Petroleum Science 23 (2026) 1015–1038

Contents lists available at ScienceDirect

Petroleum Science

journal homepage: www.keaipublishing.com/en/journals/petroleum-science

Review Paper

Research on the genesis mechanism of shale fractures

Cun-Fei Ma [a,*], Wen-Jing Sun [a], Bing Hao [b], Yi-Mei Han [c], Li-Juan Wang [d], Hui Cao [d], Jun-Ke Sun [e], Yang Li [f]

[a] *School of Geosciences, China University of Petroleum (East China), Qingdao, 266580, Shandong, China*
[b] *Oil & Gas Cooperation and Development Company, BHDC, CNPC, Tianjin, 300457, China*
[c] *Hekou Oil Production Plant, Sinopec Shengli Oilfield, Dongying, 257200, Shandong, China*
[d] *PetroChina Qinghai Oilfield Company, Dunhuang, 736202, Gansu, China*
[e] *1st Oil Plant of PetroChina Qinghai Oil Field Branch Company, Haixi, 816499, Qinghai, China*
[f] *Testing Company of PetroChina Qinghai Oilfield, Mangya, 816400, Qinghai, China*

ARTICLE INFO

Article history:
Received 11 September 2024
Received in revised form
7 January 2025
Accepted 3 September 2025
Available online 10 September 2025

Edited by Jie Hao and Xi Zhang

Keywords:
Shale fractures
Types of fractures
Controlling factors
Formation mechanisms

ABSTRACT

Shale fractures, serving as conduits for the flow and storage space of shale oil, play a critical role in resource exploration and evaluation. Shale oil is considered a highly promising unconventional natural gas resource in the 21st century, offering a significant supplement to conventional energy sources and playing an important role in addressing the growing global energy demand. Based on a comprehensive synthesis of existing research on shale fractures, this paper proposes a novel classification system aimed at investigating the formation mechanisms, developmental characteristics, and primary controlling factors of different fracture types. Rooted in geological origins, shale fractures are categorized into six major classes and eleven subcategories, including structural fractures, diagenetic fractures, bedding fractures, fluid pressure fractures, structural diagenetic fractures, and structural fluid pressure fractures, with each type's formation mechanism and development process discussed in detail. The factors influencing fracture development include both internal and external elements. The controlling factors for different fracture types vary. For instance, structural fractures are primarily influenced by tectonic stress, while diagenetic fractures are related to changes in rock properties due to diagenesis. Through an in-depth exploration, this paper reveals the causal mechanisms underlying each fracture type. Structural fractures typically arise when tectonic stress exceeds the rock's fracture strength; diagenetic fractures result from changes in rock structure and mechanical properties induced by diagenesis; bedding fractures primarily result from tectonic uplift, leading to the fracturing of bedding planes through a series of diagenetic processes; fluid pressure fractures are caused by sudden abnormal fluid pressures in the formation, leading to overpressure and subsequent fracture formation.

Moreover, the development of structural rock fractures is primarily controlled by a combination of lithology, rock structure, tectonic activity, and fluid pressure, typically formed through the coupled effects of tectonic activity and diagenesis. The formation of fluid pressure fractures, on the other hand, is facilitated by the interaction between tectonic activity and fluid pressure. This paper further analyzes the underlying causes of fracture development and systematically describes the main controlling factors, providing an essential theoretical foundation and guidance for shale oil exploration. In light of the above research, this paper also identifies several future research directions, including the establishment of unified classification standards, the refinement of micro-fracture scale characterization methods, and the further quantification of composite fracture formation mechanisms. A more in-depth and accurate understanding of fracture development processes will provide a scientific basis for shale oil exploration and development, offering both theoretical support and practical guidance for the efficient utilization of resources.

---

* Corresponding author.
E-mail address: 20170076@upc.edu.cn (C.-F. Ma).
Peer review under the responsibility of China University of Petroleum (Beijing).

https://doi.org/10.1016/j.petsci.2025.09.006
1995-8226/

1. Introduction

Shale oil, as a highly promising unconventional petroleum resource, holds significant potential for supplementing traditional energy supplies. Fractures within shale reservoirs play a critical role in enhancing oil storage and flow, particularly in low-porosity and low-permeability formations. These fractures are crucial for facilitating the movement and accumulation of hydrocarbons, greatly improving the storage and transportation capacities of shale oil reservoirs (Li et al., 2004; Chen, 2022; Hu et al., 2024a; Zhang et al., 2017). A fracture, characterized as a discontinuity within the rock mass where there is little to no displacement between adjacent blocks, is a prominent feature of shale due to its distinct geological properties, including high organic matter content, low porosity, and elevated water content (Hu et al., 2024b).

As a result, the formation, evolution, and distribution of fractures in shale directly influence the reservoir's capacity to store and transmit oil and gas, making them a fundamental factor in shale oil and gas exploration (Zhang et al., 2023; Lorenz et al., 2002; Zeng et al., 2023; Zeng and Li, 2009). Understanding the nature and behavior of fractures in shale is paramount to effective exploration and development strategies, as they serve as essential conduits for oil and gas migration within these tight reservoirs. Fractures not only enhance the connectivity between different parts of the reservoir but also play a critical role in improving the overall efficiency of production techniques, such as hydraulic fracturing (Hu et al., 2025). Comprehensive research on shale fracture characteristics provides valuable insights into reservoir management, helping to optimize the extraction process by targeting areas with the most promising fracture networks. In many countries, considerable advancements have been made in the exploration and development of fractured shale reservoirs, with well-established technologies and reservoir systems in place (Lun et al., 2010; Bruce, 1984; Machel, 1997; Rijken and Cooke, 2001). In China, the exploration of fractured mudstone reservoirs dates back to the 1960s, with major hydrocarbon discoveries in regions like Songliao and Bohai Bay. These findings have underscored the critical role of fractures in connecting adjacent reservoir zones, facilitating oil and gas migration, and providing a foundation for production enhancement through fracturing techniques.

As such, fractures are integral to both the storage and migration of hydrocarbons in shale, significantly impacting oil and gas exploration and development (Nelson, 1985). With the ongoing discovery of fractured shale reservoirs worldwide, both domestic and international research has focused on fracture classification, formation mechanisms, and strategies to optimize reservoir performance. Substantial progress has been made in understanding the types, characteristics, and controlling factors of fractures within shale formations. This article reviews the latest advancements in shale fracture research, identifying knowledge gaps and suggesting future directions for investigation. By advancing our understanding of shale fracture systems, these efforts aim to enhance theoretical and technical frameworks for identifying high-yield shale oil and gas reservoirs and optimizing their development potential.

2. Types and characterization of fractures in shale

Fractures, as pivotal components of oil and gas resources, serve as critical reservoirs for the enrichment, preservation, and migration of hydrocarbons. Given the unique characteristics of shale formations, the genesis and evolution of fractures bear significant geological implications for oil and gas exploration. Various fracture classification methods have been proposed, each tailored to different research objectives, leading to a plethora of classification schemes. Initially, foreign experts such as Stearns introduced a classification scheme based on crustal activity, distinguishing between regional and structural fractures. While foundational, this scheme lacked analysis of fracture causation (Stearns, 1968). Subsequently, scholar Felix proposed a comprehensive classification method rooted in rock mechanical properties, delineating fractures into shear rupture, tensile rupture, and dilation rupture categories (Michael, 1977). In 1988, Zhou (1998) devised a more comprehensive scheme considering geological processes, sedimentary environments, and stratigraphic systems, categorizing fractures into structural, regional, shrinkage, and surface-related types, marking the earliest and most comprehensive fracture classification in China. As research progressed, numerous classification schemes emerged, including those based on scale, development form, occurrence, mechanical properties, and geological origin (Table 1). While each offers distinct insights into fracture characteristics, they also possess inherent limitations. Scale-based classification, for instance, provides intuitive insights into fracture development but lacks depth for further analysis (Wang et al., 2014). Development-based classification, on the other hand, offers clarity on fracture forms but may overlook underlying mechanical processes (Ding et al., 2011). Similarly, mechanical properties-based classification enhances clarity but may oversimplify fracture formation mechanisms (Ding et al., 2012). Geological origin-based classification provides a structural perspective but may fail to capture all fracture types (Zeng et al., 2022).

In summary, while each fracture classification scheme offers valuable insights, they also present limitations. Their application in classifying mud shale fractures must be approached judiciously, considering both their strengths and weaknesses.

This paper integrates the primary controlling factors—fracture development morphology, geological origin, and tectonic action-into six major categories and eleven subcategories: structural fractures, diagenetic fractures, bedding fractures, fluid pressure fractures, diagenetic-fluid pressure fractures, and structure-fluid pressure fractures. Among these, tensional fractures, shear fractures, and bedding fractures emerge as the principal types of shale fractures (Table 2).

2.1. Structural fractures

Structural fractures originate from tectonic stress, delineated by their mechanical properties into tension, shear, and tension-

Table 1
Classification scheme for shale fractures.

Origin	Classification basis	Fracture types
Stearns (1968)	Crustal activity	Regional fractures, structural fractures
Nelson (1985)	Rock mechanics	Shear fractures, tensile fractures, expansion fractures
Zhou (1998)	Comprehensive geological processes	Regional fractures, structural fractures, shrinkage fractures, surface related fractures
Sun (2017)	Scale	Giant fractures, large fractures, medium fractures, small fractures, and micro fractures
Zhou et al. (2003)	Developmental morphology	Opening fractures, filling fractures, closing fractures, and mesh fractures
Ding et al. (2011)	Attitude	Vertical fractures, horizontal fractures, high angle fractures, low angle fractures
Zeng et al. (2022)	Comprehensive	Structural and non structural fractures

Table 2
Classification scheme of shale fractures in this article.

Classification basis		Main category	Subcategory
Geological genesis	Tectonic action	Structural fractures	Tensile fractures Shear fractures Tensile-shear fractures
	Diagenetic action	Diagenetic fractures	Diagenetic shrinkage fracture Dissolution fractures
	Sedimentary action	Bedding fractures	Bedding plane fractures Interlayer fractures
	Fluid pressure action	Fluid pressure fractures	Drainage fractures Hydrocarbon generation and expulsion fractures
	Composite action	Structural-diagenetic fractures	Dolomite lithification fractures
		Diagenetic-fluid pressure fracture	Bedding-parallel vein fractures

shear fractures. Tension fractures manifest in regions experiencing compressive stress across the entirety of the rock body. In some cases, localized tensile stress can lead to their formation, often accompanied by X-shaped conjugate shear fractures (Jacques and Bernard, 1983). These fractures predominantly occur above fold neutralization planes, structural hubs, and zones with significant stress fluctuations (Li et al., 2004). Tension fractures exhibit considerable scale and opening variations. Some display jagged edges, with limited extension, often traversing bedding and mineral particles. Their rough surfaces lack visible scratches and are typically filled with minerals like calcite and quartz (Fig. 1).

Shear fractures entail sliding deformation along the tangential direction of the fracture surfaces on either side of the fracture. Based on the relationship between the fracture and the bedding layer, they are categorized into bedding shear fractures and through-bedding shear fractures. Bedding shear fractures, also known as detachment fractures, develop along rock strata, typically at lithological junctions during tension or compression events. Originating from shear stress parallel to the bedding layer, they form under tectonic stress conditions (Ma et al., 2023). These fractures often exhibit small scale, minimal opening changes, extensive propagation, and develop scratches on their mirror surfaces. Their filling degree tends to be low, with common fillers including calcite and quartz minerals (Zhang et al., 2023). Bedding shear fractures can provide insights into the sequence of fracture formation, with later-formed fractures staggering earlier ones. This staggered pattern reflects the chronological sequence of fracture development (Angelier and Colletta, 1983). The formation of bedding shear fractures is influenced by the degree of structural deformation in the region; higher degrees of deformation lead to more developed bedding shear fractures. Through-bedding shear fractures, on the other hand, penetrate shale bedding. These fractures typically exhibit high-angle penetration and are characterized by large scale, significant opening changes, and extensive propagation. Unlike bedding shear fractures, through-bedding shear fractures feature smooth surfaces without prominent scratches and have a lower filling degree, with common fillers including quartz and calcite minerals. Due to their penetration through multiple layers, the lateral connectivity of cross-bedding shear fractures is typically limited (Fig. 2).

Tensile-shear fractures refer to fractures that undergo tensile deformation in the direction perpendicular to the fracture surface, and also exhibit sliding deformation in the tangential direction along the fracture surface, possessing properties of both tensile and shear fractures (Chen et al., 2023). The scale of tensile-shear fractures is relatively large, with little variation in aperture and

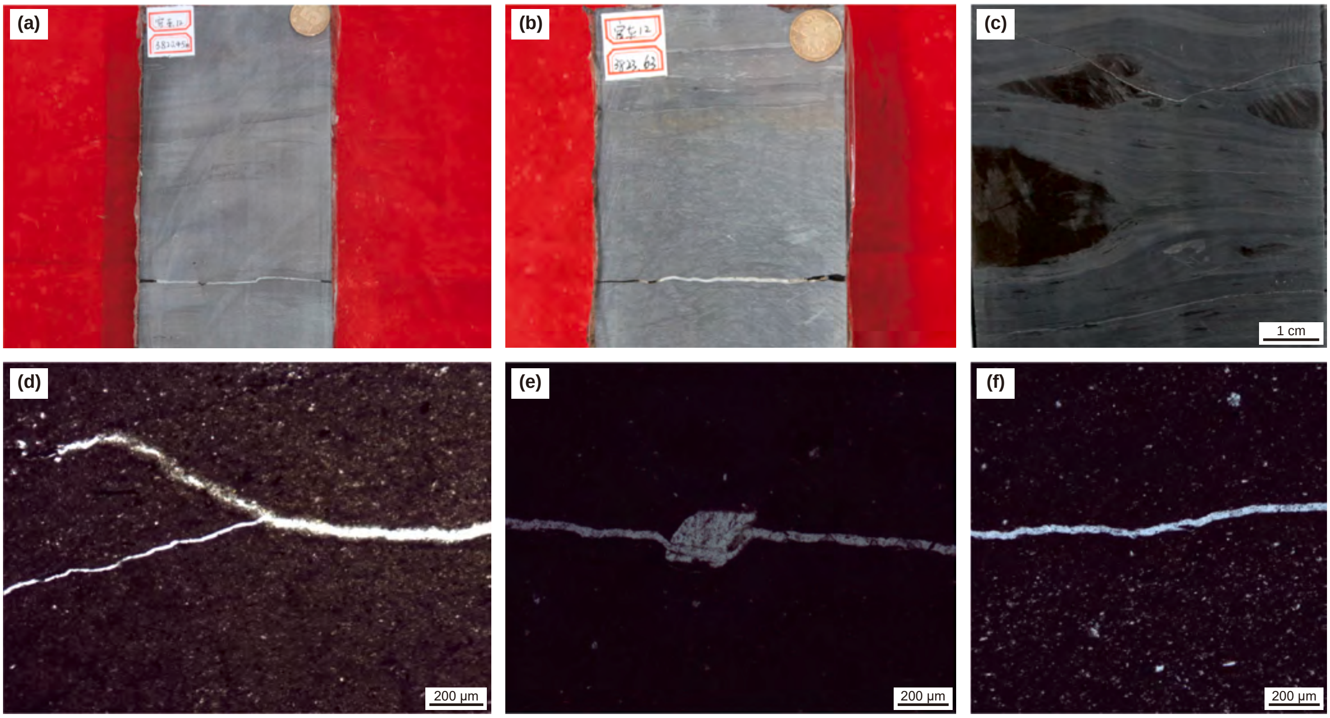


Fig. 1. Core characteristics of tensile fractures. (**a**) Tensile fractures, extended short, form straight, Well GD12, 3820.45 m; (**b**) tensile fracture, Well GD12, 3823.63 m; (**c**) tensile fracture, extended short, Wufeng-Longmaxi formations (Yang et al., 2024); (**d**) tensile fracture, fracture filled with zeolite, Well GD12, 2919.96 m; (**e**) fractures cutting quartz particles, Well GD12, 2926.73 m; (**f**) tensile fractures filled with zeolite, Well GD12, 2935.38 m.

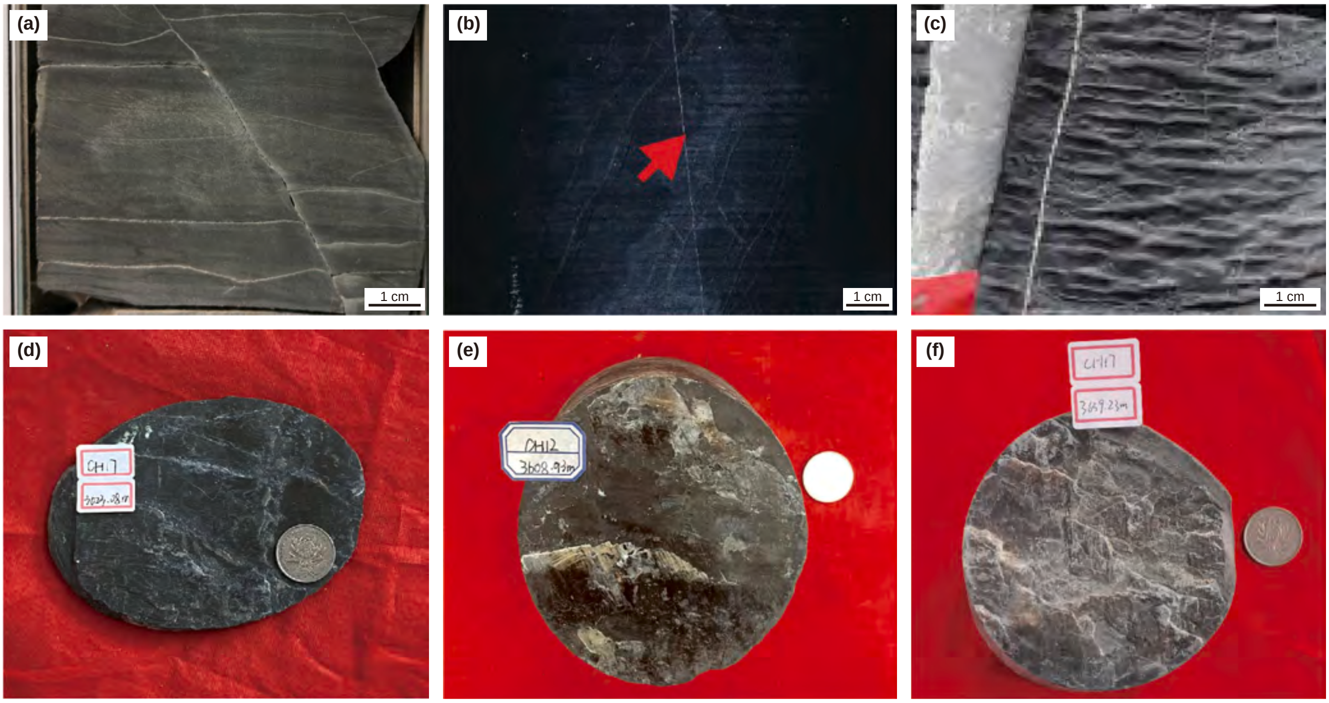


Fig. 2. Core characteristics of shear fractures. (**a**) Shear fractures, form straight, Well GD12, 2925.67 m; (**b**) shear fractures, cutting through rock layers (Yang et al., 2024); (**c**) shear fractures, form straight (Li et al., 2024); (**d**) shear fractures, developed a mirror surface, Well CH17, 3623.08 m; (**e**) shear fractures, slipping along the plane, Well CH12, 3608.93 m; (**f**) shear fractures with scratch marks, Well CH17, 3639.23 m.

limited extension. Most of the fracture surfaces are flat and relatively smooth, with some slight scratches. The degree of fracture filling is relatively high, with minerals such as calcite and quartz filling the fractures (Fig. 3).

2.2. Bedding fractures

Bedding fractures originate from sedimentation and are subsequently influenced by tectonic or diagenetic processes, resulting in fractures that run parallel to the bedding planes. Based on their development characteristics in various lithologies, bedding fractures can be categorized into lamination fractures and bedding fractures.

Lamination fractures primarily occur as pores and fractures between parallel bedding layers, marked by peeling lines. They typically form under sedimentation, especially in robust hydrodynamic environments. Comprising thin layers of shale, these fractures occur at interfaces with shale exhibiting the weakest mechanical properties, making them prone to peeling (Schrank et al., 2021). The lamination surface of shale often appears sandy, and such fractures are observable in cores, thin sections, and scanning electron microscopes. Lamination fractures typically feature small openings that develop parallel to the shale bedding plane, with high filling degrees, often completely filled, and linked to high-angle tensile fractures. They are particularly prevalent in mud shale formations with well-developed lamination. In areas where interlayer lamination fractures predominate, both fracture density and width are typically high; conversely, where leafy fractures prevail, density is higher while fracture width is smaller.

Bedding fractures, on the other hand, represent larger-scale fractures running parallel to the bedding planes, extending over considerable distances. They exhibit stable occurrences, low angles, and large openings, typically remaining unfilled and often developing at lithological junctions. Key distinguishing features between bedding and lamination fractures include differences in opening, length, and density. Lamination fractures appear fine and dense, stacked atop one another, and are not visible to the naked eye (Fig. 4). They exhibit a contact relationship with bedding

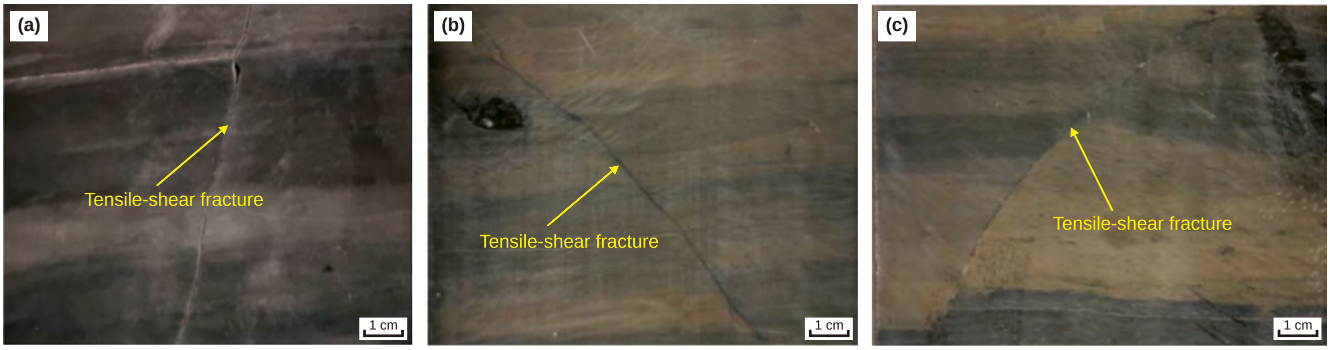


Fig. 3. Core characteristics of tensional-shear fractures. (**a**) Tensile-shear fracture, form straight, Well GD12, 2976.25 m; (**b**) tensile-shear fracture, high angle, Well GD12, 2987.65 m; (**c**) tensile-shear fracture, extend further, Well GD12, 2956.78 m.

fractures, which are much larger in scale and easily discernible within cores (Ma et al., 2023).

2.3. Diagenetic fractures

Diagenetic fractures arise during diagenesis, encompassing fractures formed by rock dehydration shrinkage in the early stages or during the diagenetic process, as well as through surface weathering, water loss, shrinkage, and mineral phase changes, among other mechanisms (Zeng et al., 2022). Diagenetic contraction fractures, primarily linear in nature, exhibit minimal extension but significant opening changes, typically less than 0.2 μm, with unstable inclination angles. Due to their minute scale, they are often observed under scanning electron microscopes. These fractures demonstrate good connectivity, moderate filling, and partial mineral fillings. Shale rich in silica content tends to shrink during diagenesis, leading to the widespread occurrence of diagenetic contraction fractures (Huo et al., 2019).

Dissolution fractures, resulting from the differential dissolution of shale minerals, play a crucial role in enhancing shale reservoir pore space (Zhao et al., 2023). Typically exhibiting a near-horizontal trend, these fractures have widths under 15 μm, extensive extensions, and significant spatial variability. Dissolution fractures tend to be later filled with calcite, with high filling degrees. While serving as favorable storage and transportation conduits for shale reservoirs, the presence of calcite fillings can impact their functionality (Wang et al., 2019a). Over time, apart from newly formed fractures, most fractures undergo dissolution, with some expanding into karst caves and others evolving into dissolved fractures (Barker and Miliken, 2008). Early-stage dissolution fractures exhibit considerable filling, often characterized by dense calcite veins in the core, which have minimal influence on oil and gas accumulation (Fig. 5). Later-stage dissolution fractures, typically semi-filled or unfilled, form interconnected networks with structural fractures, serving as primary pathways connecting dissolution fractures (caves) and establishing storage and seepage networks (Wang et al., 2019b).

2.4. Fluid pressure fracture

Fluid pressure fractures occur when the internal pore fluid pressure within a rock surpasses the rock's tensile strength, resulting in tensile rupture. Typically, these fractures exhibit irregular shapes and are not grouped together, often filled with asphalt and calcite (Fig. 6). Abnormal fluid pressure fractures can be further classified into drainage fractures and hydrocarbon generation and expulsion fractures (Ma et al., 2016; Zhang et al., 2017).

Drainage fractures primarily emerge during the early stages of burial. Distinguished by their rough surfaces and irregular shapes, they are notably different from structural and bedding fractures. These fractures feature minimal changes in opening, significant spatial variability, and limited extensions. They often display lateral bending along shale bedding, with rough surfaces and irregular shapes. Drainage fractures typically exhibit high filling degrees, initially filled with mud and later replaced by calcite, asphalt, and other minerals (Fig. 7; Ma, 2017).

Hydrocarbon generation and expulsion fractures play a crucial role as the primary pathways for oil and gas migration within organic-rich mudstones. In addition to facilitating hydrocarbon transport, these fractures also serve as important micro-reservoirs for crude oil accumulation and storage (Ma et al., 2017). Their widths generally remain relatively stable, typically ranging from just a few microns to, at most, several hundred microns. Due to their fine-scale nature, they are more effectively observed using scanning electron microscopy (SEM). These fractures can extend over considerable distances, with some reaching several centimeters in length. A notable characteristic is the presence of multiple flat kerogens interconnected within the same hydrocarbon generation and expulsion fracture, highlighting their widespread lateral continuity. Additionally, these fractures are often densely filled with various minerals, including asphalt, pyrite, and calcite, which act as primary infill materials (Fig. 8). The presence of these mineralized fillings suggests a complex diagenetic history,

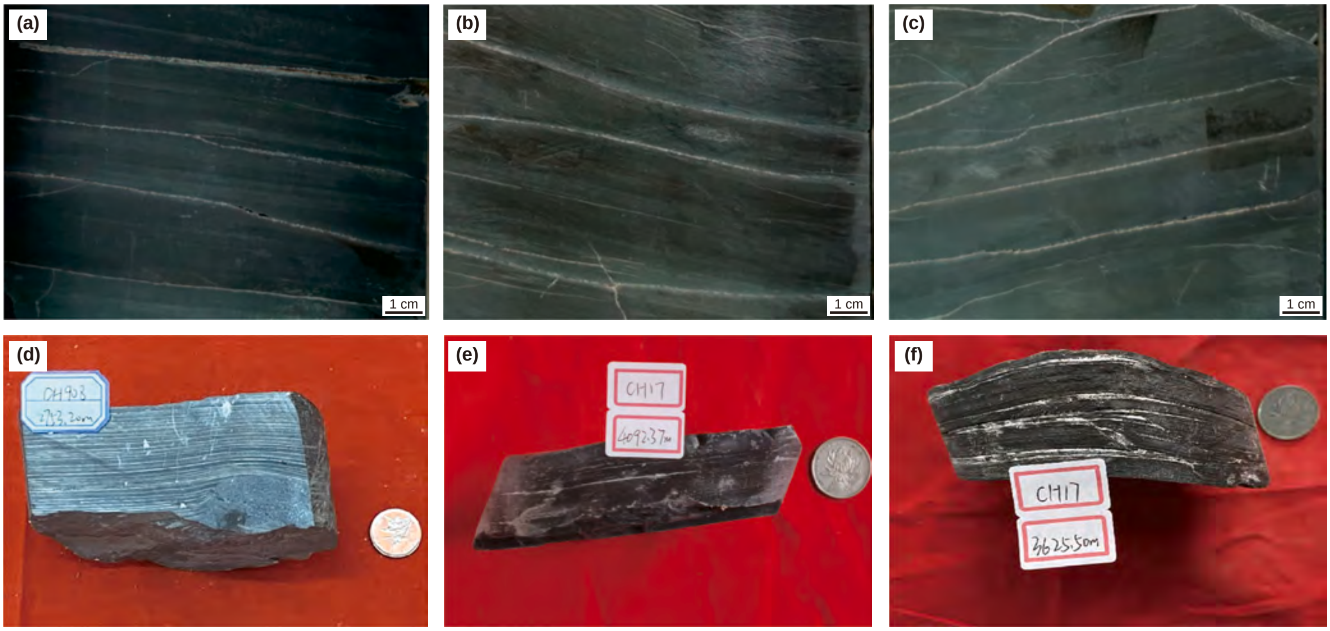


Fig. 4. Core and thin section characteristics of bedding fractures. (**a**) Bedding plane fracture filled with calcite, Well FY14, 3217.68 m; (**b**) bedding plane fracture, Well NY1,3637.75 m; (**c**) bedding fracture, Well NY1, 3349.65 m; (**d**) lamination fracture, Well CH908, 2753.20 m; (**e**) lamination fracture, Well CH17, 4092.37 m; (**f**) lamination fracture, Well CH17, 3625.50 m.

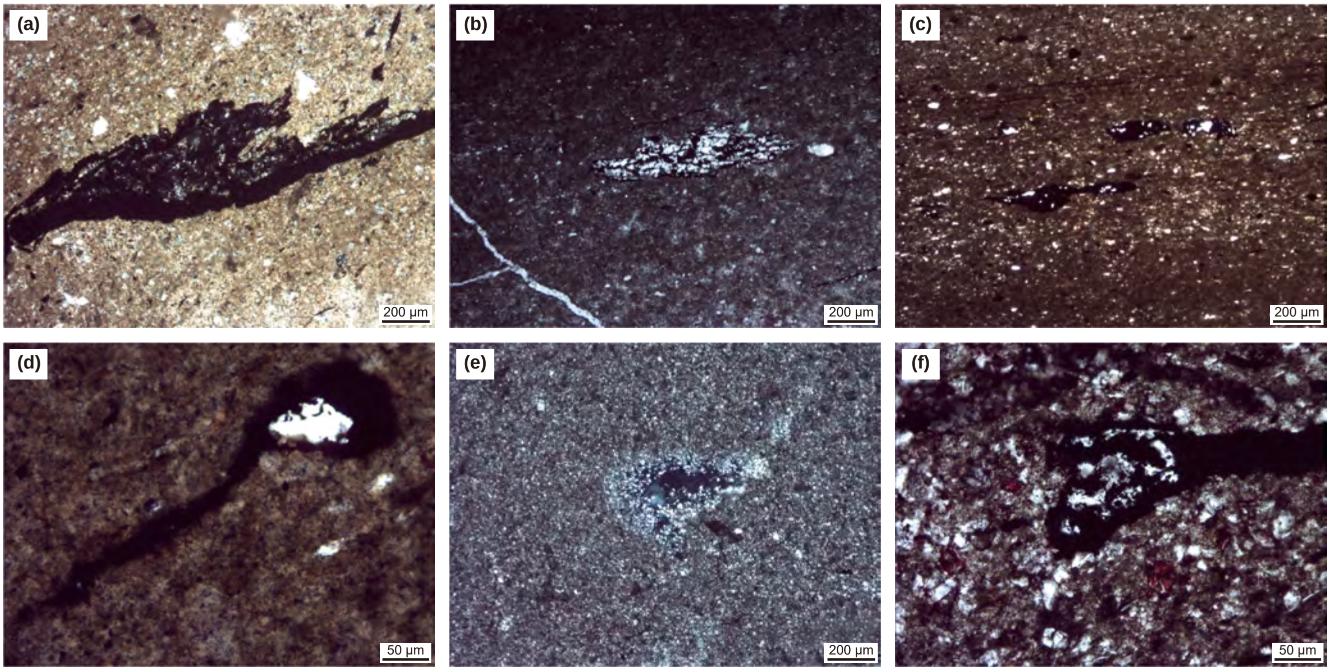


Fig. 5. Microscopic characteristics of dissolution fractures. (**a**) Zeolite-filled organic matter dissolution pores, Well FY1, 3301.69 m; (**b**), (**c**) dissolution pores, filled with sand, Well FY1, 3324.76 m, 3376.87 m; (**d**) dissolution fractures partially filled with zeolite, Well FY1, 3420.23 m; (**e**) dissolution fractures filled with zeolite, Well FY1, 3187.98 m; (**f**) organic matter dissolution pores filled with zeolite, Well FY1, 3302.35 m.

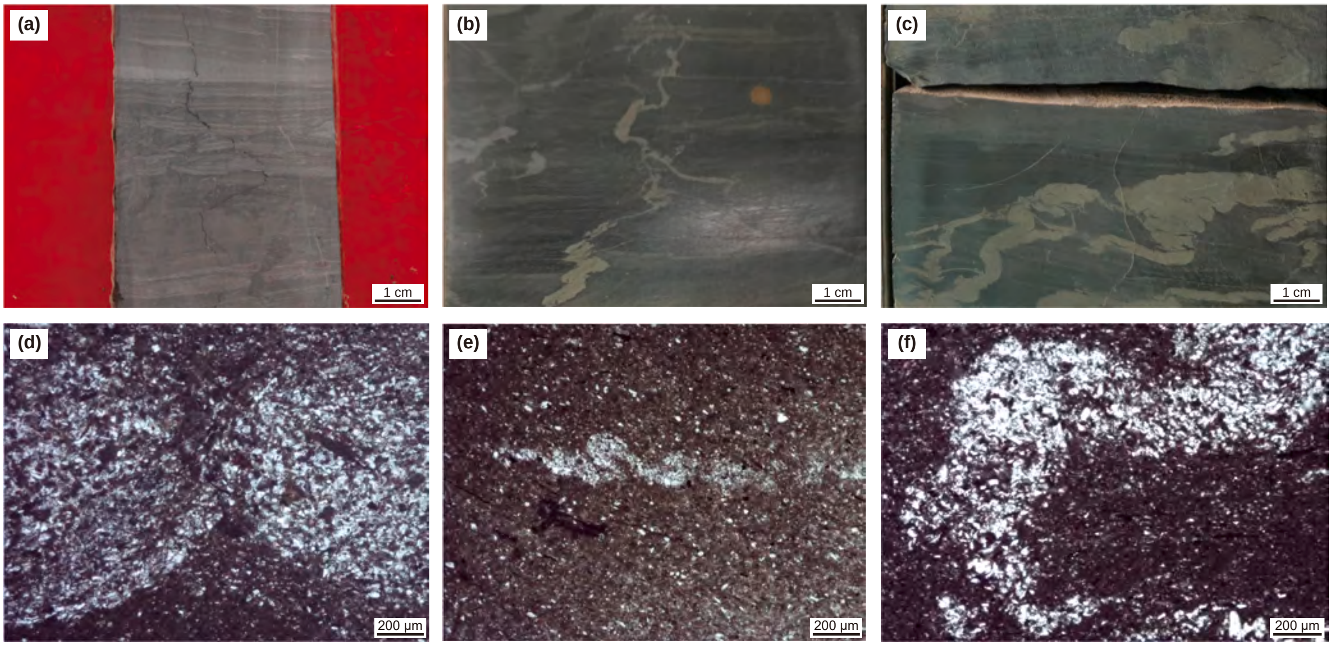


Fig. 6. Core and thin section characteristics of drainage fractures. (**a**) Drainage fracture, mudstone with partial filling, Well FY1, 3354.75 m; (**b**) drainage fracture, mudstone filling, Well FY1, 3223.55 m; (**c**) drainage fracture, serpentine shape, Well GD12, 2934.78 m; (**d**) drainage fracture, filled with sand, Well NY1, 3443.54 m; (**e**), (**f**) drainage fracture, large opening variation, Well NY1, 3398.85 m.

influencing both the porosity and permeability of the surrounding rock matrix.

2.5. Structural-diagenetic fractures

Structural-diagenetic fractures arise from the interplay between tectonic processes and diagenesis. For instance, consider the structural-diagenetic fractures observed in the dolomite of the Kong 2 Member within the Cangdong Sag of the Bohai Bay Basin. These fractures, attributed to dolomitization, are also known as dolomite sewing (Ma et al., 2023). Characterized by numerous high-angle fractures in the core, they typically exhibit short extensions, large openings, and a stout morphology, often displaying a distinct yellow or red hue on the fracture surface. These fractures are predominantly fully or semi-filled, with dolomite, calcite, or gypsum serving as the filling material.

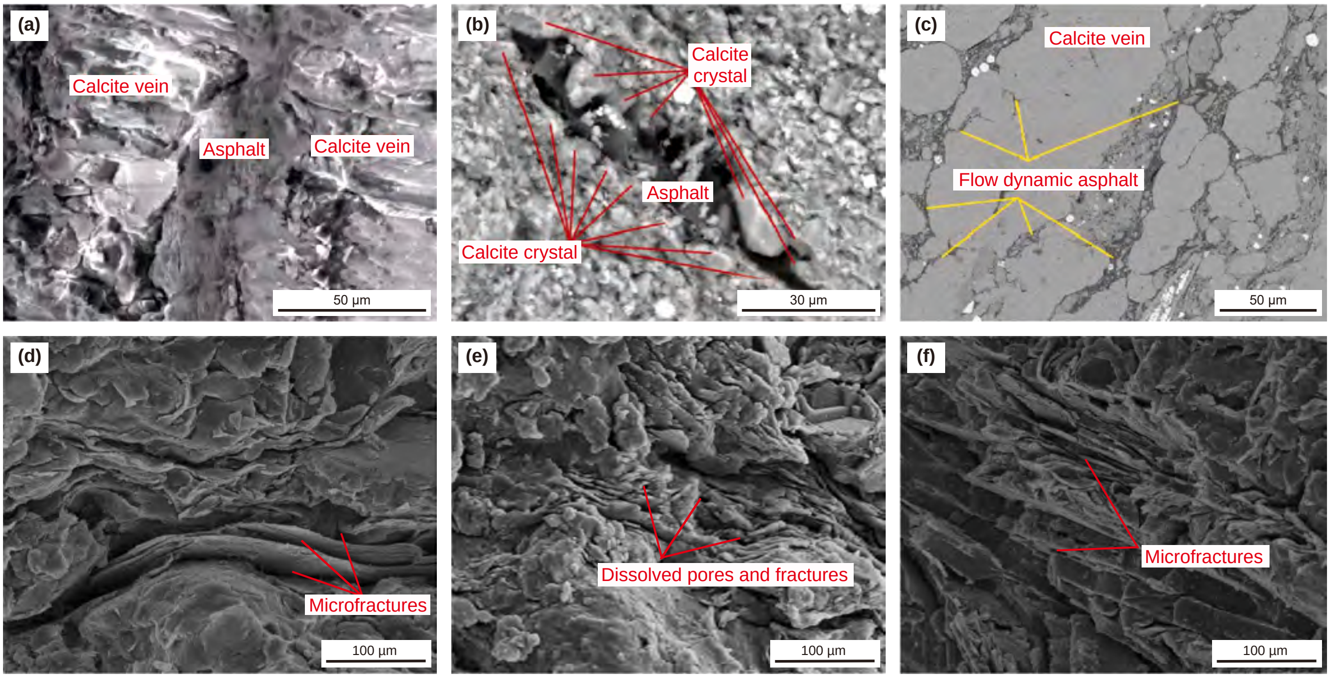


Fig. 7. Microscopic characteristics of drainage fractures. (**a**) Drainage fracture, filled with asphalt, Well NY1; (**b**) drainage fracture, filled with asphalt (Ma et al., 2017); (**c**) drainage fracture, filled with asphalt (Ma et al., 2017); (**d**) drainage fracture, dissolved micropores, Well GD14, 4077.24 m; (**e**) drainage fracture, dissolved micropores, Well GD14, 4082.35 m; (**f**) drainage fracture, dissolved micropores, Well GD14, 4085.67 m.

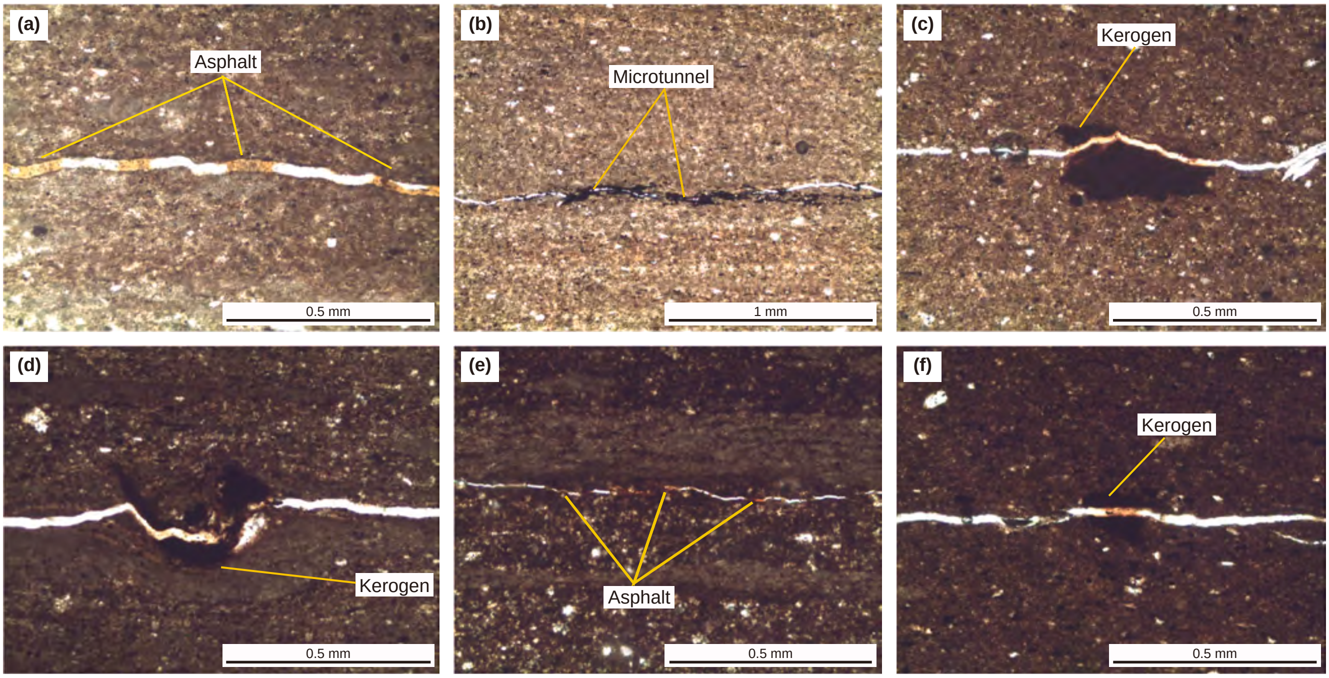


Fig. 8. Microscopic characteristics of hydrocarbon generation and expulsion fractures. (**a**) Fractures is filled with asphalt, Well FY1, 3248.65 m; (**b**) fractures is partially filled with pyrite, Well FY1, 3254.35 m; (**c**) fractures initiates from the tip of the kerogen and extend horizontally, Well NY1, 3023.35 m; (**d**) fractures extends horizontally through the kerogen, Well GD12, 2965.56 m; (**e**) fracture is filled with asphalt, Well GD12, 2977.65 m; (**f**) fracture extends horizontally through the kerogen, Well NY1, 3087.89 m.

Current research posits that the formation mechanism of these fractures is primarily governed by the recrystallization force of dolomite, resulting from the coupling of tectonic stress and fluid pressure (Fig. 9).

2.6. Bedding-parallel vein fractures

Bedding-parallel vein fractures are fractures that open along the lamination plane under the action of tectonic action and

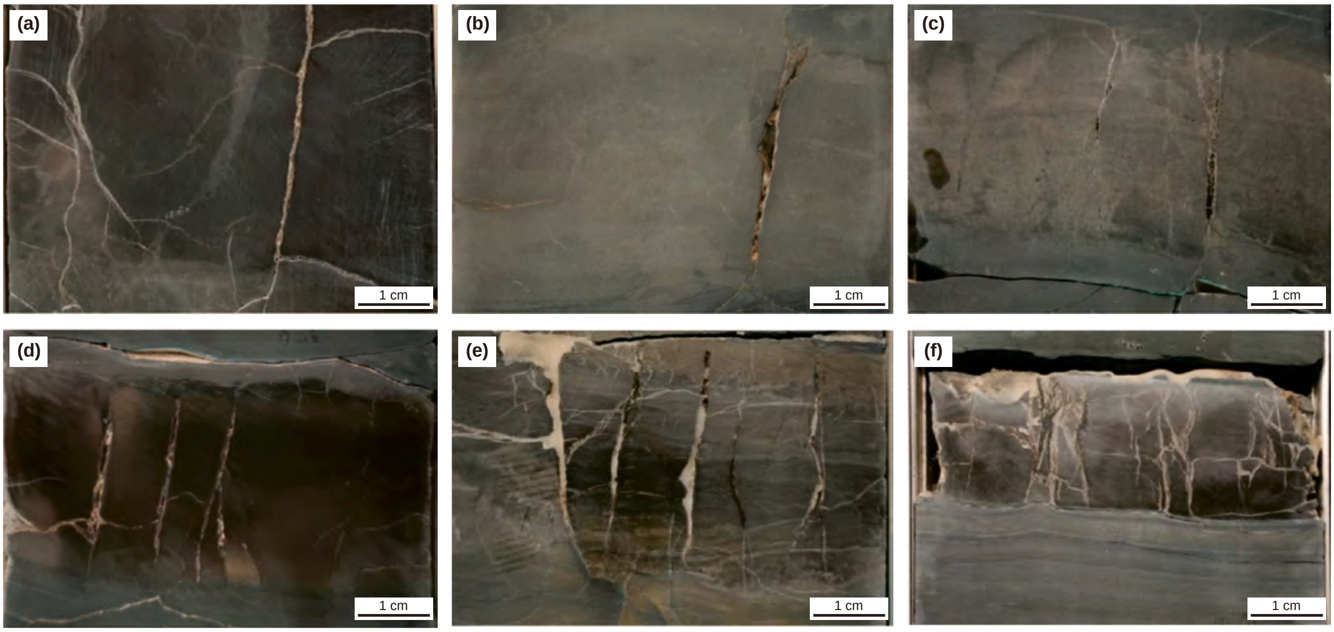


Fig. 9. Structural-diagenetic fractures. (**a**) Fractures appear at high angles and are present, Well GD14, 4078.95 m; (**b**), (**c**) fracture is filled with dolomite, Well GD14, 4085.67 m, 4087.98 m; (**d**), (**e**) fracture are developed in a systematic manner, Well GD14, 4096.78 m; (**f**) fractures are present, Well NY1, 3067.95 m.

abnormal fluid pressure (Zhan et al., 2022). They are large in scale, have small opening changes, have long extensions, have obvious tensile characteristics, are highly filled, and are mostly covered by the filling of fibrous calcite, quartz and pyrite is an important sign of high-pressure hydrocarbon expulsion and migration of oil and gas in muddy source rocks (Fig. 10).

3. Factors controlling fracture development

Natural fractures are influenced by a multitude of factors, which development conditions of natural fractures are highly adaptable and uncertain, and their distribution patterns exhibit significant randomness (Yang et al., 2020). Controlling factors influencing fracture development are primarily categorized as

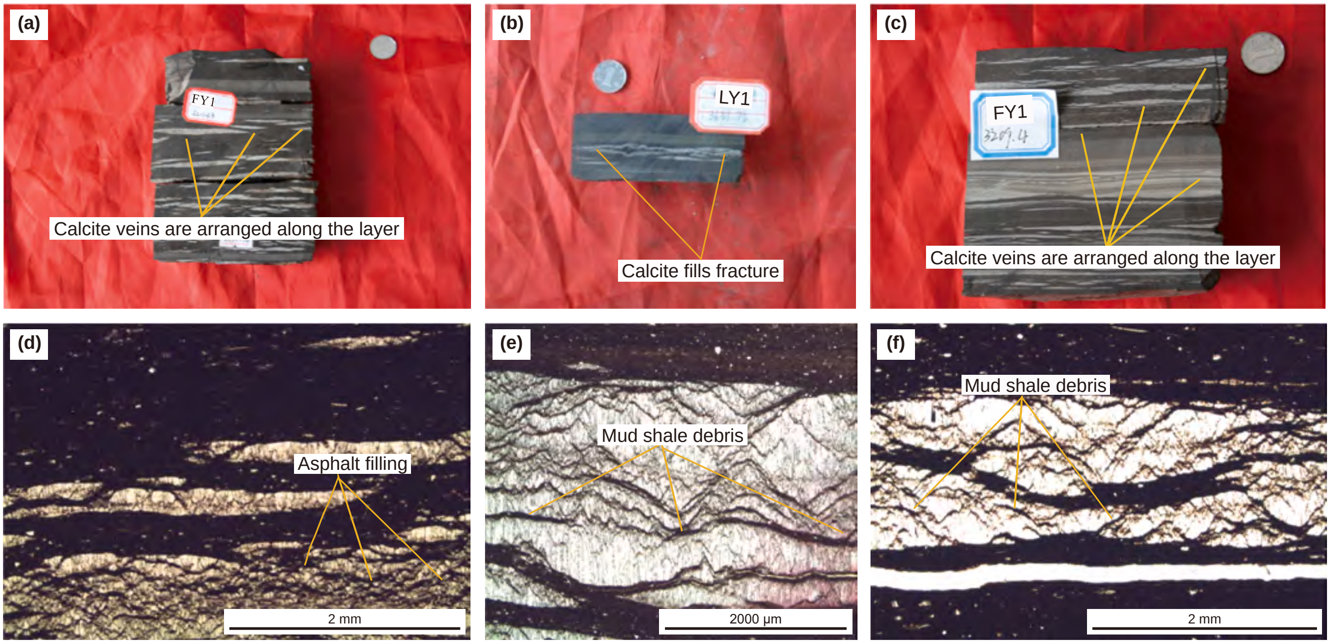


Fig. 10. Bedding-parallel vein fractures. (**a**) The calcite veins are arranged parallel to the bedding planes, Well FY1, 3211.53 m; (**b**) the calcite fills the bedding-parallel vein fractures, Well LY1, 3637.75 m; (**c**) the calcite veins are arranged parallel to the bedding planes, Well FY1, 3209.40 m; (**d**) the fracture is filled with asphalt, Well NY1, 3075.56 m; (**e**) the calcite veins are intermixed with fragments of shale, Well GD12, 2988.95 m; (**f**) the calcite veins are filled with asphalt, Well GD12,3985.75 m.

internal and external factors. Internal factors include rock layer thickness, lithofacies and lithofacies combination, lithofacies fabric characteristics, and rock mechanical properties, which are fundamental for fracture development (Guo et al., 2022; Wang, 2019). External factors encompass tectonic processes, diagenesis, and fluid pressure. Three aspects are the core factors for fracture development (Zhang et al., 2021).

3.1. Internal cause

3.1.1. Thickness of stratum

The thickness of rock layers influences the development of fractures. Fracture development within rock formations typically terminates within the formation itself, although some fractures may extend to the lithological interface (Fig. 11). Under similar conditions, a linear relationship exists between fracture spacing and rock layer thickness, indicating that thinner rock layers exhibit higher fracture density and more extensive development (Narr and Suppe, 1991; Xie, 2020). However, some studies indicate that fracture spacing may not correlate strongly with formation thickness. For instance, certain formations exhibit fracture spacing exceeding expectations, while others have smaller-than-anticipated spacing. Additionally, different sets of fractures within the same layer may display varying spacing (Jacobi, 2002; Engelder et al., 2009). The impact of rock layer thickness on fracture development hinges on the subcritical fracture index. Subcritical fracture index is used to describe the characteristics of crack propagation in a subcritical state. In the fields of materials mechanics and fracture mechanics, when the stress intensity factor acting on cracks in a material is less than the material's fracture strength, the cracks are in a subcritical state. For instance, when the index equals or exceeds 80 (indicating high values), fractures tend to form in irregular clusters. Conversely, with a medium index range (20–80), a strong correlation exists between fracture spacing and rock layer thickness, resulting in more uniform fracture distribution (Holder et al., 2001; Olson, 2014).

3.1.2. Lithofacies and lithofacies combination

Fracture development varies depending on lithofacies and their combinations. Considering the external tectonic stress field within the study area to be isotropic, variations in sedimentation and depositional conditions will influence the composition, structure, layer thickness, and lithological combination of sedimentary clasts across different locations. These variations serve as the primary factors influencing uneven fracture development. In mudstone and shale devoid of organic matter, numerous natural micro-fractures supported by clay minerals tend to form (Yuan et al., 2021). Various lithofacies types exhibit distinct mineral compositions, resulting in differing rock mechanical properties (Ma et al., 2022). Shale lacking organic matter and dissolved minerals predominantly develops microfractures formed by clay mineral particles. In shale or mudstone containing high levels of brittle minerals, intergranular pores between these minerals are filled with clay minerals, resulting in numerous parallel or subparallel micro-fractures. With an increase in organic matter content, some natural micro-fractures associated with clay minerals become filled and closed (Fig. 12). Additionally, shale or mudstone abundant in soluble minerals like calcite undergoes micro-fracture formation through particle connection via dissolution pores (Liu et al., 2023; Wei et al., 2021).

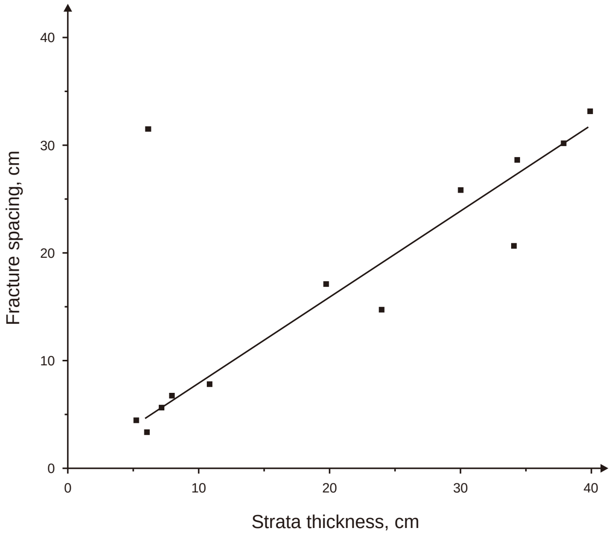


Fig. 11. Relationship diagram between shale thickness and fracture development (adapted from Zhang, 2019; Ding et al., 2011), negative correlation between rock layer thickness and fracture density.

3.1.3. Rock composition and structure

There are significant differences in the forms of organic matter occurrence and pore development and evolution characteristics in different types of shale fabrics (Fig. 13). Therefore, the development degree of fractures under different shale fabrics is also different (Zeng et al., 2022).

3.1.3.1. Mineral content. Various rock types exhibit distinct mineral compositions. Research suggests that under identical tectonic stress conditions, increased concentrations of minerals such as quartz, feldspar, and carbonate in shale result in greater shale brittleness and facilitate the occurrence of natural fractures. According to foreign scholar Nelson, besides quartz, feldspar, and dolomite are also relatively brittle mineral components in black shale (Ma et al., 2023; Nelson, 1985; Wang et al., 2016). Higher silica content increases shale brittleness, promoting fracture formation. Thus, the degree of shale fracture development is positively correlated with the presence of brittle minerals in shale (Zhang et al., 2021). Increased clay mineral content corresponds to decreased fracture development, indicating a negative correlation. In addition to the quartz mentioned above, feldspar and dolomite are also brittle minerals. Additionally, high silica content in shale renders the rock highly brittle, facilitating the development of fracture systems under tectonic stress (Wang et al., 2016).

In summary, shale fracture development typically correlates positively with the presence of brittle minerals in the rock. Increased concentrations of minerals such as quartz, feldspar, and carbonate promote fracture formation and development. Additionally, highly brittle organic-rich shale is more prone to fracture occurrence, whereas elevated clay mineral content corresponds to reduced fracture development, indicative of a negative correlation (Fig. 14).

3.1.3.2. TOC contents. Organic carbon content also influences fracture development. Shale exhibits higher organic carbon content and a greater abundance of brittle minerals under similar tectonic stress conditions, rendering it more prone to fracturing and the development of fracture systems within the same geological structure (Wang et al., 2017). The degree of fracture development correlates positively with organic carbon content (Fig. 15). Under comparable tectonic dynamics and depositional environments, shale sections with high TOC content exhibit densely developed bedding fractures (Zeng et al., 2022). However, certain studies indicate a non-linear relationship between fracture development and TOC content. Initially, fracture density increases

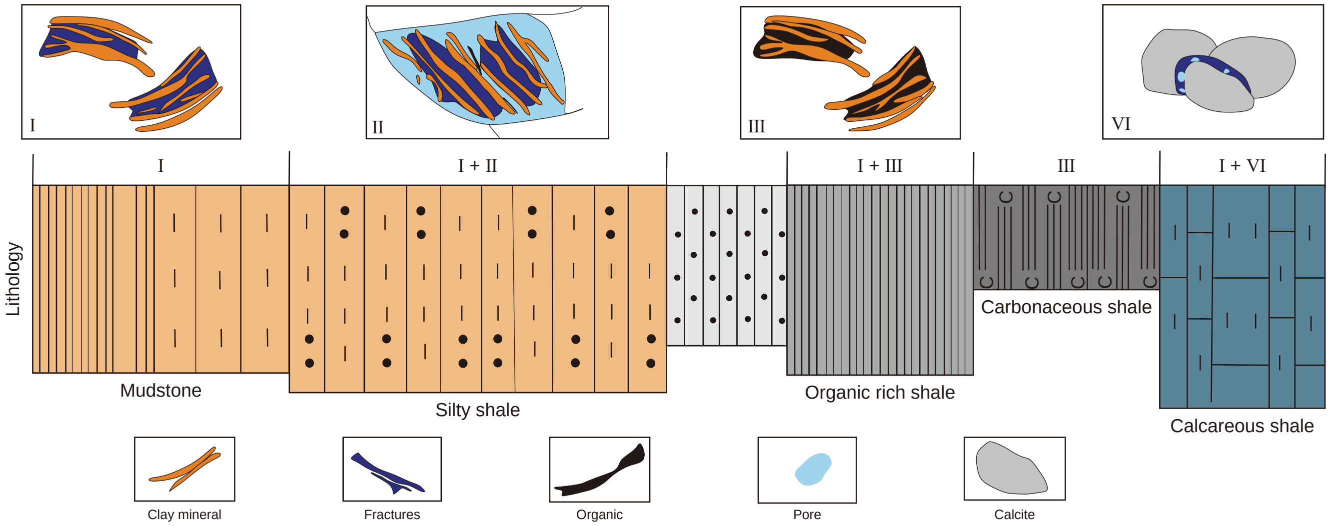


Fig. 12. Combination of microfractures in different lithofacies shale (quoted from Wei et al., 2021; Yuan et al., 2021), fractures are most developed in organic shale, followed by more developed in mudstone, and least developed in sandstone.

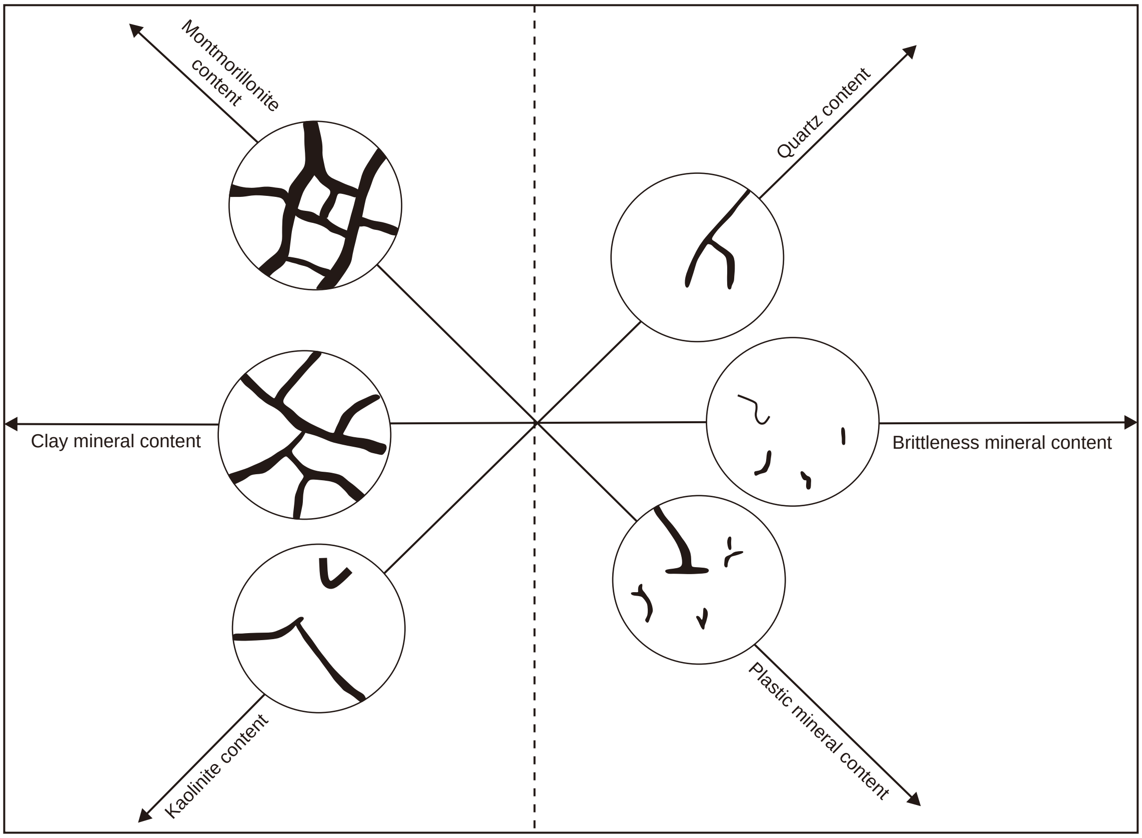


Fig. 13. The relationship between rock composition characteristics and fracture development (modified from Zeng et al., 2022; Wang et al., 2017). As the mineral content varies, the degree of fissure development also changes.

with rising TOC content, but subsequently declines. During the thermal evolution of organic matter, acidic substances such as CO_2, H_2S, and organic acids are generated, leading to the formation of dissolution fractures. Thus, the evolution of organic matter hydrocarbon generation increases pore volume and residual carbon skeleton in mud shale reservoirs, consequently decreasing internal structure stability, enhancing shale brittleness, and inducing fractures under tectonic stress. Additionally, elevated organic matter content yields higher volumes of hydrocarbon gases, elevating internal pressure within shale reservoirs. Excessive pressure leads to rock fractures and the formation of abnormal pressure fractures (Sun, 2017). However, in shale with relatively high TOC content, the residual porous carbonaceous skeleton fails to fully withstand overlying formation pressure, resulting in pore

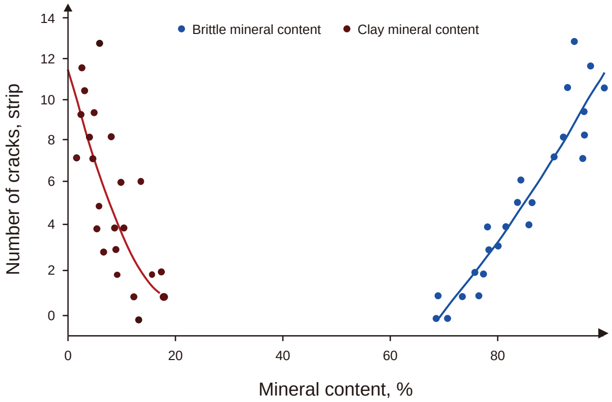


Fig. 14. The relationship between shale mineral content and fracture development (adapted from Zhang, 2019, Lai et al., 2022). Fracture density is directly proportional to the content of brittle minerals and inversely proportional to the content of clay minerals.

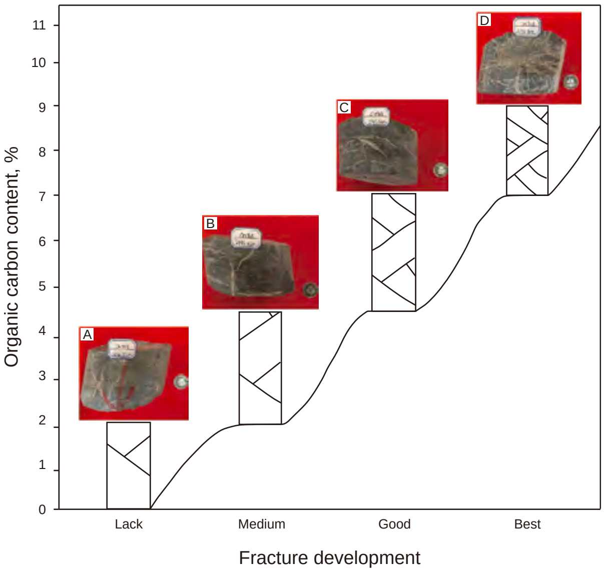


Fig. 15. The relationship between TOC content and fracture development in shale (adapted from Ma et al., 2023; Zhang, 2019). The higher the organic matter content, the more developed the fractures (A: Well CH908, 2780.76 m; B: Well CH908, 2796.85 m; C: Well CH908, 2797.68 m; D: Well CH908, 2795.30 m).

filling or compaction and reduced shale brittleness, consequently inhibiting shale fractures (Yang et al., 2020; Xue et al., 2015; Gu et al., 2020; Luo et al., 2015).

3.1.3.3. Grain size. The degree of fracture development in rocks correlates closely with the size of rock particles. On one hand, larger particle sizes weaken intergranular bonding, leading to relatively greater development of fractures and intergranular fractures in coarse-crystalline minerals and reducing overall fracture development. On the other hand, different-sized rock particles under identical external stress exhibit varying contact point distributions, consequently influencing local stress distribution and resulting in differing degrees of fracture development. In shale with identical mineral composition, finer rock particles promote fracture development, whereas coarser particles hinder fracture formation (Chen et al., 2000; Yuan et al., 2017). Under identical thickness conditions, finer grain sizes yield greater development of structural fractures. Zhao et al. (2015) concluded that the fracture surface density and particle size in medium-thin layers exhibit a negative power exponential fitting relationship, expressed as $y = 1.061x - 0.231$, further quantifying the relationship between particle size and fracture density. However, the influence of grain size on fracture development is relatively weak compared to shale layer thickness (Fig. 16).

Achuhan et al. (2002) observed fracture development in rocks of varying grain sizes at the thin section scale. Their experimental findings indicate that larger particle sizes correspond to increased fracture development and a higher proportion of particles generating fractures. When mineral particles compact and stress exceeds their maximum withstand limit, fracturing occurs. Smaller particles have more support points during mutual contact, while larger particles have fewer, resulting in localized stress surpassing rupture strength and fracturing, leading to intense tectonic extrusion of large particles. Medium particles are prone to breakage and intra-particle micro-fractures, while smaller particles resist crushing and do not develop intra-particle fractures (Achuhan et al., 2002).

3.1.3.4. Laminated structure. Shale laminae typically form through a combination of factors, including low-energy, slow-flowing hydrostatic sedimentary environments, biological processes such as carbonate deposition and humus biodegradation, structural deformation, compaction, hydrothermal processes, etc. Geological and chemical processes, such as hydration, oxidation, and reduction, primarily influence shale lamina formation (Qian, 1995). The impact of laminae on fracture development primarily manifests in variations in laminae type, thickness, density, and direction (Zhang et al., 2017). Different types of laminae have different effects on the formation and preservation of fractures. Specifically, homogeneous laminae with higher mud content can effectively connect with organic pores due to their elevated organic matter content and widespread distribution. This not only provides a material foundation for abnormally high pressure formation but also facilitates fracture network development (Shi et al., 2018). Conversely, laminae with higher sandy-silty content contain fewer organic pores and exhibit uneven distribution, resulting in limited fracture formation opportunities (Lash et al., 2005; Rokosh et al., 2009) Secondly, the interface between different types of laminae serves as a mechanically weak surface, facilitating the formation of leafing fractures. The development of shale bedding fractures is closely associated with laminae thickness. Shales with thin

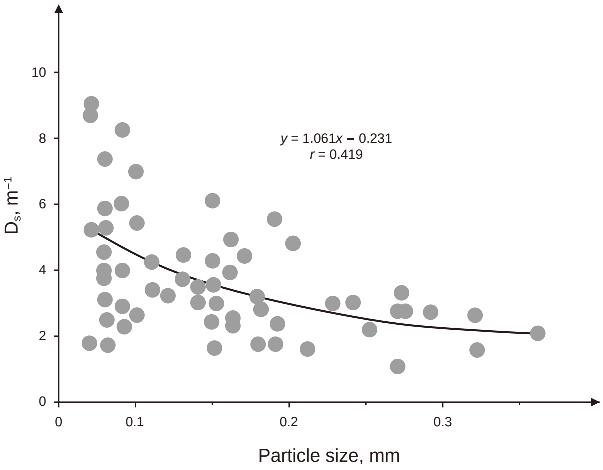


Fig. 16. The relationship between fracture development (D_s) and particle size (quoted from Zhao et al., 2015). The smaller the mineral particles, the easier the rock is to fracture and form fractures.

laminae tend to develop small micro-fractures, whereas those with thicker laminae are inclined to form larger fractures. Lamina density refers to the spacing between two adjacent laminae, significantly affecting fracture development. A smaller lamina density implies uneven stress distribution within the shale, leading to decreased resistance to fracture expansion and facilitating fracture propagation (Fig. 17). The lamination direction of shale also influences fracture development. Fractures develop more readily when the lamina direction is perpendicular to the stress direction, whereas they face greater difficulty when the lamina direction is parallel to the stress direction (Zeng et al., 2022; Lai et al., 2022).

3.1.4. *Rock mechanical property*

Shale is a naturally occurring multi-scale complex material characterized by significant horizontal and vertical heterogeneity (Li et al., 2023). Changes in paleoclimate and depositional environments during various stages of shale diagenesis result in the gradation and mutual superposition of lithofacies in the longitudinal direction. Strata composed of single or multiple lithofacies types aligned in the longitudinal direction are termed mechanical stratigraphic units. The primary factors influencing mud shale fracture development are lithology and physical properties. Different lithologies exhibit variations in the physical properties of the formation. Mechanical parameters such as elastic modulus, Poisson's ratio, residual cohesion, and internal friction angle vary among rock masses, affecting their tensile and shear strength (Labani and Rezaee, 2015). The elastic deformation ability of rock is described by several parameters: shear modulus indicates rock shear strength, bulk elastic modulus indicates rock compressive strength, Young's modulus indicates rock tensile strength, and Poisson's ratio describes the lateral relative compression coefficient of rock (Zhan et al., 2022). Young's modulus and Poisson's ratio indirectly reflect rock brittleness. Under the same in-situ stress, shale with low Poisson's ratio and high elastic modulus exhibits better brittleness characteristics, facilitating fracture formation (Rokosh et al., 2009). Conversely, rocks with high plasticity undergo a more prolonged plastic deformation stage and are less prone to fracture (Fig. 18).

3.2. *External factors*

3.2.1. *Tectogenesis*

Structural factors primarily influence the development of shale structural fractures and serve as external catalysts for fracture formation. Structural fractures predominantly arise during tectonic stress accumulation and release, with their development and distribution notably dictated by tectonic settings and stress conditions (Yan, 2017).

The influence of folds on fracture development ultimately stems from changes in the curvature of rock strata. Structural elements such as the fold axis and turning points, with greater strata curvature, experience bedding extrusion or perpendicular extrusion forces (Qi and Yang, 2010). It is suggested that compared to other regions, areas within the fold's structural stress zone are more conducive to structural fracture formation, serving as the primary site for fracture development (Figs. 19 and 20). A negative correlation exists between fracture density and distance from the fold axis; the farther from the axis, the less developed the fractures, and conversely, the more developed they become (Zhu et al., 2018; Wang et al., 2022).

Regions characterized by significant variations in shale layer occurrence, such as fault turning points and fold hinge zones, exhibit more pronounced deformation and greater fluctuations in structural stress gradients, thereby increasing the likelihood of structural fractures. Furthermore, structural fractures tend to occur in areas with intense faulting, substantial fault displacement, and high fault density (Fig. 21). With increasing distance from the fault, the extent of structural fracture development diminishes (Wang et al., 2016; Zeng et al., 2016a).

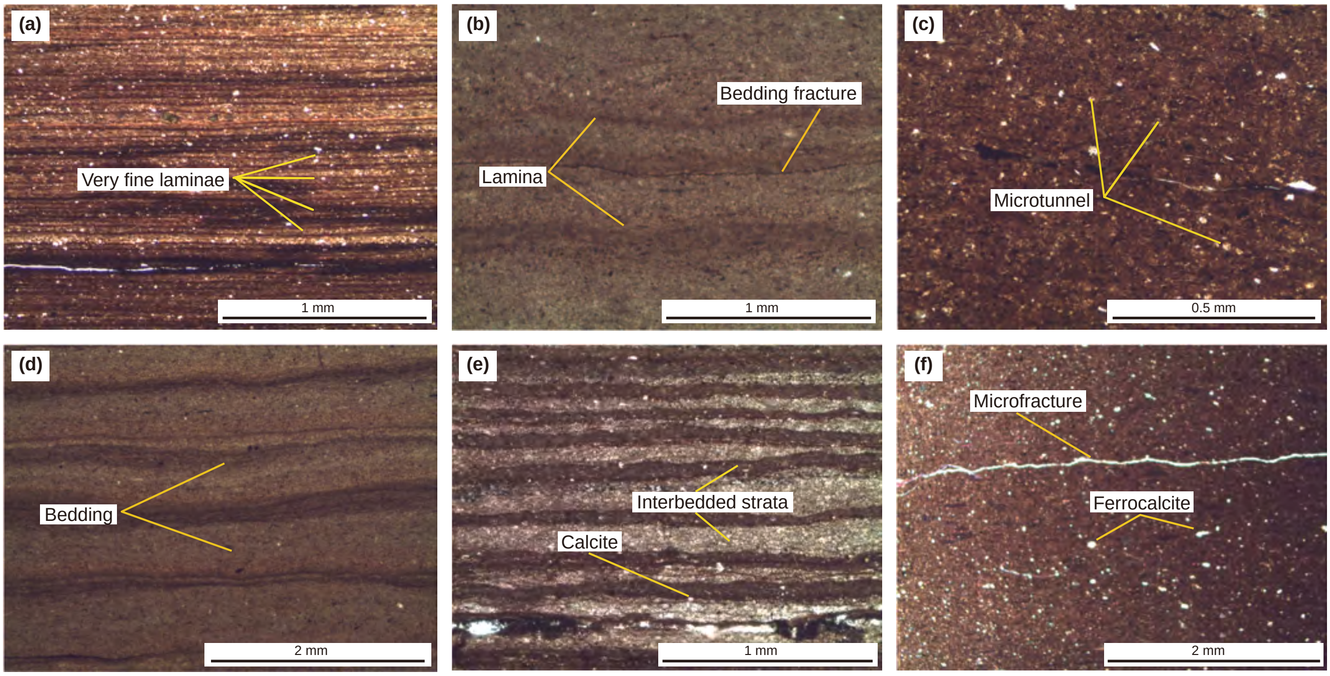


Fig. 17. Microscopic characteristics of different laminations. (**a**), (**e**) Siliceous mudstone laminations, Well NY1, 3428.74 m, 3249.88 m; (**b**), (**d**) layering fractures developed at the boundary of laminations, Well FY1, 3250.98 m, 3255.87 m; (**c**) pyrite particles developed in laminationsl, Well NY1, 3430.95 m; (**f**) microfractures formed by dissolution, Well FY1, 3245.86 m.

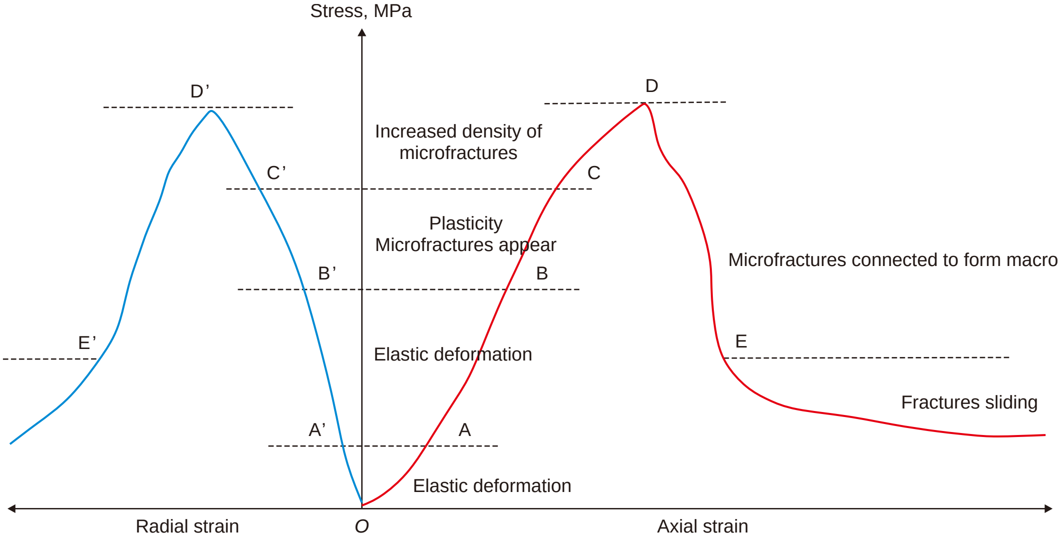


Fig. 18. The process of rock fracturing under stress to form fractures (adapted from Yang et al., 2020; Liang et al., 2021). As stress continuously increases, fissures undergo various deformations, leading to the formation of fractures.

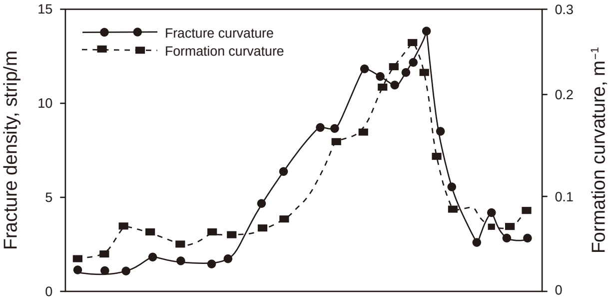


Fig. 19. The relationship between formation curvature and fracture development (modified from Zeng et al., 2022). The trend of changes in formation curvature is nearly identical to the trend of changes in fractures density.

Within a given range of stress changes, an increase in stress change gradient is positively associated with the likelihood of fracture formation. For instance, fractures are more prone to develop in convex areas, transfer zones, and fault intersection

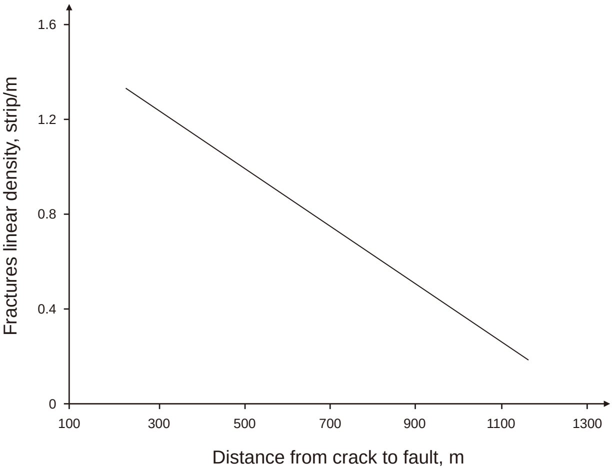


Fig. 21. Relationship between the distance of fractures to faults and the development of fractures (modified from Ma et al., 2023; Zeng et al., 2022, Zeng and Li, 2009). The closer to the fault, the more developed the structural fractures.

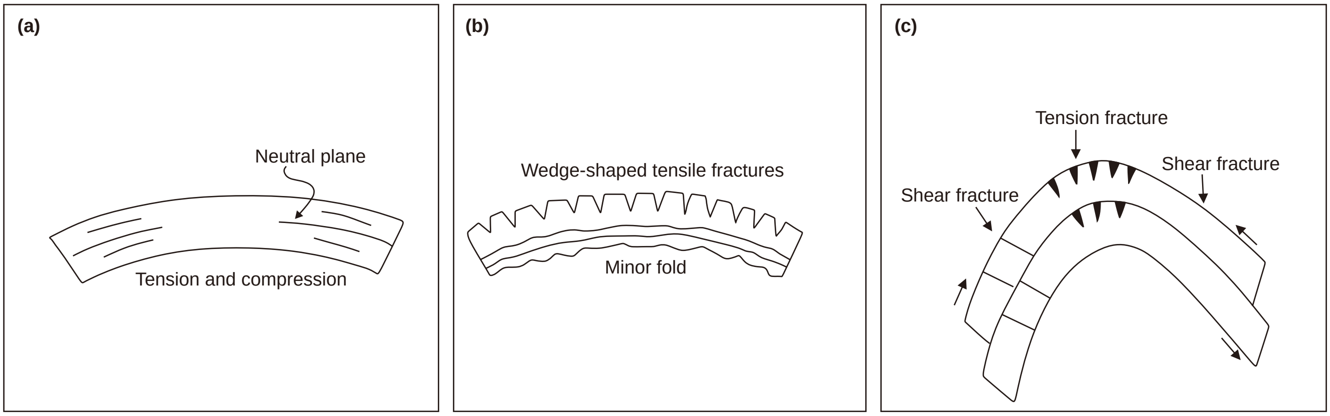


Fig. 20. Schematic diagram of folds related fractures (adapted from Zhang, 2019). (**a**) Tension and compression forces coexist on the neutral surface; (**b**) wedge-shaped tensile fractures develop on minor folds; (**c**) fractures were more developed in locations such as the axis and inflection points of folds.

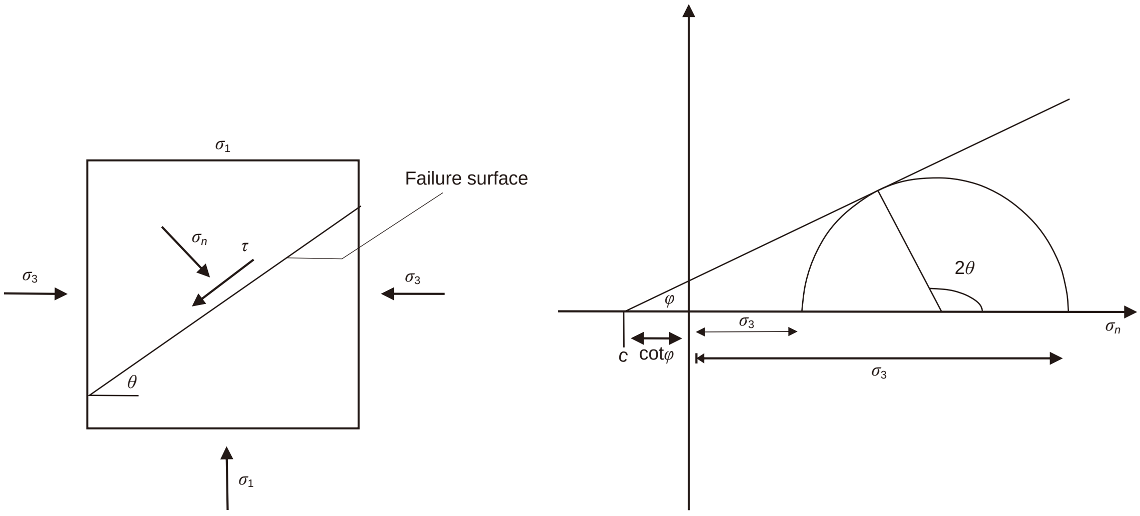
zones, as well as on the crests and steep flanks of anticlines, the transitional zones between depression slopes and gentle bottoms, and other locations with significant variations in stratigraphic occurrences, where stress changes are more pronounced. Variations in local tectonic stress lead to discrepancies in fracture development (Zeng et al., 2013). When tectonic stress exceeds the rock's limit, fractures occur, and their extent of development correlates positively with stress magnitude (Fig. 22). A specific angular relationship exists between fracture orientation and tectonic stress direction (Gasparrini et al., 2014).

3.2.2. *Diagenesis*

Due to variations in diagenesis, rocks exhibit different mechanical properties and fracture development levels across different diagenetic phases. Diagenesis can both initiate new fractures in shale and modify pre-existing ones (Fig. 23). Diagenetic effects on fractures can be categorized into two primary types: (1) diagenesis that facilitates fracture formation, primarily involving dissolution, pressure solution, and clay mineral transformation; (2) diagenesis that inhibits fracture formation, which mainly includes cementation, metasomatism, and alteration (Rossi and Alaminos, 2014; Qian, 1995).

Compaction reduces rock particle and pore volume through dehydration and degassing, thereby densifying the reservoir and increasing rock strength, affecting fracture effectiveness and promoting fracture formation. Cementation further reduces pore space in clastic rock reservoirs. Common shale cements include mud, carbonate, and occasionally iron cements, which include illite mixed layers, illite, and kaolinite. While they contribute to cementation, they reduce mud shale pore space, decreasing permeability (Zeng et al., 2016b). Early cementation (before compaction) may weaken compaction intensity to some extent, creating conditions for subsequent cement dissolution and the formation of numerous secondary fractures, indicating the dual-sided impact of cementation on reservoir fractures (Laubach et al., 2004; Durhan, 1997). Volume remains largely unchanged before and after metasomatism, minimally impacting fractures, but it can provide more soluble substances for later dissolution, facilitating dissolution (Xie et al., 2021). For instance, carbonate minerals formed after carbonate rock minerals metasomatize clastic particles may dissolve during later dissolution, leading to increased secondary fractures, positively affecting reservoir fracture transformation (Zhang, 2020). Dissolution, mainly from infiltrated atmospheric water early and organic acids produced during thermal maturation of organic matter later, is the primary factor in secondary fracture formation. It not only adds new fractures by about 5% on average but also interconnects microfractures formed when dissolution fluid seeps through shale, forming a fracture network, negatively impacting reservoir oil and gas. Water migration channel formation is crucial. Pressure dissolution refers to obvious dissolution occurring at particle contact points, such as pressure transfer points, resulting in four convex and suture contacts connecting (Zhang et al., 2023). Under pressure, dissolved clastic particles cause quartz and feldspar particles to enlarge and cement at low pressure. The sutures formed by pressure solution can become channels for the migration of oil, gas, and water (Zhang et al., 2020). There is substantial evidence that sutures actively facilitate the migration and accumulation of oil and gas. During the transformation process of clay minerals, the volume of mineral particles decreases, enhancing the porosity of the reservoir. This makes it easier to generate fractures and improve the storage capacity of shale reservoirs (Liang et al., 2018). The impact of the conversion of clay minerals on reservoir pores mainly depends on the shape of the clay minerals generated by the conversion, which is hairline Shape or lamellar shape, such as the transformation of montmorillonite to illite, which is manifested by dehydration under compaction and the enrichment of K^+ in the system (Lavenu et al., 2014). The illite formed is hairlike, which plays a role in the formation of reservoir fractures. Positive effect; if it is lamellar, it is destructive (Xian, 2019).

Diagenesis affects fracture development by altering the mechanical properties of rocks. Dashti et al. (2007) conducted a study on fracture development intervals and rock mechanics intervals in a naturally fractured reservoir in the Gross area (Zhao and Li, 2022). They found that natural fractures primarily reflect ancient rock mechanics layers, while drilling-induced fractures represent modern rock mechanics layers, suggesting a possible relationship with changes in mechanical properties induced by diagenesis. Research by Ross, D.J. and others also indicates that diagenesis affects changes in rock mechanical properties (Peter, 2008; Dashti et al., 2007; Ross and Bustin, 2008).



(a) Force state of unit body

(b) Mohr Coulomb fracture criterion

Fig. 22. The relationship between tectonic stress and fracture development (adapted from Rossi and Alaminos, 2014, Wang et al., 2019a, 2019b; Wang, 2019).

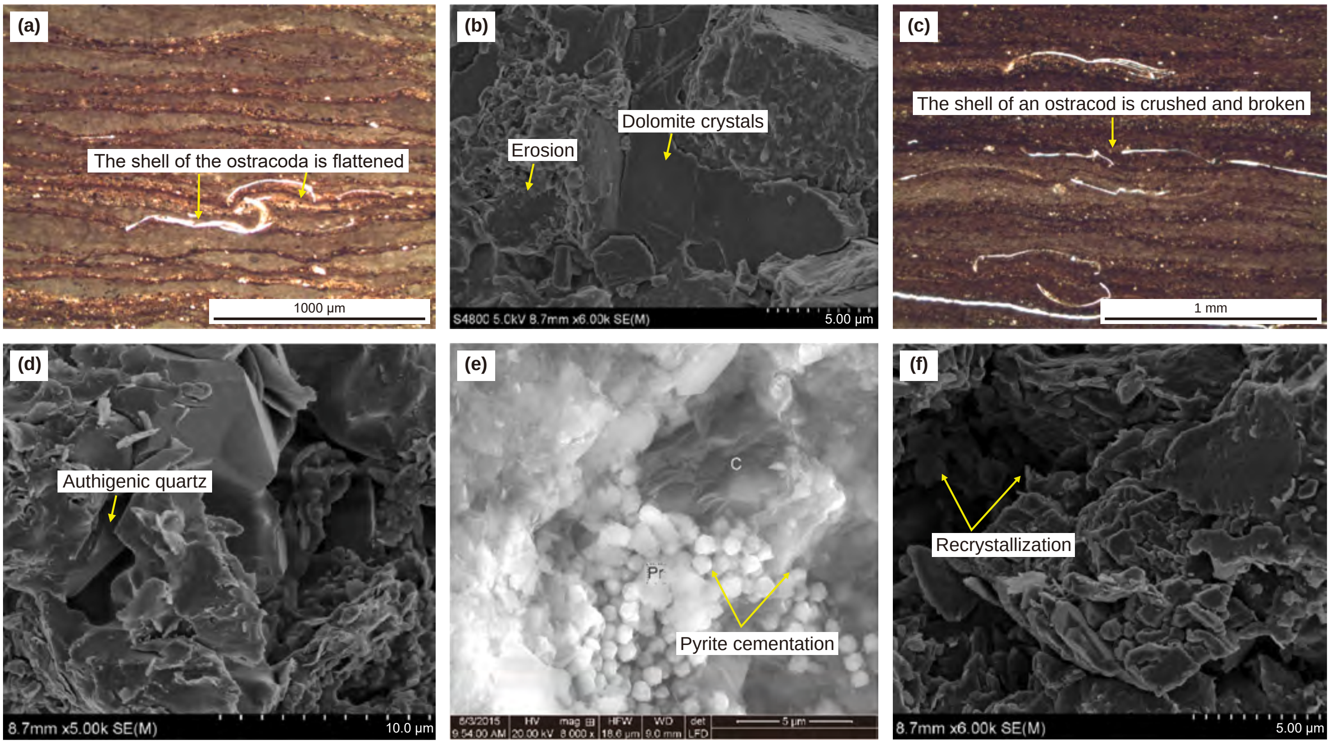


Fig. 23. Diagenetic processes related to fractures. (**a**) The foraminifera shells are flattened under compaction, indicating strong compaction, Well FY1, 3074.60 m; (**b**) organic matter dissolves mud crystal iron siderite, Well FY1, 3076.88 m; (**c**) the foraminifera shells are broken under compaction, Well FY1, 3068.80 m; (**d**), (**f**) dissolution occurs, Well FY1, 3066.50 m, 3060.85 m; (**e**) cementation occurs, with pyrite particles cemented together, Well FY1, 3044.58 m.

3.2.3. *Fluid pressure*

Fluid pressure significantly influences fracture development, especially in low-porosity and low-permeability shale formations where fluid flow is restricted, leading to increased pressure. During burial, rising formation depth elevates underground temperature and pressure, inducing compaction and escalating fluid pressure, sometimes resulting in abnormally high pressure (Fig. 24). Organic matter hydrocarbon generation and clay mineral transformation are primary drivers of this overpressure (Zhang et al., 2023; Cobbold et al., 2013; Liu et al., 2022). The conversion of smectite to illite releases mineral-bound water into mudstone pore spaces, expanding fluid volume and contributing to overpressure in low-permeability systems (Freed and Peacor, 1989; Meng et al., 2021).

Excessive pore fluid pressure, surpassing 1.5 times the hydrostatic pressure, typically induces abnormally high-pressure fractures that commonly propagate along mechanically weak surfaces like shale lamina interfaces or pre-existing micro-fractures. Abnormal fluid pressure alters the stress conditions within shale, influencing the expansion or closure of fractures. Specifically, it elevates water pressure in shale, decreasing effective stress and promoting fracture expansion. Conversely, if abnormal fluid pressure reduces water pressure in shale, effective stress increases, leading to fracture closure (Fig. 25). Moreover, as shale enters the oil generation window, increasing organic matter maturity converts kerogen into denser liquid hydrocarbons, accelerating hydrocarbon generation. Simultaneously, escalating fluid pore pressure spawns localized abnormal fluid high pressure, facilitating hydrocarbon migration and accumulation in shale (Colten-

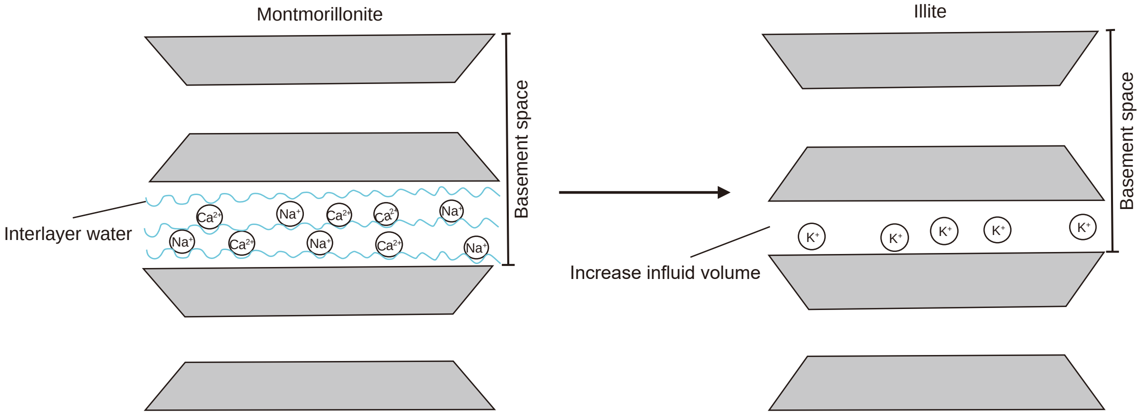


Fig. 24. Montmorillonite transformation to illite leads to overpressure (modified from Colten-Bradley, 1987). During the conversion process from montmorillonite to illite, the fluid volume increases, resulting in fluid overpressure.

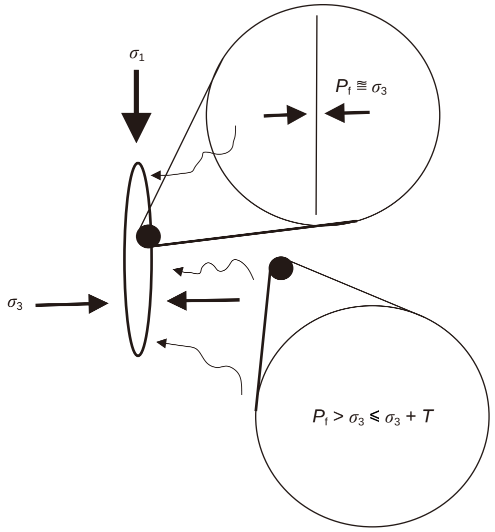


Fig. 25. Fluid pressure changes cause fractures to open (taken from Cristescu, 1982). The increase in fluid pressure within shale reduces the effective stress by increasing the water pressure, thereby promoting fracture propagation. Conversely, if abnormally low fluid pressure reduces the water pressure within the shale, the effective stress increases, leading to fracture closure.

Bradley, 1987). Additionally, fluid pressure affects rock stress states, shifting Mohr's stress circle to the left, approaching fracture rupture strength. At a critical level, excessive abnormal fluid pressure shifts the minimum principal stress from compression to tension, resulting in the formation of abnormally high-pressure fractures (Meng et al., 2019; Oliver and Bons, 2001).

4. Fractures formation mechanism

4.1. The formation mechanism of structural fractures

Structural fractures are primarily influenced by structural stress. Their formation involves three processes: micro-fracture initiation, subsequent coalescence into larger fractures, and ultimately the development of large-scale structural fractures or faults (Zhou et al., 2003). Horizontal tectonic extrusion predominantly drives the creation of tight reservoir fractures. This process elevates the maximum principal stress, reduces the minimum principal stress, and expands the stress Mohr's circle (Fig. 26). The expanded Mohr's circle becomes tangent to the fracture envelope, increasing the likelihood of rock fracturing and the formation of shear fractures (Cristescu, 1982).

The second is the influence of fluid pressure. The compaction caused by fluid pressure leads to particle fracturing to form fractures and pressure solution to a certain extent transform the fractures formed by tectonic stress, making them larger in scale. The properties of the rock itself (lithology, lithofacies, mineral composition) and crystallization have little impact on structural fractures (Wu et al., 2023; Zhong et al., 2015).

4.1.1. The formation mechanism of shear fractures

The development of shear fractures is influenced not only by shear stress but also by the normal stress acting on them. When the shear stress exceeds the rock's strength limit, shear fractures form. Fig. 26(a) illustrates the process of shear fracture formation. When the angle between the bedding plane and the principal stress is substantial, micro-fracture expansion is constrained, resulting in micro-fractures parallel to the bedding plane

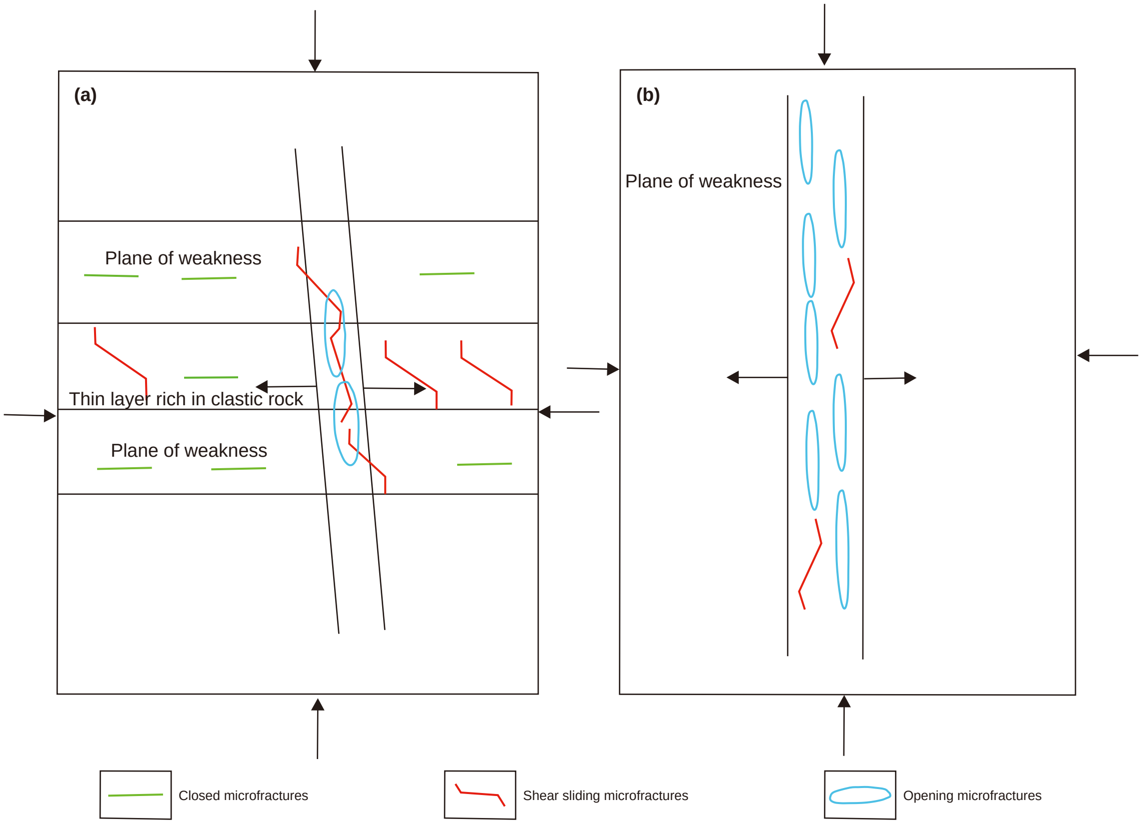


Fig. 26. Mechanisms of shear and tensile fracture formation (modified from Zhong et al., 2015). (**a**) Mechanism of shear fracture formation; (**b**) mechanism of tensile fracture formation.

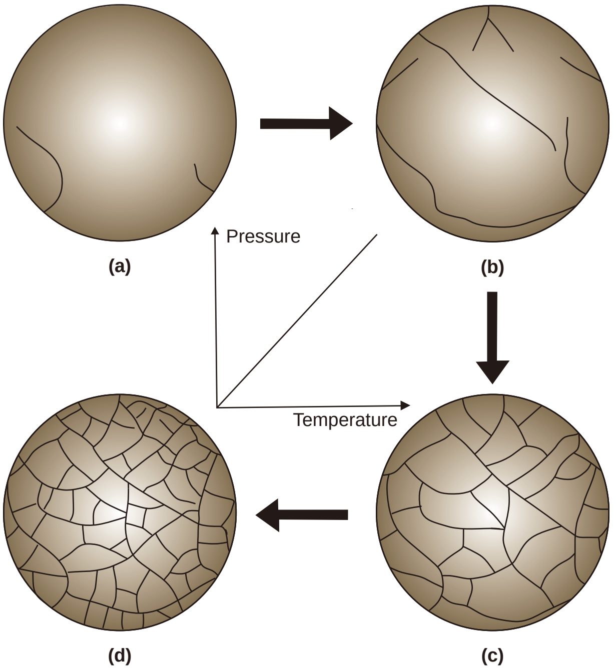


Fig. 27. Formation process of diagenetic shrinkage fractures (modified from Wei et al., 2021). At the beginning, the fractures were relatively sparse, and as the dehydration and contraction process progressed, a network of fractures gradually formed.

remaining closed. Micro-fractures oriented at a significant angle to the bedding plane may experience stretching or shearing (Han et al., 2013). When subjected to compressive stress, micro-fractures in adjacent planes and clastic-rich laminae may experience tension or shear, resulting in localized fractures. With increasing stress, conjugate shear fractures intersect and eventually develop into complete shear fractures. Moreover, the presence of clastic-rich laminae dictates the formation of localized fractures. Complete fractures only form when the shear strength surpasses that of the microfractures (Bao et al., 2024).

4.1.2. *The formation mechanism of tensile fractures*

Formation deformation occurs under tectonic compression stress. The portion of the rock layer above the neutral plane of the formation experiences tensile stress, leading to the formation of tensile fractures. As distance from the neutral plane increases, the rock layer expands further and tensile stress strengthens. Tensile fractures become more pronounced, resulting in wider opening fractures that gradually diminish towards the neutral plane. Below the neutral plane is the compressive stress zone (Walsh, 1965). Fig. 26(b) illustrates the formation mode of tension fractures. When β is small or 0° and the peripheral surface is close to the structural surface, the tensile strength is low, resulting in mainly micro-fractures near the peripheral and structural surfaces. Under compressive stress, the shale system becomes unstable, and micro-fractures parallel to the bedding plane do not close but stretch and extend along the direction parallel to the bedding. With increasing pressure, through-fractures develop (Liu et al., 2018).

4.2. *The formation mechanism of diagenetic fractures*

4.2.1. *The formation mechanism of diagenetic shrinkage fractures*

Three main mechanisms contribute to the formation of shrinkage fractures. Underwater shrinkage fractures result from the dehydration and shrinkage of mud layers under water or increased salinity, common in subtidal shallow lake sediments. The overall process of their formation includes four stages: initial turbidity of the mud-water mixture, stable sediment compaction, fracture formation, and fracture filling (Barker and Miliken, 2008). In the late Precold Brachina Subgroup sequence of the Flinders Ranges in South Australia, heavy-load structures and mudstone shrinkage fracture impressions appear simultaneously on the bottom surface of sandstone or siltstone. In this scenario, shrinkage fractures in the underlying mudstone cannot appear earlier than heavy-load structures, ruling out dry exposure as the cause; rather, it is due to the overlying sandstone causing dehydration and shrinkage of the mudstone. Thermal shrinkage fractures result from the baking and metamorphism of the mud shale layer by magma intrusion. Due to the temperature gradient, the heated rock shrinks during the cooling process (Fig. 27). Dehydration shrinkage fractures occur during early or subsequent diagenesis of mud shale. These fractures form through the chemical process of clay syneresis, reducing sediment volume and creating a three-dimensional polygonal network (Guo et al., 2022; Perez and Boles, 2005).

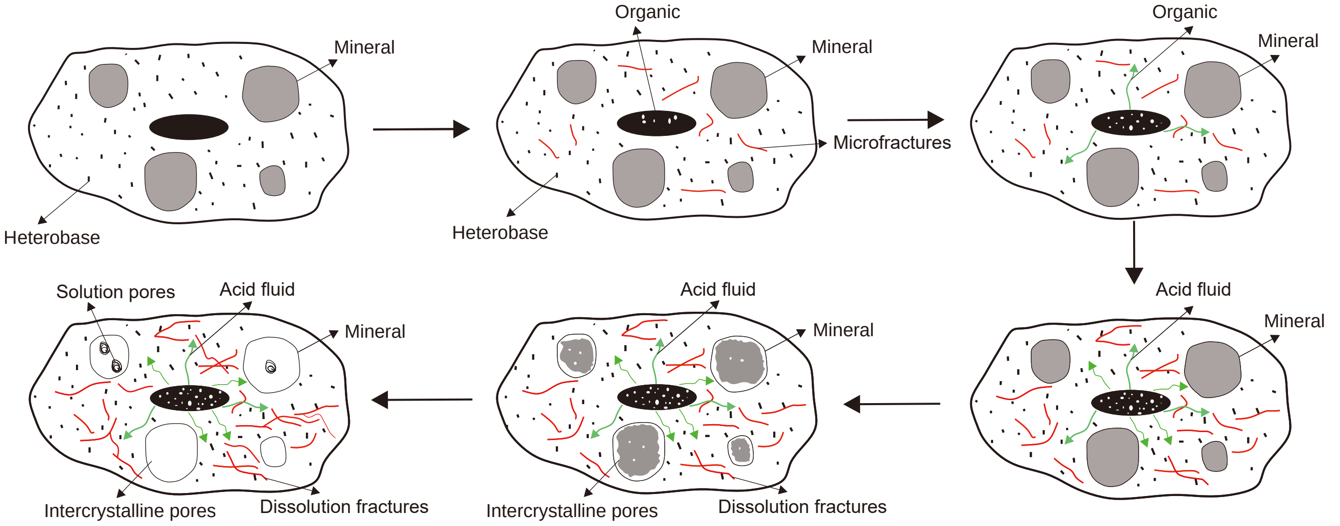


Fig. 28. Formation mechanism of dissolution fractures (modified from Zeng and Li, 2009). Organic acids and other acidic substances formed during the evolution of organic matter dissolve primary pores and fractures, forming larger scale corrosion fractures.

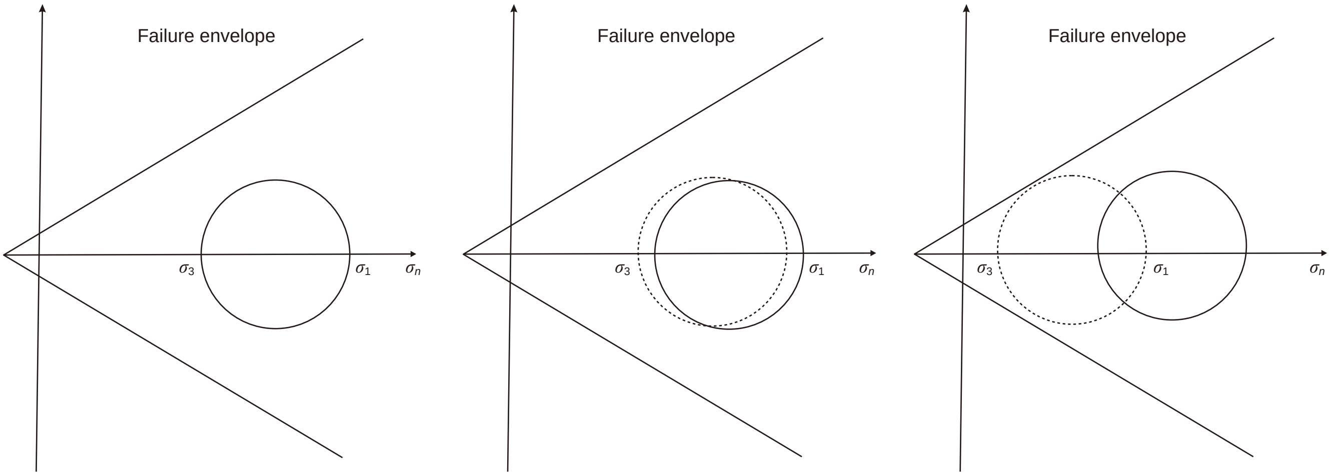


Fig. 29. Formation mechanism of abnormal fluid pressure fractures (modified from Sun, 2017). The hydrocarbons and fluids generated during the continuous compaction and hydrocarbon generation process result in abnormal fluid pressure in the rock formation, causing the Mohr circle to shift left and intersect with the fracture envelope line to generate fractures.

4.2.2. *The formation mechanism of dissolution fractures*

Dissolution fractures primarily result from the later modification of existing fractures. The evolution of organic matter produces significant amounts of organic acid and carbonic acid, creating an acidic environment. This acidic fluid dissolves surrounding mineral particles and primary pores, leading to the dissolution of mineral particles with high solubility and the expansion of primary fractures, forming a larger-scale and better-connected fracture network (Fig. 28; Yang et al., 2020), which enhances the storage and transportation of shale oil (Wang et al., 2019b; Fig. 28).

4.3. *The formation mechanism of bedding fractures*

The formation of bedding fractures can be attributed to various mechanisms. He et al. (2011) propose a strong correlation between the development of bedding fractures and tectonic processes. Structural uplift provides the driving force for their formation, with rocks fracturing under tectonic stress to create bedding fractures. Furthermore, ongoing fault activity contributes to the induction of bedding fractures. However, research by Zeng et al. (2022) suggests that tectonic extrusion plays a minor role in bedding fracture formation. Instead, they posit that later structural

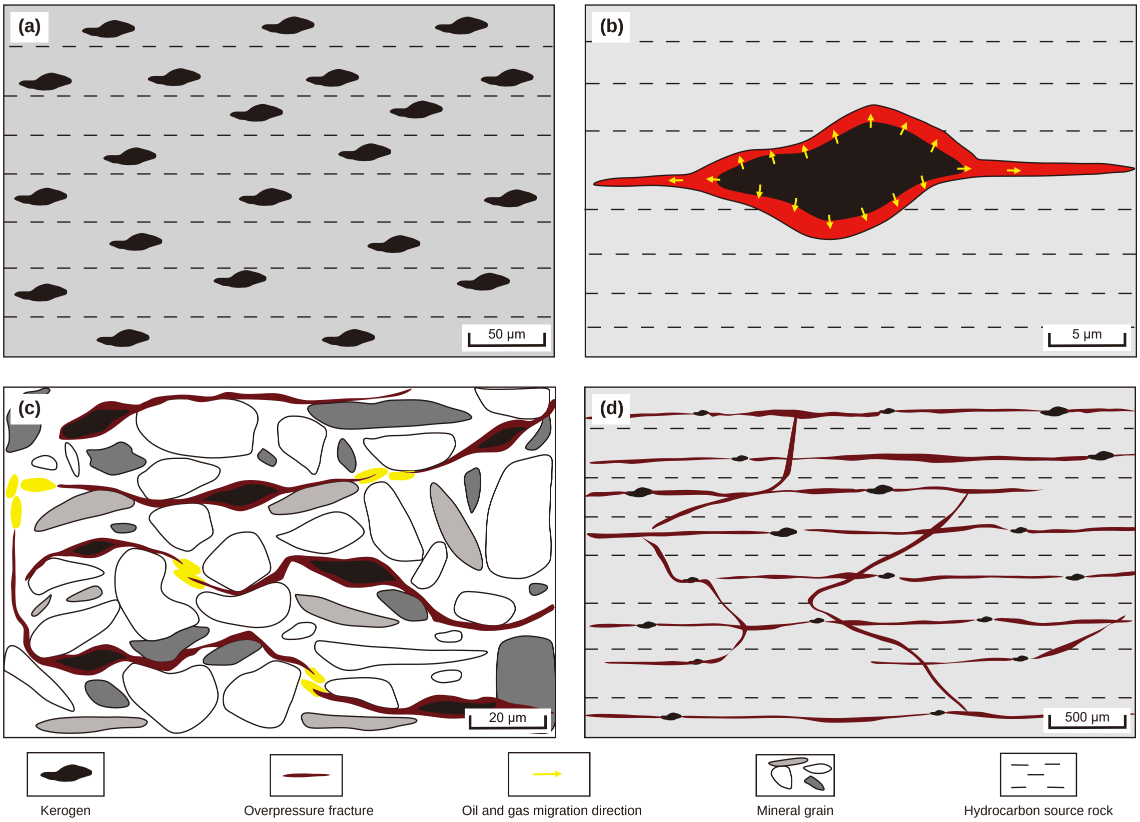
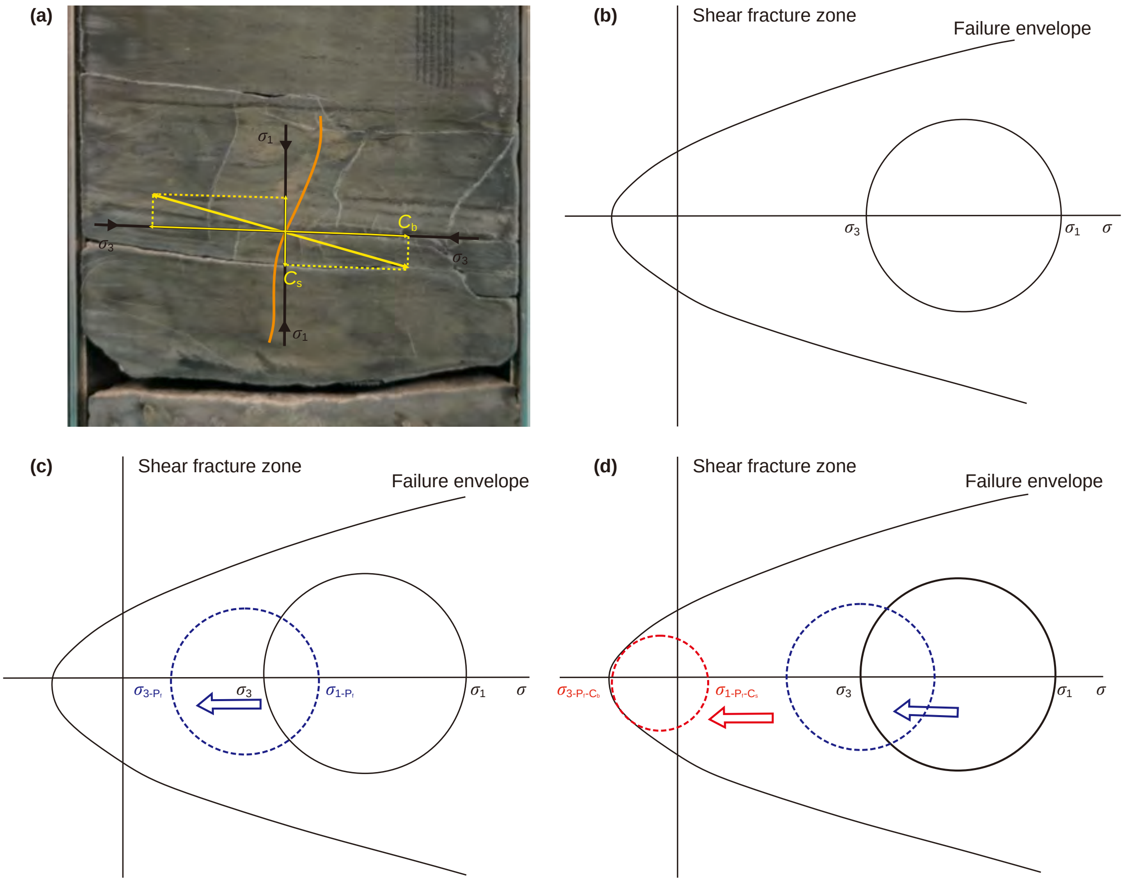


Fig. 30. Illustrates the formation mechanism of primary migration pathways (modified from Ma, 2017). The kerogen produced during the hydrocarbon generation process undergoes fractureing to generate gas, which increases the pore fluid pressure and forms overpressure. Overpressure causes rock fracture and forms fractures.

uplift and denudation promote the expansion and transformation of bedding fractures, enhancing their development. Observations by Zeng and Li (2009) indicate that minerals like quartz exhibit directional orientation, suggesting that micro-fractures develop during diagenesis due to geological processes like compaction and pressure dissolution, and are distributed along bedding planes. The pressurization resulting from hydrocarbon generation significantly influences the formation of bedding fractures. As organic matter undergoes hydrocarbon generation and pressurization, bedding fractures form and open up (Zhang et al., 2017). Natural fluid fracturing occurs when oil and gas accumulate in the reservoir, forming an effective closed system. When the pressure gradient within this closed system exceeds the threshold for fracturing tight sandstone bedding, natural fluid fracturing occurs along the bedding surfaces, creating a bedding fracture system (Wu et al., 2003). Although the bedding plane is mechanically weak, not all bedding layers develop fractures. Fracture initiation occurs only when the mudstone content in the bedding layer is moderate, and stress on the textured surface reaches critical strength levels (Tan et al., 2017). Yuan et al. (2017) describe horizontal bedding in mud shale as comprising straight, parallel fine layers, which form under relatively stable hydrodynamic conditions such as riverbanks, closed bays, deep-water shelf zones in oceans, and deep-water zones in lakes. These layers slowly deposit from suspension or solution. Dewhurst et al. (2011) suggest that sedimentation and compaction processes result in the stratification and preferential arrangement of various structural minerals, leading to differences in physical and mechanical properties between layers, thereby creating theoretically parallel mechanical weak surfaces. When shale cores are retrieved from deep underground, the release of in-situ stress generates micro-fractures parallel to these weak layers. When rock layers are nearly horizontal and buried deeply without overpressure, bedding (lamellar) fractures in mud shale are closed by overburden instead of opening due to the weak cementation of shale bedding, resulting in smaller fracture toughness and weaker prevention of fracture expansion. Conversely, in the vertical bedding (leafing) direction, fracture toughness is higher, and the ability to resist fracture expansion is stronger.

4.4. *The formation mechanism of fluid pressure fractures*

According to the structural-burial history analysis, the formation mechanism of fluid pressure fractures can be explained as: during the subsidence and burial stage, the closed mud shale undergoes montmorillonite transformation and hydrocarbon generation processes. Montmorillonite gradually transforms into mixed-layer clay, and the mixed-layer clay is further transformed into illite and chlorite (Dewhurst et al., 2015; Zeng, 2010). As the matrix undergoes irreversible processes such as compression, shrinkage fractures will develop in intervals rich in clay minerals. Coupled with the continuous compaction and hydrocarbon generation process, a large amount of water and hydrocarbon fluids are generated, forming abnormal fluid pressure. The



Note: C_b refers to larger recrystallization force; C_s refers to smaller recrystallization force

Fig. 31. Formation mechanism of structural-diagenetic fractures. Under the coupling of tectonic stress, fluid pressure, and dolomite recrystallization force, dolomitization fractures are formed.

pressure causes the fracture Mohr circle to move left, exceeding the rock fracture strength, thus forming abnormally high pressure fractures (Fig. 29).

Hubert and Willis suggest that fractures may occur when the overpressure of fluid pressure (the portion exceeding the hydrostatic column pressure) reaches 1/2 or 1/3 of the matrix pressure. Shrinkage fractures form due to the transformation and dehydration of clay minerals, and excessive fluid pressure can sustain and enlarge shrinkage fractures, potentially inducing new fractures (Luo et al., 2015).

4.4.1. *The formation mechanism of drainage fracture*

Drainage fractures primarily develop during the early stages of sediment consolidation. Under-compaction hinders the smooth drainage of formation fluids, mainly formation water, altering hydrodynamic conditions and increasing fluid pressure in localized areas. Consequently, sediments experience longitudinal tearing and upward migration, resulting in the formation of fractures serving as drainage pathways (Ma, 2017). This phenomenon is common in loosely consolidated sedimentary rock formations like mud shale due to their higher porosity, slower consolidation rates, and typically high-pressure environments conducive to drainage fracture formation.

4.4.2. *The formation mechanism of hydrocarbon generation and expulsion fractures*

Hydrocarbon generation and expulsion fractures form within organic-rich mud shale (source rock) as temperature gradually increases with increasing burial depth (Zhang et al., 2020). During this process, hydrocarbons are generated within the source rock, leading to significant transformations in organic matter. Specifically, dense kerogen undergoes thermal maturation, converting into less dense oil and natural gas. Additionally, crude oil within the rock may experience thermal cracking, further breaking down into gaseous hydrocarbons. These transformations result in the expansion of pore fluids due to the lower density of the generated hydrocarbons compared to the original organic material.

As kerogen and crude oil fracture and release hydrocarbons, the associated increase in pore fluid pressure can become substantial, ultimately exceeding the rock's mechanical strength. This elevated pressure induces fracturing within the shale, leading to the formation of hydrocarbon generation-induced overpressure fractures (Fig. 30). The development and propagation of these fractures are primarily controlled by the rock framework and the degree of cementation, which dictate the rock's overall mechanical behavior. In contrast, mineral crystallization plays a relatively minor role in governing the formation of these fractures (Ma et al., 2017).

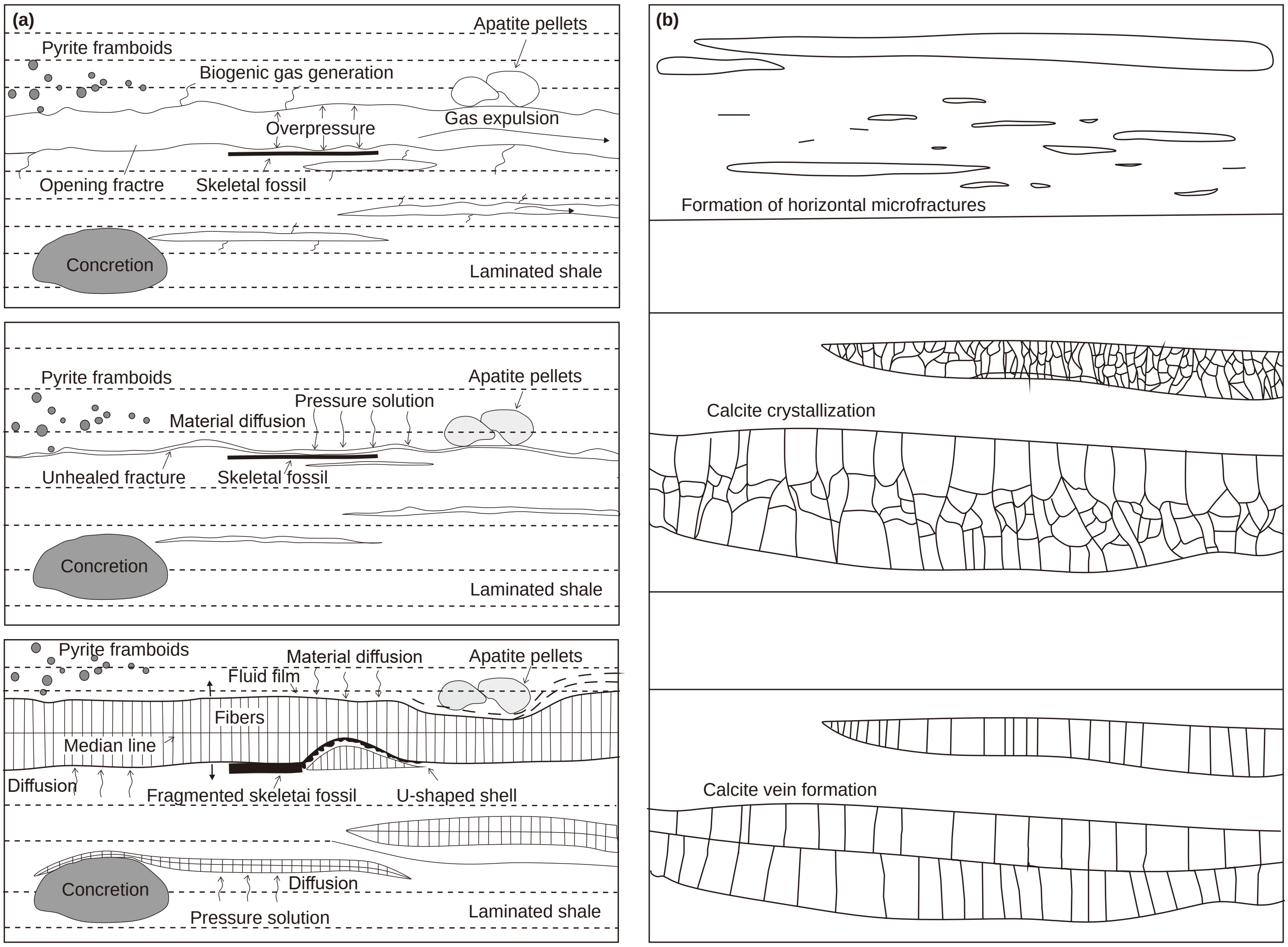


Fig. 32. Formation mechanism of bedding-parallel vein fractures (modified from Ao et al., 2021). Under the compression of horizontal structures, horizontal microfractures are formed. Afterwards, under the action of fluid pressure and crystallization force, calcium carbonate crystals precipitate in the fractures.

4.5. The formation mechanism of structural-diagenetic fractures

Tectonic-diagenetic fractures result from the interaction of tectonic stress and diagenesis. For instance, dolomite fractures in the Kong 2 Member of the Cangdong Sag, Bohai Bay Basin, are influenced by tectonic stress, abnormal fluid pressure, and dolomite recrystallization (Ma et al., 2023). Unlike previous concepts of tectonic-diagenetic fractures, dolomite recrystallization is the primary factor in their formation, with tectonic stress serving as background stress (Olson et al., 2009). Since most fractures are vertical or high-angle, it suggests that the crystallization force on fractures aligns with the minimum principal stress direction, counteracted by the overlying rock layer's stress against dolomite weight, resulting in high-angle fractures eventually (Fig. 31; Bons et al., 2012).

4.6. The formation mechanism of bedding-parallel vein fractures

Bedding-parallel vein fractures, under horizontal compression stress, when pore fluid pressure exceeds rock fracture strength, horizontal fractures can form (Zhan et al., 2022). Once formed, organic acid dissolves micrite calcite, which then migrates vertically within the fracture. Subsequently, fluid pressure and crystallization force collaborate to expand the fracture. Continuing fluid pressure leads to calcium carbonate crystal deposition, resulting in a single calcite vein within the fractures. Under crystallization force, recrystallization produces fibrous calcite veins, filling the entire bedding vein fracture (Bons et al., 2012). Calcite occupies fracture spaces, supporting and promoting symbiosis (Fig. 32).

5. Conclusion and outlook

5.1. Conclusion

The study of fractures is crucial for guiding shale oil exploration, serving as essential storage space and migration channels. Research on shale fractures has made progress in classification, characterization, controlling factors, and formation mechanisms. Shale fractures, classified into six major categories with eleven subcategories, are influenced by internal (formation thickness, lithology, rock composition, mechanics, and lamination) and external (tectonic activity, diagenesis, fluid pressure) factors. Structural fractures form due to tectonic stress reaching fracture strength. Diagenetic fractures result from diagenetic alterations. Bedding fractures depend on rock strata thickness, composition, environment, and lamination, forming via structural uplift and diagenesis. Fluid pressure joints form due to abnormal pressure. Structural-diagenetic and structural-fluid pressure fractures' development depends on lithofacies, rock composition, tectonic activity, fluid pressure, mechanics, and diagenesis. Nonetheless, some problems remain unresolved.

5.2. Existing problems

The main problems in the study of shale fractures are as follows:

(1) There is currently no unified standard for the classification of shale fractures, and the existing criteria are too numerous and lack uniformity, with little research value for some types of fractures. Due to differences in research focus, the mainstream classification schemes proposed so far have used fracture size, morphology, occurrence, mechanical properties, geological origin, and other criteria to classify fractures into 36 subtypes. However, due to time and resource constraints, it is not possible to conduct detailed studies on every type of fracture. A unified classification standard can not only reduce confusion in classification, but also exclude fractures with extremely low research value.

(2) There is relatively little research on quantitative characterization parameters for microfractures. When observing fractures under a scanning electron microscope, only some qualitative descriptions can be made, which is far from sufficient for more refined characterization research.

(3) In the parameter analysis of the genesis mechanism of shale fractures, there are more qualitative analyses and fewer quantitative analyses, and the genesis mechanism equations formed are not yet mature enough. The study of the genesis mechanism of shale fractures started relatively late in China, so most of the research is qualitative analysis of the genesis mechanism. Previous studies have shown through numerical simulations that tectonic stress can to some extent suppress the activity of ground fractures, but when it exceeds a certain limit, it will reverse and enhance the activity of ground fractures. However, reliable numerical models have not yet been established for other controlling factors.

5.3. Development trend

With the comprehensive progress of shale exploration and exploitation technology, it will be increasingly important to quantitatively analyze the genesis mechanism of shale and numerically simulate the parameters of artificially fractured fractures. The development trends mainly include the following aspects:

(1) Taking into account the characteristics and geological origin of fractures, a unified classification standard for shale fractures should be established to reflect more clearly the morphological distribution characteristics, geological origin, mechanical properties and their effects on shale oil and gas, in order to meet the needs of real distribution characteristics and further evaluation of shale fractures.

(2) More in-depth research should be conducted on some parameters of micro-fractures and artificial fracturing patterns. With the gradual deepening of research on macro-shale fractures, research on micro-fractures will also be more comprehensive. Currently, research on micro-fractures is still limited to their identification and characterization, and specific parameters have not been studied in depth. Therefore, in future research, more attention will be paid to micro-fractures.

(3) More reliable equations should be established to explain the genesis of composite fractures. With the further development of genesis mechanism research, quantitative analysis is more important for the assessment of the collection and migration ability of fractures. Therefore, it is more important to establish more mechanism equations for composite fractures.

CRediT authorship contribution statement

Cun-Fei Ma: Conceptualization, Formal analysis. **Wen-Jing Sun:** Writing – review & editing. **Bing Hao:** Project administration. **Yi-Mei Han:** Supervision. **Li-Juan Wang:** Software. **Hui Cao:** Investigation. **Jun-Ke Sun:** Funding acquisition. **Yang Li:** Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cun-Fei Ma reports financial support was provided by National Natural Science Foundation of China. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by Natural Science Foundation of China (Grant Nos. 42172153, 41802172), National Key Technology Research and Development Program (2024ZD1405102) and Xinjiang Key Research and Development Program (2024B03007).

References

Achuhan, F., Kjeldstad, A., Bjorlykke, K., et al., 2002. Porosity loss in sand by grain crushing —Experimental evidence and relevance to reservoir quality. Mar. Petrol. Geol. 19 (1), 39–53. https://doi.org/10.1016/S0264-8172(01)00049-6.

Angelier, J., Colletta, B., 1983. Tension fractures and extensional tectonics. Nature 301 (5895), 49–51. https://doi.org/10.1038/301049a0.

Ao, S., Bons, P.D., Honghan, C., et al., 2021. Age, material source, and formation mechanism of bedding-parallel calcite beef veins: Case from the mature Eocene lacustrine shales in the Biyang Sag, Nanxiang Basin, China. Geol. Soc. Am. Bull. 134 (7–8), 1811–1833. https://doi.org/10.1130/b35866.1.

Bao, H.Y., Liu, C., Gan, Y.P., et al., 2024. Paleotectonic stress field and fracture characteristics of shales of Ordovician Wufeng formation to Silurian Longmaxi Formation in southern Fuling area, Sichuan Basin. Lithologic Reservoirs 36 (1), 14–22. https://doi.org/10.12108/yxyqc.20240102 (in Chinese).

Barker, D.S., Miliken, K.L., 2008. Cementation of the footprint tuff, Laetoli, Tanzania. Can. Mineral. 46 (4), 831–841. https://doi.org/10.3749/canmin.46.4.831.

Bons, P.D., Elburc, M.A., Gomez-rivas, E., 2012. A review of the formation of tectonic veins and their microstructures. J. Struct. Geol. 43, 33–62. https://doi.org/10.1016/j.jsg.2012.07.005.

Bruce, C.H., 1984. Smectite dehydration; its relation to structural development and hydrocarbon accumulation in northern Gulf of Mexico Basin. AAPG Bull 68 (6), 673–683. https://doi.org/10.1007/BF01081374.

Chen, L.Q., Wu, J., He, Y.F., et al., 2023. Fracture vein characteristics and paleofluid activities in the Lower Cambrian Qiongzhusi shale in the central portion of the Mianyang-Changing intracratonic Sag, Sichuan Basin. Bulletion of Geological Science and Technology 42 (3), 142–152.

Chen, X.M., Yang, B., Cao, J.K., et al., 2000. Analysis of micro fracture characteristics and influencing factors of oil and gas bearing clastic reservoirs in the Yanqi basin. J. Chengdu Univ. Technol. 27 (3), 286–290. https://doi.org/10.3969/j.issn.1671-9727.2000.03.013 (in Chinese).

Chen, Y.B., 2022. Research on the calculation model and application of shear wave fracture permeability in tight fractured reservoirs. Yangtze University (in Chinese).

Cobbold, P.R., Zanella, A., Rodrigues, N., et al., 2013. Bedding-parallel fibrous veins (beef and cone-in-cone): Worldwide occurrence and possible significance in terms of fluid overpressure, hydrocarbon generation and mineralizationMarine and petroleum geology. Mar. Petrol. Geol. 43, 1–20. https://doi.org/10.1016/j.marpetgeo.2013.01.010.

Colten-Bradley, V.A., 1987. Role of pressure in smectite dehydration — effects on geopressure and Smectite-to-IUite transformation. AAPG (Am. Assoc. Pet. Geol.) Bull. 71 (11), 1414–1427. https://doi.org/10.1306/703C8092-1707-11D7-8645000102C1865D.

Cristescu, N., 1982. Rock dilatancy in uniaxial tests. Rock Mechanics Felsmechanik Mecanique des Roches 15 (3), 133–144. https://doi.org/10.1007/BF01238260.

Dashti, R., Ulu, M.O., Albayram, S., et al., 2007. Concomitant fracture of bilateral occipital condyle and inferior clivus: What is the mechanism of injury. Eur. Spine J. 16 (Suppl. 3), 261–264. https://doi.org/10.1007/s00586-006-0270-1.

Dewhurst, D.N., Sarout, J., Delle, P.C., et al., 2015. Empirical strength prediction for preserved shales. Mar. Petrol. Geol. 67, 512–525. https://doi.org/10.1016/j.marpetgeo.2015.06.004.

Dewhurst, D.N., Siggins, A.F., Sarout, J., et al., 2011. Geomechanical and ultrasonic characterization of a Norwegian Sea shale. Geophysics 76 (3), 101–111. https://doi.org/10.1190/1.3569599.

Ding, W.L., Xu, C.C., Jiu, K., 2011. The research progress on shale fractures. Progress in Earth Science 26 (2), 135–144. https://doi.org/10.1007/s12182-011-0118-0.

Ding, W.L., Li, C., Li, C.Y., et al., 2012. Dominant factor of fracture deveipoment in shale and its relationship to gas accumulation. Earth Sci. Front. 19 (2), 212–220.

Durhan, W.B., 1997. Laboratory observations of the hydraulic behavior of a permeable fracture from 3800 rn depth in the KTB pilot hole. J. Geophys. Res. 102 (B8), 18405–18416. https://doi.org/10.1029/96JB02813.

Engelder, T., Lash, G.G., Uzcategui, R.S., 2009. Joint sets that enhance production from middle and Upper Devonian gas shales of the appalachian basin. AAPG (Am. Assoc. Pet. Geol.) Bull. 93 (7), 857–889.

Freed, R.L., Peacor, D.R., 1989. Geopressured shale and sealing effect of smectite to lUite transition. Am. Assoc. Petrol. Geol. Bull. 73 (10), 1223–1232. https://doi.org/10.1029/JB094iB10p14249.

Gasparrini, M., Sassi, W., Gale, J.F.W., 2014. Natural sealed fractures in mudrocks: a case study tied to burial history from the Barnett Shale, Fort Worth Basin, Texas, USA. Mar. Petrol. Geol. 55, 122–141. https://doi.org/10.1016/j.marpetgeo.2013.12.006.

Gu, Y., Ding, W.L., Tian, Q., et al., 2020. Developmental characteristics and dominant factors of natural fractures in lower Silurian marine organic-rich shale reservoirs: A case study of the Longmaxi formation in the Fenggang block, southern China. J. Petrol. Sci. Eng. 192, 107–277. https://doi.org/10.1016/j.petrol.2020.107277.

Guo, Z., Zhang, J.C., Liu, Y., et al., 2022. Experimental study on the effect of mineral composition on shrinkage fractures: Implications for the origin of the diagenetic shrinkage fractures in marine–continental transitional shales. Minerals 12 (11), 1381.

Han, J.X., Li, S.C., Li, S.C., 2013. A model for switching mechanism and criteria of structure control and stress control on rock mass failure. Sci. China Phys. Mech. Astron. 43 (2), 177–185. https://doi.org/10.1360/132012-367.

He, Z.J., Liu, B.J., Wang, P., 2011. Genesis of Jurassic bedding fractures in Yongjin area of the Junggar Basin and its impact on reservoirs. Oil and Gas Geology and Recovery 18 (1), 15–17. https://doi.org/10.1016/S1003-9953(10)60145-4. +112.

Holder, J., Olson, J.E., Philip, Z., et al., 2001. Experimental determination parameters in sedimentary rock of subcritical fracture growth. Geophys. Res. Lett. 28 (4), 599–602. https://doi.org/10.1029/2000GL011918.

Hu, T., Liu, Y., Jiang, F.J., et al., 2024a. A novel method for quantifying hydrocarbon micromigration in heterogeneous shale and the controlling mechanism. Energy 288, 129712. https://doi.org/10.1016/j.energy.2023.129712.

Hu, T., Jiang, F.J., Pang, X.Q., et al., 2024b. Identification and evaluation of shale oil micro-migration and its petroleum geological significance. Petrol. Explor. Dev. 51 (1), 127–140. https://doi.org/10.1016/S1876-3804(24)60010-8.

Hu, T., Jing, Z.H., Zhang, Q., et al., 2025. Shale oil micro-migration characterization: Key methods and outlook. Advances in Geo-Energy Research 15 (1), 5–12. https://doi.org/10.46690/ager.2025.01.02.

Huo, Z.P., Peng, J.L., Zhang, J.C., et al., 2019. Factors influencing the development of diagenetic shrinkage macro-fractures in shale. J. Pet. Sci. Eng. 183, 106–365.

Jacobi, R.D., 2002. Basement faults and seismicity in the appalachian basin of New York state. Tectonophysics 353 (1), 75–113. https://doi.org/10.1016/S0040-1951(02)00278-0.

Jacques, A., Bernard, C., 1983. Tension fractures and extensional tectonics. Nature 301 (5895), 49–51. https://doi.org/10.1038/301049a0.

Labani, M.M., Rezaee, R., 2015. The importance of geochemical parameters and shale composition on rock mechanical properties of gas shale reservoirs: A case study from the Kockatea Shale and Carynginia Formation from the Perth Basin, Western Australia. Rock Mech. Rock Eng. 48 (3), 1249–1257. https://doi.org/10.1007/s00603-014-0617-6.

Lai, J., Liu, B.C., Li, H.B., et al., 2022. Bedding parallel fractures in fine-grained sedimentary rocks: Recognition, formation mechanisms, and prediction using well log. Pet. Sci. 19 (2), 554–569. https://doi.org/10.1016/j.petsci.2021.10.017.

Lash, G.G., Engelder, T., 2005. An analysis of horizontal microcracking during catagenesis; example from the Catskill Delta complex. AAPG Bull. 89 (11), 1433–1449.

Laubach, S.E., Olson, J.E., Gale, J.F.W., 2004. Are open fractures necessarily aligned with maximum horizontal stress. Earth Planet Sci. Lett. 222 (1), 191–195. https://doi.org/10.1016/j.epsl.2004.02.019.

Lavenu, A.P.C., Lamarche, J., Salardon, R., et al., 2014. Relating background fractures to diagenesis and rock physical properties in a platform–slope transect. Example of the Maiella Mountain (Central Italy). Mar. Petrol. Geol. 51, 2–19. https://doi.org/10.1016/j.marpetgeo.2013.11.012.

Li, Q., Kang, R., Liu, K., et al., 2004. Geological model and genesis mechanism of fractured shale oil and gas reservoirs. China University of Geosciences Press, Beijing (in Chinese).

Li, Z.M., Liu, Y.H., He, J., et al., 2023. Limits of critical parameters for sweet-spot interval evaluation of lacustrine shale oil. Oil Gas Geol 44 (6), 1453–1467. https://doi.org/10.11743/ogg20230610.

Li, Y., He, J.C., Deng, H.C., et al., 2024. Analysis of connectivity characterization and mechanical effectiveness of natural fracture in deep shale reservoirs: A case study of the Wufeng-Longmaxi Formations in the Dingshan-Dongxi area, southeastern margin of Sichuan Basin. Nat. Gas Geosci. 35 (2), 230–244. https://doi.org/10.11764/j.issn.1672-1926.2023.09.019 (in Chinese).

Liang, C., Cao, Y., Liu, K., et al., 2018. Diagenetic variation at the lamina scale in lacustrine organic-rich shales: implications for hydrocarbon migration and accumulation. Geochem. Cosmochim. Acta 229, 112–128.

Liang, C.G., Xie, J.Y., Chen, Y.W., et al., 2021. Genesis and coupling relationship of fractures in shale reservoir of Lucaogou Formation in Jimsar Sag, Junggar Basin. Xinjing Pet. Geol. 42 (5), 521–528 (in Chinese).

Liu, Z., Gao, B., Hu, Z., et al., 2018. Pore characteristics and formation mechanism of high-maturity organic-rich shale in Lower Cambrian Jiumenchong Formation, southern Guizhou. Petroleum Research 3 (1), 57–65. https://doi.org/10.1016/j.ptlrs.2018.03.002.

Liu, P., Zhang, T., Xu, Q., et al., 2022. Organic matter inputs and depositional palaeoenvironment recorded by biomarkers of marine-terrestrial transitional shale in the southern north China Basin. Geol. J. 57 (4), 1617–1627.

Liu, M.M., Fu, X.P., Ni, K., 2023. Characteristics of lithofacies combinations and its influence on shale gas-bearing property: A case study of the Lianggaoshan Formation in Fuling area. Fault-block oil & gas filed 30 (1), 1–8.

Lorenz, J.C., Sterling, J.L., Schechter, D.S., et al., 2002. Natural fractures in the Spraberry formation, Midland basin, Texas: The effects of mechanical stratigraphy on fracture variability and reservoir behavior. AAPG Bull 86 (3), 505–524. https://doi.org/10.1306/61EEDB20-173E-11D7-8645000102C1865D.

Lun, Z., Li, J.X., Li, K.C., et al., 2010. Development and genetic mechanism of complex carbonate reservoir fractures: A case from the Zanarol oilfield, Kazakhstan. Petrol. Explor. Dev. 37 (3), 304–309. https://doi.org/10.1016/S1876-3804(10)60034-1.

Luo, X.P., Wu, P., Zhao, J.H., et al., 2015. Study advances on organic pores in organic matter-rich mud shale. Chengdu Univ. Technol. (Sci. Technol. Ed.) 42 (1), 50–59 (in Chinese).

Ma, C.F., 2017. Study on Characteristics and Effectiveness of Lacustrine Shale Reservoir. China University of Petroleum (East China) (in Chinese).

Ma, C.F., Dong, C.M., Luan, G.Q., et al., 2016. Types, characteristics and effects of natural fluid pressure fractures in shale: a case study of the Paleogene strata in Eastern China. Petrol. Explor. Dev. 43 (4), 634–643. https://doi.org/10.1016/S1876-3804(16)30074-X.

Ma, C.F., Elsworth, D., Dong, C., et al., 2017. Controls of hydrocarbon generation on the development of expulsion fractures in organic-rich shale: Based on the Paleogene Shahejie Formation in the Jiyang depression, Bohai Bay Basin, East China. Mar. Petrol. Geol. 86, 1406–1416. https://doi.org/10.1016/j.marpetgeo.2017.07.035.

Ma, C.F., Huang, W.J., Du, Z.L., et al., 2022. Shale lithofacies classification scheme of continental lake basin and its significance: A case of E2 member of Kongdian Formation in Cangdong Sag. J. Cent. S. Univ. 53 (9), 3287–3300 (in Chinese).

Ma, C.F., Sun, W.J., Zeng, L.P., et al., 2023. Mathematical analysis of structural fracture scale in shale based on core fracture observation of the second member of Kongdian formation in Cangdong Sag. Journal of China University of Petroleum (Edition of Natural Science) 47 (4), 1–11 (in Chinese).

Ma, S.J., Zeng, L.B., Shi, X.W., et al., 2023. Characteristics and main controlling factors of natural fractures in marine shale in Luzhou area, Sichuan Basin. Earth Sci 48 (7), 2630–2642. https://doi.org/10.3969/J.ISSN.1672-7703.2017.04.004.

Machel, H.G., 1997. Recrystallization versus neomorphism, and the concept of “significant recrystallization” in dolomite research. Sediment. Geol. 113 (3–4), 161–168. https://doi.org/10.1016/S0037-0738(97)00078-X.

Meng, Q.F., Hooker, J., Cartwright, J., 2019. Role of pressure solution in the formation of bedding-parallel calcite veins in an immature shale (Cretaceous, southern UK). Geol. Mag. 156 (5), 918–934.

Meng, Q.F., Hao, F., Tian, J., 2021. Origins of non-tectonic fractures in shale. Earth Sci. Rev. 222, 103–825. https://doi.org/10.1016/j.earscirev.2021.103825.

Michael, P. Felix, 1977. Determination of stress levels for dynamic fracture of oil shale. Exp. Mech. 77 (10), 381–384. https://doi.org/10.1007/BF02324204.

Narr, W., Suppe, J., 1991. Joint spacing in sedimentary rocks. J. Struct. Geol. 13 (9), 1037–1048. https://doi.org/10.1016/0191-8141(91)90055-N.

Nelson, R.A., 1985. Geologic Analysis of Naturally Fracture Reservoirs:Contributions in Petroleum Geology and Engineering. Gulf Publishing Company, Houston, pp. 1–320. https://doi.org/10.2118/15627-PA.

Oliver, N.H.S., Bons, P.D., 2001. Mechanisms of fluid flow and fluid-rock interaction in fossil metamorphic hydrothermal systems inferred from vein-wallrock patterns, geometry and microstructure. Geofluids 1 (2), 137–162. https://doi.org/10.1046/j.1468-8123.2001.00013.x.

Olson, J.E., 2014. Predicting fracture swarms - the influence of subcritical fracture growth and the fracture-tip process zone on joint spacing in rock. Geological Society (231), 73–87.

Olson, J.E., Laubach, S.E., Lander, R.H., 2009. Natural fracture characterization in tight gas sandstones; integrating mechanics and diagenesis. AAPG Bull 93 (11), 1535–1549. https://doi.org/10.1306/08110909100.

Perez, R.J., Boles, J.R., 2005. Interpreting fracture development from diagenetic mineralogy and thermoelastic contraction modeling. Tectonophysics 400 (1–4), 179–207. https://doi.org/10.1016/j.tecto.2005.03.002.

Peter, C. van de Kamp, 2008. Smectite-illite-muscovite transformations, quartz dissolution, and silica release in shales. Clays Clay Miner 56 (1), 66–81. https://doi.org/10.1346/CCMN.2008.0560106.

Qi, J.F., Yang, Q., 2010. Cenozoic structural deformation and dynamic processes of the Bohai Bay basin province, China. Mar. Petrol. Geol. 27 (4), 757–771. https://doi.org/10.1016/j.marpetgeo.2009.08.012.

Qian, M.P., 1995. Marine Triassic stromatolites and their environmental evolution in the middle and lower Yangtze region. Acta Palaeontol. Sin. (6) 731-741, 801-804.

Rijken, P., Cooke, M.L., 2001. Role of shale thickness on vertical connectivity of fractures; application of fracture-bridging theory to the Austin Chalk, Texas. Tectonophysics 337 (1–2), 117–133. https://doi.org/10.1016/S0040-1951(01)00107-X.

Rokosh, D., Pawlowicz, J., Andersons, S., et al., 2009. Shale Fabric, Mineralogy and Effective Porosity of the Upper Colorado Group. Canadian Society of Petroleum Geologists, Calgary, AB, pp. 572–576.

Ross, D.J.K., Bustin, R.M., 2008. Characterizing the shale gas resource potential of Devonian-Mississippian strata in the Western Canada sedimentary basin; application of an integrated formation evaluation. AAPG Bull. 92 (1), 87–125.

Rossi, C., Alaminos, A., 2014. Evaluating the mechanical compaction of quartzarenites: The importance of sorting (Llanos foreland Basin, Colombia). Mar. Petrol. Geol. 56, 222–238. https://doi.org/10.1016/j.marpetgeo.2014.04.012.

Schrank, C.E., Jones, M.W., Kewish, C.M., et al., 2021. Micro-scale dissolution seams mobilise carbon in deep-sea limestones. Commun. Earth Environ. 2 (1), 1–10. https://doi.org/10.1038/s43247-021-00257-w.

Shi, L., Wang, X.Z., Fan, B.J., et al., 2018. Characteristics of sandy lamination and its hydrocarbon accumulation,Yanchang Formation, Ordos Basin. Oil Gas Geol 39 (3), 522–530. https://doi.org/10.11743/ogg20180309 (in Chinese).

Stearns, D.W., 1968. Certain aspects of fracture in naturally deformed rocks. In: Riecker, R.E. (Ed.), NSF Advanced Science Seminar in Rock Mechanics. Air Force Cambridge Research Laboratories Special Report, MA, pp. 97–118.

Sun, W.F., 2017. Research on multi-scale Structural Characteristics and Characterization Methods of Shale Reservoirs. Northeast University of Petroleum (in Chinese).

Tan, Y.L., Pan, Z.J., Liu, J.S., et al., 2017. Experimental study of permeability and its anisotropy for shale fracture supported with proppant. J. Nat. Gas Sci. Eng. 44, 250–264. https://doi.org/10.1016/j.jngse.2017.04.020.

Walsh, J.B., 1965. The effect of cracks on the compressibility of rock. J. Geophys. Res. 70 (2), 381–389. https://doi.org/10.1029/JZ070i002p00381.

Wang, H., He, Z., Zhang, Y., et al., 2019a. Dissolution of marine shales and its influence on reservoir properties in the Jiaoshiba area, Sichuan Basin, China. Mar. Petrol. Geol. 102, 292–304. https://doi.org/10.1016/j.marpetgeo.2018.12.017.

Wang, H., He, Z.L., Zhang, Y.G., et al., 2019b. Microfracture types of marine shale reservoir of Sichuan basin and its influence on reservoir property. Oil Gas Geol. 40 (1), 41–49.

Wang, H., He, Z., Jiang, S., et al., 2022. Genesis of bedding fractures in Ordovician to Silurian marine shale in Sichuan basin. Energies 15 (20), 7738.

Wang, H.C., 2019. The Distribution Pattern and Control Factors of the Reservoir Space of the Jurassic Ahe Formation in the Northern Structural Belt of the Kuqa Depression. Changjiang University.

Wang, R.Y., Ding, W.L., Zhang, Y.P., et al., 2016. Analysis of developmental characteristics and dominant factors of fractures in Lower Cambrian marine shale reservoirs: A case study of Niutitang Formation in Cen’gong block, southern China. J. Petrol. Sci. Eng. 138, 31–49. https://doi.org/10.1016/j.petrol.2015.12.004.

Wang, X.H., Wang, R.Y., Ding, W.L., et al., 2017. Development characteristics and dominant factors of fractures and their significance for shale reservoirs: a case study from Є1b2 in the Cen'gong block, southern China. J. Petrol. Sci. Eng. 159, 988–999.

Wang, Y.M., Dong, D.Z., Yang, H., et al., 2014. Quantitative characterization of reservoir space in the Lower Silurian Longmaxi Shale, southern Sichuan, China. Sci. China Earth Sci. 57, 313–322. https://doi.org/10.1007/s11430-013-4645-y.

Wei, X.L., Zhang, Y.X., Zhang, S., et al., 2021. A study on the morphology of natural microfractures in marine and Continental transitional shale based on scanning electron microscopy image. Micron 148, 103–105. https://doi.org/10.1016/j.micron.2021.103105.

Wu, J., Wang, Q., Cheng, X., et al., 2023. Formation of multi-stage and clustered fractures at 3.6–4.9 km in the Shizigou structure, SW Qaidam Basin. J. Struct. Geol. 169, 104–845. https://doi.org/10.1016/j.jsg.2023.104845.

Wu, Z.J., Tang, H.J., An, F.S., 2003. Causes of bedding fractures of tight sand gas reservoir in Xinchang West Sichuan region. Petrol. Explor. Dev. 30 (2), 109–111. https://doi.org/10.1007/BF02873153.

Xian, Y.K., 2019. The transformation of clay minerals and its impact on shale reservoirs. Acta Geol. Sichuan 39 (2), 244–247 (in Chinese).

Xie, J.T., 2020. Shale fractures in complex tectonic zones and their effects on shale gaspreservation: a case study of Longmaxi Formation in Dongxi-Songkan area of Southeast Sichuan. Southwest Petroleum University, Chengdu (in Chinese).

Xie, G.Y., Wang, Z.L., Liu, B., et al., 2021. Diagenesis of the Shaximiao Formation reservoir in southwest sichuan and its influence on the reservoir. Acta Geol. Sichuan 41 (4), 609–612 (in Chinese).

Xue, L.H., Yang, W., Zhong, J.A., et al., 2015. Porous evolution of the organic-rich shale from simulated experiment with geological constrains, samples from Yanchang Formation in Ordos Basin. Acta Geol. Sin. 89 (5), 970–978 (in Chinese).

Yan, L.Z., 2017. Research on Fracture Prediction Based on Tectonic Stress Field in Shale Gas Reservoirs. China University of Petroleum (East China) (in Chinese).

Yang, G., Ding, W.L., Tian, Q., et al., 2020. Developmental characteristics and dominant factors of natural fractures in lower Silurian marine organic-rich shale reservoirs: A case study of the Longmaxi formation in the Fenggang block, southern China. J. Petrol. Sci. Eng. 192, 107–277. https://doi.org/10.1016/j.petrol.2020.107277.

Yang, X.F., Xia, Z.Q., Zhao, S.X., et al., 2024. Development characteristics of natural fractures in horizontal wells for deep shale gas and their implications for enhanced development: A case study of Wufeng-Longmaxi formations in Luzhou area, southern Sichuan Basin. Petroleum Geology & Experiment 46 (4), 735–747. https://doi.org/10.11781/sysydz202404735 (in Chinese).

Yuan, J., Cao, Y., Li, J., et al., 2017. Diversities and disparities of fracture systems in the Paleogene in DN gas field, Kuqa depression, Tarim Basin. Oil Gas Geol 38 (5), 840–850. https://doi.org/10.11743/ogg20170502.

Yuan, Y.Y., Li, H., Wang, Y., et al., 2021. A study on the influence of shale facies on the formation and evolution of fractures - taking the Longmaxi Formation in northwest Guizhou as an example. Geological Science 56 (1), 82–97. https://doi.org/10.12017/dzkx.2021.006 (in Chinese).

Zeng, L.B., 2010. Microfracturing in the Upper Triassic Sichuan Basin tight-gas sandstones; tectonic, overpressure, and diagenetic origins. AAPG Bull. 94 (12), 1811–1825.

Zeng, L.B., Li, X.Y., 2009. Fractures in sandstone reservoirs with ultra-low permeability: A case study of the Upper Triassic Yanchang Formation in the Ordos Basin, China. AAPG (Am. Assoc. Pet. Geol.) Bull. 93 (4), 461–477. https://doi.org/10.1306/09240808047.

Zeng, L.B., Lyu, W.Y., Li, J., et al., 2016a. Natural fractures and their influence on shale gas enrichment in Sichuan basin, China. J. Nat. Gas Sci. Eng. 30, 1–9. https://doi.org/10.1016/j.jngse.2015.11.048.

Zeng, L.B., Zhu, R.K., Gao, Z.Y., et al., 2016b. Structural diabetes and its petroleum geological significance. Petroleum Science Bulletin 1 (2), 191–197. https://doi.org/10.3969/j.issn.2096-1693.2016.02.015 (in Chinese).

Zeng, L.B., Lv, W.Y., Xu, X., et al., 2022. Development characteristics, formation mechanism and hydrocarbon significance of bedding fractures in typical tight sandstone and shale. Acta Petrol. Sin. 43 (2), 180–191. https://doi.org/10.7623/syxb202202002 (in Chinese).

Zeng, L.B., Ma, S.J., Tian, H., et al., 2023. Research progress of natural fractures in organic rich shale. Earth Sci 48 (7), 2427–2442. https://doi.org/10.3799/dqkx.2022.190 (in Chinese).

Zeng, W.T., Zhang, J., Ding, W.L., et al., 2013. Fracture development in Paleozoic shale of Chongqing area (South China). Part one: Fracture characteristics and comparative analysis of main controlling factors. J. Asian Earth Sci. 75, 251–266. https://doi.org/10.1016/j.jseaes.2013.07.015.

Zhan, H., Fang, F., Li, X., et al., 2022. Shale reservoir heterogeneity: A case study of organic-rich Longmaxi shale in southern Sichuan, China. Energies 15 (3), 913. https://doi.org/10.3390/en15030913.

Zhang, C., Zhu, D., Luo, Q., et al., 2017. Major factors controlling fracture development in the middle Permian Lucaogou Formation tight oil reservoir, Junggar Basin, NW China. J. Asian Earth Sci. 146, 279–295. https://doi.org/10.1016/j.jseaes.2017.04.032.

Zhang, W.Z., Xie, L.Q., Yang, W.W., et al., 2017. Micro fractures and pores in lacustrine shales of the Upper Triassic Yanchang Chang7 Member, Ordos Basin, China. J. Petrol. Sci. Eng. 156, 194–201. https://doi.org/10.1016/j.petrol.2017.03.044.

Zhang, X.M., Wang, R., Shi, W.Z., et al., 2023. Structure- and lithofacies-controlled natural fracture developments in shale: implications for shale gas accumulation in the Wufeng-Longmaxi formations, Fuling field, Sichuan Basin, China. Geoenergy Sci. Eng. 223, 211–572. https://doi.org/10.1016/j.geoen.2023.211572.

Zhang, Y., Zhao, Y., Yang, H., et al., 2020. A semianalytical solution for a Griffith crack nonuniformly pressurized by internal fluid. Rock Mech. Rock Eng. 53 (5), 2439–2460.

Zhang, Y.P., 2019. A Study on the characteristics of shale fractures in the Lujiaping Formation of the Lower Cambrian in the Chengkou area of northeastern Chongqing. Southwest University of Petroleum (in Chinese).

Zhang, Z.P., Kong, X.Y., Chen, Q., et al., 2021. Quantitative characterization and determination of the main factors that control fracture development in the lower Paleozoic shale in Southeastern Chongqing, China. Geofluids 2021, 1–11. https://doi.org/10.1155/2021/5591681.

Zhang, Z.X., 2020. Research progress of diagenesis and diagenetic facies of low and ultra-low permeability reservoirs. Liaoning Chemical Industry 49 (8), 1026–1028 (in Chinese).

Zhao, B.S., Li, R.X., 2022. Formation mechanism of bedding-parallel antitaxial fibrous veins in shale: A review. J. Struct. Geol. 161, 104–653. https://doi.org/10.1016/j.jsg.2022.104653.

Zhao, W.T., Hou, G.T., Zhang, J.Z., et al., 2015. Study on the development law of structural fractures of Yanchang Formation in Longdong area, Ordos Basin. Acta Sci. Nauralium Univ. Pekin. 51 (6), 1047–1058. https://doi.org/10.13209/j.0479-8023.2015.064.

Zhao, S.X., Xia, Z.Q., Li, H., et al., 2023. Quantitative evaluation and development control factors of natural fractures in shale reservoirs: A case study of the deep shale of the Wufeng-Longmaxi Formation in Luzhou area. Acta Sedimentol. Sin. 43 (1), 212–225. https://doi.org/10.14027/j.issn.1000-0550.2023.015 (in Chinese).

Zhong, J., Liu, S., Ma, Y., et al., 2015. Macro-fracture mode and micro-fracture mechanism of shale. Petrol. Explor. Dev. 42 (2), 269–276. https://doi.org/10.1016/S1876-3804(15)30016-1.

Zhou, W., 1998. Evaluation methods for fractured oil and gas reservoirs. Sichuan Science and Technology Press, Chengdu, pp. 275–285 (in Chinese).

Zhou, X.G., Cao, C.J., Yuan, J.Y., 2003. Current status and progress in quantitative prediction of reservoir structural fractures and research on oil and gas permeability laws. Progress in Earth Science 18 (3), 398–404.

Zhu, H.J., Ju, Y.W., Qi, Y., et al., 2018. Impact of tectonism on pore type and pore structure evolution in organic-rich shale: Implications for gas storage and migration pathways in naturally deformed rocks. Fuel 228, 272–289.