing the driving force for hydrocarbon flow. New and pre-existing fractures serve mainly as channels for pressure transmission and redistribution, rather than just as fluid pathways.

5.1.3 New Parameters for Evaluating Fracturing Effectiveness

Traditional evaluations of fracturing success are based mainly on fracture geometry, but this method fails to fully capture the production enhancement effects under the confined-space model. Based on the new understanding, parameters such as residual proppant volume and post-fracturing reservoir fluid pressure should be introduced to more accurately assess the effectiveness of reservoir stimulation.

5.1.4 Rethinking the Production Mechanism

There are misconceptions in understanding the mechanism of production enhancement after fracturing—placing too much emphasis on fracture geometry while ignoring the crucial role of increased pore pressure. This misalignment has skewed the objectives of fracturing operations. A shift in perspective is needed—from generating local fractures to modifying the reservoir as a whole.

5.2 Geological Significance

5.2.1 Well Placement and Trajectory Optimization

In heterogeneous reservoirs such as shale oil and tight oil formations, differential compressive deformation is pronounced, and the internal stress distribution is uneven—making shear fracture formation more likely. Therefore, well placement and trajectory design should prioritize high-heterogeneity zones and formations with significant compressive variation to maximize activation of the reservoir's potential flow space.

5.2.2 Enhancing Reservoir Utilization and Recovery Factor

By strengthening differential deformation, not only can a more effective fracture network be developed, but the overall utilization of the reservoir can also be significantly improved. This holistic stimulation strategy is particularly effective in low-permeability reservoirs, where it can notably increase the oil recovery factor and ultimate recovery.

5.3 Engineering Significance

5.3.1 Optimizing Fracturing Design

Through refined design, the degree of differential deformation in the rock mass during fracturing can be increased, leading to the creation of more complex fracture networks. Meanwhile, optimizing the staging and sequence of proppant injection enhances overall proppant placement efficiency.

5.3.2 Well Trajectory Optimization

While ensuring casing integrity, the horizontal section of the well should be as parallel as possible to the direction of minimum principal stress. This facilitates the formation of slice-like fracture structures, which not only reduce wellbore interference but also make full use of the natural stress field to achieve more uniform and farther-reaching fractures.

5.3.3 Proppant Optimization

By reducing fluid volume and increasing proppant concentration, proppants of varied sizes can be injected sequentially into the formation, enhancing differential deformation, generating more shear fractures, and further increasing reservoir fluid pressure. During the flowback stage, minimizing proppant return not only maintains fracture conductivity but also helps retain the elevated post-fracturing reservoir pressure, providing sustained driving energy for hydrocarbon production.

6. Conclusions

1. Artificial fractures and proppant-bearing spaces formed under a confined space system are the result of adjustment and redistribution of pre-existing pore space. Differential compaction-induced deformation is the mechanical basis for the formation of shear fractures. The sequential process of rock deformation and failure is: compression (creating fracture

space) → tension (controlling fracture propagation direction) → differential deformation (generating shear fractures).

2. Reservoir fluid pressure increase is a key controlling factor for production enhancement through hydraulic fracturing. Based on this mechanism, well placement and trajectory design can be further optimized, target intervals for fracturing can be better selected, and reservoir utilization and recovery efficiency can be improved. This also provides a new conceptual framework for numerical simulation of reservoir development.

3. Post-reservoir formation processes such as compaction of the strata, secondary growth of diagenetic minerals, and the swelling of clay minerals can all increase the fluid pressure within the reservoir, which is conducive to enhancing the recovery factor of oil and gas field development.

4. The effectiveness of hydraulic fracturing can be quantitatively evaluated and production can be predicted using the three-dimensional distribution of porosity and the post-fracturing reservoir fluid pressure parameters, which yields better results than relying on fracture geometry obtained through microseismic monitoring.

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