# A Study on the Existence of Bedding-Parallel Fractures Under Formation Conditions Based on the Coupling Relationship Between Multi-Stage Stress Fields and Clastic Particle Contacts

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## Abstract

To clarify the existence of bedding-parallel fractures (including bedding fractures) under subsurface conditions in tectonically stable regions of sedimentary basins, reveal the discrepancies between fractures observed in surface cores and natural subsurface fracture systems, and guide shale-type shale oil exploration, this study applies principles of sedimentology and rock mechanics, employs a research methodology integrating macroscopic and microscopic analyses, conducts coupling analysis of multi-stage stress fields and clastic grain contacts, and incorporates fracture observations from cores at hydraulic fracturing test sites to systematically investigate fracture response mechanisms in multi-stage stress fields. The research results indicate: During the burial stage, high-angle tensile-shear fractures can form under high confining pressure; during the uplift stage, differential strain resulting from partial effective stress unloading can generate two types of secondary shear fractures: in the pre-exposure stage, differential strain concentrates primarily at lithologic interfaces, forming high-angle shear fractures; in the surface exposure stage, low-angle shear fractures (i.e., pseudo-bedding fractures) can form. Under subsurface conditions in tectonically stable regions of sedimentary basins, low-angle bedding-parallel fractures (including bedding fractures) cannot form; bedding-parallel fractures observed in surface cores are products of unloading (stress unloading), which causes irreversible damage to the internal structure of the core, weakening mechanical parameters such as elastic modulus and tensile strength (with significantly greater weakening of mechanical parameters perpendicular to bedding than parallel to bedding), resulting in mechanical property "distortion". Bedding-parallel fractures observed in surface cores exhibit fundamental differences from natural fracture systems and cannot directly represent original subsurface conditions. Current understanding of bedding-parallel fractures suffers from disciplinary fragmentation: sedimentary geology focuses on primary static characteristics of clastic grain contacts, neglecting their dynamic response in multi-stage stress fields; rock mechanics emphasizes controlling mechanisms of the present-day stress field on clastic grain contacts, while neglecting constraints imposed by multi-stage stress fields throughout the sedimentation-diagenesis history. For shale-type shale oil exploration, it is necessary to transcend conventional understanding of matrix pore systems, shift exploration targets toward tectonically originated high-angle fracture systems, and develop high-angle fracture prediction technologies. This understanding provides guidance for shale-type shale oil exploration in areas lacking large-scale sand bodies.

## Full Text

## Preamble

### Exploring the Existence of Parting Fractures under Stratigraphic Conditions Based on Multi-Stage Stress Field-Clastic Particle Contact Coupling Relationship

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**Abstract:** To clarify the existence of bedding-parallel fractures (including stratification fractures) under formation conditions in tectonically stable regions of sedimentary basins, reveal the differences between fractures observed in surface cores and the actual subsurface fracture system, and guide the exploration of shale-type shale oil, this study applies principles of sedimentology and rock mechanics using a combined macroscopic and microscopic approach. Through analysis of multi-stage stress field-clastic particle contact coupling relationships and integration with core fracture observations from hydraulic fracturing test sites, the response mechanisms of fractures in multi-stage stress fields were systematically investigated. The results indicate: (1) During the burial stage, high-angle tensile-shear fractures can form under high confining pressure. During the uplift stage, differential strain from partial effective stress unloading can generate two types of secondary shear fractures: before exposure to the surface, differential strain concentrates primarily at lithological interfaces, forming high-angle shear fractures; upon surface exposure, low-angle shear fractures (i.e., pseudo-bedding-parallel fractures) can form. (2) Low-angle bedding-parallel fractures (including bedding fractures) cannot form under formation conditions in tectonically stable regions of sedimentary basins. The bedding-parallel fractures observed in surface cores are products of unloading (stress unloading), which causes irreversible damage to the internal structure of the core and weakens mechanical parameters such as elastic modulus and tensile strength (with significantly greater weakening perpendicular to bedding planes than parallel to them), resulting in "distorted" mechanical properties. (3) There is an essential difference between bedding-parallel fractures observed in surface cores and the real fracture system, and they cannot directly represent the original subsurface state. (4) Current understanding of bedding-parallel fractures suffers from disciplinary compartmentalization: sedimentary geology focuses on the primary static characteristics of clastic particle contacts while neglecting their dynamic response in multi-stage stress fields; rock mechanics emphasizes the regulatory mechanism of the present-day stress field on clastic particle contacts while overlooking constraints imposed by multi-stage stress fields throughout the sedimentary-diagenetic history. (5) For shale-type shale oil exploration, it is necessary to break through traditional understanding of matrix pore systems and shift exploration targets to structurally formed high-angle fracture systems, developing high-angle fracture prediction technologies. This understanding provides guidance for shale-type shale oil exploration in areas lacking large-scale sand bodies.

**Keywords:** fracture formation mechanism; parting fracture; stress unloading; tensile-shear fracture; dual-porosity system; shale oil exploration; multi-stage stress field

Shale, as a typical fine-grained sedimentary rock, exhibits layered enrichment of components that form distinct bands differing in color and composition from the surrounding matrix—these are called laminae. Shale primarily consists of a matrix and millimeter-to-centimeter-scale laminae: the matrix represents a disordered mixture of clastic particles (quartz, feldspar, etc.), clay minerals (illite, illite/smectite mixed layers), and organic matter, while laminae represent ordered, layered accumulations of single components such as felsic materials, tuffaceous minerals (dominated by felsic minerals, illite, and pyrite), or organic matter [**?**]. The compositional differences between matrix and laminae lead to significant variations in rock mechanical properties and weathering resistance. When such lithological assemblages are exposed at the surface, differential weathering creates a book-page-like parting structure. Laminae are primary sedimentary structures that can exist under both subsurface and surface conditions, whereas parting is a secondary structure that develops only under surface conditions [**?**].

Parting fractures, as low-angle natural fracture systems developed along shale bedding planes, are generally considered the shale expression of bedding fractures. The concept has evolved through multiple developmental stages. The concept of bedding fractures originated from studies of dolomite and sandstone reservoirs, where they were recognized as important storage spaces [**?**]. As research progressed, the widespread development of bedding fractures in shale was documented [**?**], though a complete conceptual framework had not yet formed. In the 1990s, parting fractures were explicitly defined as products of structural stress or dissolution alteration of depositional partings, becoming a focus of shale reservoir research.

Recent studies based on core observations and simulation tests have found that parting fractures, as potential mechanical weak planes, can significantly enhance shale storage and permeability performance. They are easily activated to promote hydraulic fracture propagation and form complex fracture networks, improving fracturing effectiveness, which has propelled them into a hot topic in exploration and development [?]. However, regarding the existence of parting fractures under formation conditions in tectonically stable regions of sedimentary basins, academic viewpoints remain divided [?], with ongoing controversies continuously driving research forward. This study abandons traditional empirical analogy methods based on core appearance and strictly follows first principles (fundamental axioms and laws). Through systematic analysis of stress field evolution patterns and clastic particle contact mechanical mechanisms, we progressively derive and demonstrate the existence of parting fractures (including bedding fractures) under formation conditions in tectonically stable regions of sedimentary basins, providing a solid theoretical foundation and scientific basis for shale reservoir evaluation and fracturing design.

## 1 Engineering Identification Criteria for Parting Fractures

Fractures are mechanically discontinuous interfaces that serve as preferential fluid flow pathways. The development state of fractures under formation conditions (macroscopic) fundamentally reflects the clastic particle contact relationships (microscopic). If low-angle parting fractures exist under formation conditions, it indicates that vertically adjacent clastic particles have lost contact, with this phenomenon extending laterally to some degree. Clastic particle contact relationships are controlled by interparticle stress. Cores retrieved to the surface have experienced clastic particles undergoing sedimentation, burial, and hydrocarbon generation evolution stages—essentially a process from surface to formation and back to surface. Correspondingly, the stress experienced by clastic particles undergoes dynamic changes of gradual increase followed by decrease. Analyzing the existence of parting fractures requires tracing the evolution of clastic particle contact states and making comprehensive judgments combined with multi-stage stress field evolution characteristics.

## 2.1 Stress Loading Stage (Burial Process)

The coupling relationship between the stress field and clastic particle contacts during this stage can be divided into four substages: sedimentation, burial, diagenesis, and hydrocarbon generation (Figure 1).

[Figure 1: see original paper]

### 2.1.1 Sedimentation Stage

Under surface conditions, the gravitational load of overlying clastic particles must be transmitted downward through interparticle contact points (force chains). Complete "loss of contact" between vertically adjacent clastic particles would interrupt the force chain at that location, causing local stress field collapse, which is mechanically unstable and unsustainable. To maintain mechanical equilibrium, clastic particles must rearrange to rebuild the force chain network [?]. During this stage, vertically adjacent clastic particles are in point contact, making loss of contact difficult to maintain [?, ?], and low-angle parting fractures are unlikely to form [?].

### 2.1.2 Burial Stage

As burial depth increases, the weight of overlying sediments increases and clastic particles become fully saturated with water. According to Terzaghi' s effective stress principle [?], the weight of overlying rock (total stress, $\sigma$) consists of two components: effective stress ($\sigma'$) transmitted through particle contact points, which directly controls particle compression, sliding and rearrangement, and pore water expulsion, thereby controlling particle skeleton deformation; and pore pressure ($P$) borne by pore water, which does not directly participate in interparticle force transmission (Equation 1). The effective stress borne by particles and the pore pressure borne by pore water together balance the weight of overlying sediments [?]. Particle skeleton compression deformation is primarily driven by effective stress. As effective stress increases, interparticle contacts become tighter and pore volume decreases [?]. Effective stress links macroscopic loading with microscopic particle contacts, establishing a macroscopic mechanical framework for particle contact relationship studies.

$$\sigma' = \sigma - \alpha P \quad (1)$$

During this stage, clastic particles have not yet been lithified. As burial depth increases, vertical effective stress ($\sigma'_v$) gradually increases, approaching and exceeding horizontal effective stress ($\sigma'_H$ and $\sigma'_h$). Under vertical effective stress, complete loss of contact between vertically adjacent particles violates force chain transmission principles. Absolute separation can only exist transiently, after which clastic particles rotate and readjust to restore contact and the force chain [?]. Contact patterns transition from initial loose point contacts to tighter point-line contacts, making it impossible to form low-angle parting fractures with rhythmic characteristics [?]. Shale has low elastic modulus ($E$) and strong stress sensitivity. As net overlying vertical effective stress increases, its confining pressure porosity ($\phi$) and permeability ($K$) decrease exponentially, reflecting further reduction of intergranular pores and increased compaction between clastic particles with increasing burial depth and effective stress. Low-angle parting fractures are difficult to form during this stage [?].

### 2.1.3 Diagenesis Stage

Diagenesis includes cementation and dissolution. Cementation consolidates clastic particles through mineral precipitation, inheriting and strengthening the point or point-line contacts from the burial stage. Dissolution adjusts interparticle contact relationships through varying degrees of dissolution of clastic particles or cements. Particle morphological characteristics can serve as microscopic evidence for judging dissolution intensity and fluid activity history. Under formation conditions, if clastic rocks experience only weak dissolution, clastic particles typically retain angular outlines. When dissolution is intense, particle edges become rounded through selective dissolution, forming smoother shapes. The dissolution-recontact process of clastic particles is jointly controlled by chemical dissolution and elastic-plastic mechanical feedback.

**a) Weak Dissolution:** When dissolution amount is less than the original elastic closure between particles (in the absence of cementation, the micron-to-submicron Hertz elastic deformation produced between two spherical particles under applied effective stress), dissolution occurs primarily near stress concentration areas in the contact zone. As material is removed, the elastic strain energy ($\delta$) stored at particle contacts unloads, and particles undergo elastic rebound (Equation 2, Hertz contact theory) [?], restoring point or point-line contacts with only reduced contact area. Cement is not completely destroyed, and the rock maintains its original strength [?]. This stage can be summarized as “weak dissolution-elastic rebound-contact restoration” [?].

$$F = \frac{4}{3}E^{*}\sqrt{R^{*}}\delta^{3/2} \quad (2)$$

**b) Intense Dissolution:** When dissolution continues and exceeds the limit compensable by elastic rebound: (1) original quartz or carbonate cement is completely dissolved, and particles lose rigid “welding” [?]; (2) local suspended particle arches form (temporary self-stable structures formed by several particles after cement dissolution) [?], and stress paths are redistributed; (3) under differential stress, arch structures become unstable, and particles undergo 微小位移与旋转, adjusting to a new force equilibrium configuration [?]; (4) readjusted particles still tend toward point-line contacts, but contact directions, coordination numbers, and force chain networks are redistributed [?]. This stage can be summarized as “intense dissolution-cement loss-arch structure instability-particle rearrangement-new point-line contact” [?].

Dissolution cannot cause complete loss of contact between vertically adjacent clastic particles, and low-angle parting fractures lack the mechanical conditions for formation and preservation.

### 2.1.4 Hydrocarbon Generation Stage

As burial depth increases, source rocks enter the hydrocarbon generation stage. If pore pressure ($P$) exceeds formation fracture pressure ($P_f$), the formation rock undergoes tensile failure. The propagation direction of natural fractures follows the Hubbert-Willis tensile fracture criterion: fractures always extend along the path requiring the lowest energy and least resistance. The macroscopic extension direction of fractures results from the combined action of in-situ stress and rock tensile strength (Equation 3), determined by the minimum value of their sum [?].

$$P_f > \sigma' + T \quad (3)$$

Rock tensile strength is primarily controlled by cement type (e.g., quartz, carbonate, clay), cementation pattern (basal, porous, contact), and rhythmic structure determined by clastic composition and grain size (Figure 2a). Among these factors, cement type and pattern are the main determinants of rock tensile strength, typically distributed uniformly at the microscopic scale without strong directionality (Figures 2b-2f), resulting in weak directional macroscopic tensile strength. Although clastic composition and grain size distribution show strong directionality microscopically (Figure 2a), their influence on rock tensile strength is minor. Even if directional differences exist, they are weakened at the macroscopic scale by cement uniformity, leading to non-significant directional tensile strength. The difference in rock tensile strength between two determined directions under formation conditions ($\Delta T$) is far less than that measured under surface conditions (where stress unloading causes much greater weakening perpendicular to bedding planes than parallel to them). Fractures mainly extend perpendicular to the minimum effective principal stress direction ($\sigma'_3$) [?].

Vertical effective principal stress ($\sigma'_v$) originates from overburden weight and pore pressure. Horizontal effective principal stress ($\sigma'_H$ and $\sigma'_h$) is contributed by components generated through Poisson’ s effect ($\nu$) and tectonic stress. The minimum effective principal stress direction depends primarily on burial depth and tectonic activity intensity.

In areas with intense tectonic activity, horizontal effective stress is dominated by tectonic stress, typically exceeding vertical effective stress and making vertical effective stress the minimum principal stress. Under this stress state, fractures propagate perpendicular to the minimum principal stress direction, forming low-angle fractures.

In tectonically stable regions, the stress state is influenced by both burial depth and tectonic stress. Based on statistical results from 450 borehole datasets across mainland China: at depths less than 500 m, the ratio of minimum horizontal principal stress to vertical principal stress ($\sigma_h/\sigma_v$) exceeds 1 at approximately 50% of measurement points [?], indicating vertical principal stress as the minimum principal stress; at depths between 1,000-3,000 m, this ratio mainly distributes between 0.5-1.0; at depths exceeding 3,000 m, the ratio further converges to 0.5-0.8 [?]. This shows that as burial depth increases, horizontal effective principal stress becomes the minimum principal stress. The critical depth range for fracture morphology transition from low-angle to high-angle is approximately 0.5-1.0 km.

1) At burial depths less than the critical depth, horizontal effective principal stress is primarily controlled by tectonic stress, with vertical principal

stress as the minimum effective principal stress, theoretically favoring low-angle fracture development. However, original formation pore pressure in this depth interval is typically below rock fracture pressure, making spontaneous fracture formation difficult. Even with local overpressure, rocks would preferentially fracture at the weakest tensile strength locations. Limited by pressure unloading mechanisms, only isolated single fractures typically form, making it difficult to develop rhythmic low-angle fracture systems.

2) At burial depths greater than the critical depth, tectonic stress influence significantly weakens, horizontal effective principal stress becomes less than vertical effective principal stress, and the minimum effective principal stress shifts to the horizontal direction. If fracturing occurs, fractures will propagate perpendicular to the minimum horizontal principal stress direction, forming high-angle fractures rather than low-angle fractures.

It should be noted that although paleo-stress fields during hydrocarbon generation may differ from present-day stress fields, the variation pattern of stress with burial depth is consistent, and fracture opening and propagation under current conditions remain controlled by the present-day stress field.

## 2.2 Stress Unloading Stage (Uplift Process)

Mineral fabric determines properties such as hardness, density, and crystal structure, which in turn determine mechanical properties including elastic modulus, shear modulus, and Poisson's ratio. Clastic rocks composed of multiple minerals have rock mechanical parameters that depend on mineral composition, diagenetic intensity, and fabric. Clastic rocks under in-situ stress fields at formation conditions are in a compressed state, similar to compressed springs ($F = kx$, where $F$ is elastic force, $k$ is stiffness coefficient, and $x$ is deformation). The stress-strain response during formation uplift (unloading effect) is controlled by the degree of confining pressure release and lithological differences. Analysis of stress field-clastic particle contact coupling during this stage can be divided into pre-exposure and post-exposure phases (Figure 1).

### 2.2.1 Pre-Exposure Stage (Partial Confining Pressure Release)

Spatial lithological variations in actual formations can be summarized by two patterns: vertical abrupt change and lateral abrupt change. Different lithological variation patterns result in different rock mechanical properties, clastic particle contact relationships, and rock deformation.

**a) Vertical Lithological Abrupt Change:** A typical example is sand-mud interbedding. During uplift and erosion, horizontal effective stress constraints remain while vertical effective stress decreases. Due to different elastic moduli between sand and mudstone, under partial vertical effective stress unloading, the vertical rebound strain of low-modulus mudstone far exceeds that of high-modulus sandstone. The difference in rebound strain between the two lithologies creates "interlayer incompatible strain."With lateral constraints ($\varepsilon_x \approx 0, \varepsilon_y \approx 0$), the interlayer incompatible strain difference is converted into interlayer shear stress at the sand-mud contact interface (Equation 4). According to the Mohr-Coulomb shear fracture criterion, when accumulated shear stress exceeds the Coulomb shear strength of the interface (Equation 5) [?], interface instability and micro-shear slip are triggered.

$$\tau = G\gamma \quad (4)$$

$$\tau = \sigma_n \tan\phi + c \quad (5)$$

Coulomb shear strength is primarily controlled by cohesion at the interface (determined by diagenetic intensity), normal stress acting on the slip plane (determined by vertical effective stress), and internal friction angle of the bedding plane (determined by rigid particle content, diagenetic intensity, pore pressure, etc.).

When sand-mud interfaces are uncemented or weakly cemented, interface cohesion is minimal. Interfaces rich in clay minerals that are smooth and water-saturated have low internal friction angles. Large-scale uplift significantly reduces effective normal stress, substantially decreasing shear strength and facilitating bedding-parallel shear slip.

When sand-mud interfaces are strongly cemented, interface cohesion is greater. Interfaces with high rigid particle (quartz, etc.) content and cementation have larger internal friction angles. Smaller uplift magnitude results in less normal stress reduction and higher shear strength, making bedding-parallel shear slip less likely.

When interface instability and micro-shear slip are triggered, particles within the micro-shear slip zone rotate and reorganize, forming force chain arch structures [?]. Force chain arches can only form in regions where particle rotation and reorganization occur, with thickness equal to the micro-shear slip zone thickness. The arch length (span) is determined by spontaneous adjustment of the mechanical system to achieve effective stress transmission and bearing [?]. Through arch feet, vertical effective stress is converted into lateral thrust and transmitted to unmoved domains, achieving stress redistribution and load continuity [?]. Force chain arches are not equivalent to micro-shear slip zones but represent the load transmission mechanism within them. Micro-shear zones are complex networks formed by multiple force chain arch structures connected end-to-end and nested within each other [?]. Micro-shear slip zones are the carriers for force chain arch formation and existence, while force chain arch structures are the core mechanisms for stress transfer and load bearing within micro-shear slip zones [?]. Micro-shear zones always remain within the "friction-arch transfer" regime, with Coulomb' s criterion providing the theoretical framework and primary controlling factor for micro-shear zone dip angles. Micro-shear zones cannot evolve into low-angle parting fractures (Equation 6).

**b) Lateral Lithological Abrupt Change:** A typical example is sand-mud lateral contact. For this lithological combination, partial vertical effective stress unloading and horizontal effective stress redistribution occur. First, overlying rock stripping causes vertical effective stress unloading. Under lateral confinement, vertical rebound strain occurs (Equation 7). Controlled by elastic modulus, high-modulus rocks exhibit weak rebound strain while low-modulus rocks show significant rebound strain. Lateral lithological variations create vertical strain differences at lithological interfaces, generating shear stress (Equations 4 and 8). When the Coulomb fracture criterion is satisfied, high-angle (60°-85°) shear fractures form (Equation 6), representing vertical effective stress unloading and differential rebound. Second, while vertical differential rebound causes shear stress accumulation at lithological interfaces, horizontal effective stress difference redistribution further influences fracture patterns. Horizontal effective stress difference ($\sigma'_H - \sigma'_h$) is jointly controlled by tectonic stress field relaxation and Poisson' s effect (Equation 9) [?], developing conjugate shear fractures.

$$\theta = \pm(45° - \frac{\phi}{2}) \quad (6)$$

Uplift and erosion reduce effective vertical stress, inducing two types of local deformation under surrounding rock lateral constraints: (1) Microscopic shear zones formed by uneven lateral rebound, manifested as force chain arches and micro-slip. Although 微小滑移和开度 exist within force chain arches (indicating microscopic damage), this damage is distributed, limited, and stable, without localizing and connecting into a dominant macroscopic fracture. (2) High-angle fractures induced by vertical rebound differences. Interbedded lithological interfaces cannot enter tensile fracture mode (the system maintains $\sigma_n > 0$ and $\sigma_h - P > 0$ throughout), and low-angle fractures do not form laterally. Therefore, low-angle parting fractures are naturally absent.

### 2.2.2 Surface Exposure Stage (Complete Confining Pressure Release)

Griffith proposed that brittle material failure originates from the propagation of internal microcracks under tensile stress, controlled by Poisson' s effect and Griffith' s tensile fracture criterion [?]. Vertical and horizontal effective stress coordinate unloading, causing tensile or shear fracture along bedding planes.

**a) Strain Differentiation Dominated by Vertical Rebound:** Vertical effective stress unloads due to overlying rock stripping, triggering vertical rock rebound. Low-modulus rocks exhibit significantly greater vertical rebound strain than high-modulus rocks.

**b) Lateral Rebound and Bedding Plane Fracture:** Confining pressure release converts vertical strain into lateral rebound strain through Poisson' s effect (Equation 10), with obvious differentiation in lateral rebound strain: high-modulus rocks show small rebound strain while low-modulus rocks show large rebound strain, accumulating tensile or shear strain energy at lithological interfaces. When tensile strain energy exceeds rock tensile strength [**?**], or when shear strain energy exceeds rock cohesion, low-angle shear fractures form along bedding planes— “pseudo-bedding-parallel fractures.”

$$\varepsilon_h = -\nu \varepsilon_v \quad (10)$$

When cores are retrieved to the surface, they lose surrounding rock constraint, and the effective stresses ($\sigma'_H$, $\sigma'_h$, $\sigma'_v$) they experience are completely unloaded, similar to springs losing elastic force. The core deforms in different directions, generating differential deformation and microfractures. The internal structure of the core suffers irreversible damage, and mechanical properties become “distorted,”unable to reflect the true mechanical properties of rocks under formation conditions.

In summary, from the sedimentation stage through burial to hydrocarbon generation, and from burial (surface to formation) to uplift (formation to surface), vertically adjacent clastic particles and the rocks they constitute remain under in-situ stress fields. The conditions for vertically adjacent clastic particles to lose contact do not exist, making it impossible to form rhythmic low-angle parting fractures [**?**].

Using shale as an example, microscopically it mainly consists of a matrix and millimeter-to-centimeter-scale laminae: the matrix is a disordered mixture of clastic particles like felsic minerals, clay minerals such as illite and illite/smectite mixed layers, and organic matter; laminae are ordered layered accumulations of certain components like felsic materials, tuffaceous minerals (dominated by felsic minerals, illite, and pyrite), or organic matter (Figure 2a). Unlike tensile strength, which exhibits weak directionality, rock mechanical parameters such as elastic modulus and Poisson’ s ratio are highly sensitive to internal particle arrangement and bedding structures, showing obvious directionality. Assuming shale under formation conditions in an in-situ stress field consists of organic matter laminae (with elastic modulus $E_1$ and Poisson’ s ratio $\nu_1$) and felsic laminae (with elastic modulus $E_2$ and Poisson’ s ratio $\nu_2$). When shale is retrieved to the surface, both the stress field and rock mechanical properties change: first, surrounding rock constraint is lost; then, due to compositional and structural differences, laminae experience elastic modulus decay during weathering and water loss, with organic matter laminae decaying more than felsic laminae. This causes vertical deformation (organic matter $\varepsilon_{v1} = \Delta\sigma'_v / E_1$, felsic $\varepsilon_{v2} = \Delta\sigma'_v / E_2$) and lateral deformation (organic matter $\varepsilon_{h1} = -\nu_1 \varepsilon_{v1}$, felsic $\varepsilon_{h2} = -\nu_2 \varepsilon_{v2}$). Vertically, organic matter laminae with lower elastic modulus experience greater vertical strain, causing their relative elongation to exceed that of felsic laminae. Laterally, rebound differences accumulate tensile or shear strain energy at lithological interfaces. If interface shear strain energy exceeds cohesion, shear slip occurs along laminae surfaces forming microfractures (shear-dominated). If interface tensile strain energy exceeds felsic tensile strength, tensile fractures form directly (tension-dominated). These processes create "pseudo-bedding-parallel fractures." Differences in rock mechanical parameters between laminae cause vertical and lateral strain differentiation, and the accumulation of shear and tensile strain energy at interfaces is the core mechanism for "pseudo-bedding-parallel fracture" formation.

The cognitive dilemma regarding parting fractures stems from disciplinary compartmentalization: sedimentary geology focuses on the primary static characteristics of clastic particle contacts while neglecting their dynamic response in multi-stage stress fields; rock mechanics emphasizes the regulatory mechanism of the present-day stress field on clastic particle contacts while overlooking constraints imposed by multi-stage stress fields throughout the burial-uplift history. This compartmentalization creates an imbalance in the stress-fabric relationship between static and dynamic, historical and present-day perspectives.

## 3 Engineering Verification

To reveal the spatial distribution of natural and artificial fractures under formation conditions, drawing on field practices from hydraulic fracturing test sites in North America, PetroChina deployed China' s first hydraulic fracturing test site in the Ordos Basin. The hydraulic fracturing test platform is located in the core area of the Qingcheng Oilfield, targeting the Chang 7 member deposited in semi-deep to deep lake subfacies gravity flow deposits at a depth of 1,700-1,800 m. Construction began in July 2021, with five test wells implementing 10 types of tests across 16 well runs, including fiber optics, dual-well microseismic, borehole television, tracers, and coring. The project includes two horizontal wells with spacing of 250-300 m and horizontal sections of 1,300 m, fractured in 23 stages with 85 clusters and 21 stages with 84 clusters, respectively. Two coring monitoring wells were drilled: a high-angle coring well with 300 m of core covering the sweet spot area, and a horizontal coring well with 361.8 m of core in the middle of the oil layer. The test site was completed in June 2024.

Field statistics show that natural fractures in the test area are dominated by high-angle shear fractures [?]. So-called parting fractures (including bedding fractures) observed in surface cores show no mud invasion, are mostly closed under formation conditions, and open after core retrieval due to stress unloading [?]. Artificial fracture orientations are controlled by the present-day stress field, cutting through bedding interfaces as high-angle fractures parallel to the maximum horizontal effective principal stress [?], with dips mainly distributed between 80°-90° [?], not low-angle fractures.

Parting fractures observed in surface cores are products of unloading (stress unloading), which causes microfractures at various scales in the core. The internal structure of the core suffers irreversible damage, weakening mechanical parameters such as elastic modulus and tensile strength (with significantly greater weakening perpendicular to bedding planes than parallel to them), resulting in "distorted" mechanical properties. Parting fractures observed in surface cores are fundamentally different from the real fracture system under formation conditions and cannot directly represent the original subsurface state.

## 4 Control of Parting Fractures on Reservoir Types

The existence of low-angle parting fractures under formation conditions in tectonically stable regions of sedimentary basins directly impacts reservoir type determination, posing dual challenges of theoretical 颠覆 and technical reconstruction for shale-type shale oil exploration and development.

If low-angle parting fractures exist under formation conditions, they constitute a "dual-porosity system" together with nano-to-micron scale matrix pores, significantly enhancing effective storage capacity and seepage capability by connecting isolated matrix pores [?], forming matrix-type reservoirs and substantially increasing technically recoverable reserves and resource abundance estimates [?]. The technical focus would be on quantitative evaluation of parting fracture development degree and optimization of volumetric fracturing parameters, significantly reducing technical complexity and development costs.

Conversely, if low-angle parting fractures do not exist under formation conditions, relying only on single matrix pores and sparse structurally formed high-angle fractures limits storage capacity. Seepage becomes highly dependent on high-angle fracture density and connectivity, forming highly heterogeneous fracture-type reservoirs [?], significantly reducing technically recoverable reserves and leading to conservative resource abundance estimates. Production from existing test wells requires re-evaluation. The technical focus must shift to prediction of structurally formed high-angle fractures, significantly increasing technical complexity and development costs.

**Conclusions:**

1) During the burial stage (stress loading), rocks can form high-angle tensile-shear fractures under high confining pressure and vertical effective stress dominance. During the uplift stage (stress unloading), rocks not exposed to the surface can form high-angle tensile-shear fractures along lithological interfaces due to lateral lithological variations causing vertical differential strain. Rocks exposed at the surface can form low-angle "pseudo-bedding-parallel fractures" due to vertical effective stress release and horizontal effective stress unloading. Fracture orientation is controlled by the dynamic evolution of stress states during burial-uplift processes. Low-angle parting fractures (including bedding fractures) cannot form and exist under formation conditions in tectonically stable regions of sedimentary basins.

2) Parting fractures observed in surface cores are products of unloading (stress unloading). Stress unloading causes irreversible damage to core internal structure, resulting in artificially high laboratory-measured porosity and permeability, and weakening mechanical parameters such as elastic modulus and tensile strength (with significantly greater weakening perpen-

dicular to bedding planes than parallel to them). Physical and mechanical properties become "distorted." Under formation conditions in tectonically stable regions, fracture orientation is jointly controlled by rock tensile strength and in-situ stress fields, dominated by high-angle tensile-shear fractures.

3) Parting fractures observed in surface cores are fundamentally different from the real fracture system and cannot directly represent the original subsurface state.

4) The cognitive dilemma regarding parting fractures stems from disciplinary compartmentalization: sedimentary geology focuses on static lithological descriptions of clastic particle contacts while neglecting their dynamic response in multi-stage stress fields; rock mechanics emphasizes the regulatory mechanism of the present-day stress field on clastic particle contacts while overlooking constraints imposed by multi-stage stress fields throughout the burial-uplift history. A multidisciplinary cross-validation framework integrating sedimentation, diagenesis, and mechanics needs to be established.

5) Low-angle parting fractures cannot form and exist under formation conditions in tectonically stable regions and cannot constitute an effective "dual-porosity system" with strong storage and seepage capacity together with nano-to-micron scale matrix pores. For shale-type shale oil in areas lacking large-scale sand bodies, exploration direction must shift from "matrix-type reservoirs" relying on matrix pore systems to "fracture-type reservoirs" dependent on high-angle tensile-shear fractures, with technical focus shifting to prediction of structurally formed high-angle fractures.

**Symbol Notations:**

$\sigma$ - total stress, MPa; $\sigma'$ - effective stress, MPa; $\sigma_v$ - vertical stress, MPa; $\sigma'_v$ - vertical effective stress, MPa; $\sigma_H$ - maximum horizontal principal stress, MPa; $\sigma'_H$ - maximum horizontal effective principal stress, MPa; $\sigma_h$ - minimum horizontal principal stress, MPa; $\sigma'_h$ - minimum horizontal effective principal stress, MPa; $\sigma_n$ - normal stress acting on shear plane, MPa; $\tau$ - shear stress, MPa; $P$ - pore pressure describing fluid support on particles, MPa; $T$ - rock tensile strength, MPa; $P_f$ - formation fracture pressure, MPa; $F$ - elastic force or contact force, N; $W$ - gravity, N; $E$ - elastic modulus describing material resistance to elastic deformation, MPa; $E^*$ - equivalent elastic modulus, MPa; $G$ - shear modulus describing material resistance to shear deformation, MPa; $\nu$ - Poisson's ratio describing relationship between lateral and vertical deformation, dimensionless; $\varepsilon_h$ - horizontal strain, dimensionless; $\varepsilon_v$ - vertical strain, dimensionless; $\varepsilon_x, \varepsilon_y$ - strain in x, y directions, dimensionless; $\gamma$ - shear strain describing shape change under shear force, dimensionless; $\delta$ - normal overlap, m; $R^*$ - equivalent curvature radius, m; $\phi$ - internal friction angle related to particle roughness and mineral composition, °; $\theta$ - angle between shear failure plane and maximum principal stress direction, °; $\alpha$ - Biot coefficient, dimensionless (0-1); $c$ - cohesion describing interparticle chemical cementation strength, MPa.

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*Note: Figure translations are in progress. See original paper for figures.*