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Original Paper

Development characteristics and controlling factors of fractures in lacustrine shale and their geological significance for evaluating shale oil sweet spots in the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin

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A B S T R A C T

Natural fractures are critical for shale oil and gas enrichment and development. Due to the extremely high heterogeneity of shale, the factors controlling the formation of internal fractures, especially horizontal fractures, remain controversial. In this study, we integrate thin section analysis and micro-computed tomography (CT) data from several lacustrine shale samples from the third member (Es_3) of the Shahejie Formation, Qikou Sag, Bohai Bay Basin, to assess the fractures in detail. The goal is to reveal the development characteristics, controlling factors, and geological significance for evaluating sweet spots in a shale oil play. The fractures in the Es_3 contain high-angle structural and horizontal bed-parallel fractures that are mostly shear and extensional. Various factors influence fracture development, including lithofacies, mineral composition, organic matter content, and the number of laminae. Structural fractures occur predominantly in siltstone, whereas bed-parallel fractures are abundant in laminated shale and layered mudstone. A higher quartz content results in higher shale brittleness, causing fractures, whereas the transformation between clay minerals contributes to the development of bed-parallel fractures. Excess pore pressure due to hydrocarbon generation and expulsion during thermal advance can cause the formation of bed-parallel fractures. The density of the bed-parallel and structural fractures increases with the lamina density, and the bed-parallel fractures are more sensitive to the number of laminae. The fractures are critical storage spaces and flow conduits and are indicative of sweet spots. The laminated shale in the Es_3 with a high organic matter content contains natural fractures and is an organic-rich, liquid-rich, self-sourced shale play. Conversely, the siltstone, massive mudstone, and argillaceous carbonate lithofacies contain lower amounts of organic matter and do not have bed-parallel fractures. However, good reservoirs can form in these areas when structural fractures are present and the source, and storage spaces are separated.

1. Introduction

As an important part of global oil and gas production, large-scale commercial shale play development has changed the structure of the global energy supply (Zou et al., 2020). Shale plays are being widely explored in the United States and China. The Mesozoic and Cenozoic lacustrine shale areas in China are considered at their peak of oil generation or in the early stages of gas generation. The geological conditions of these shale plays are relatively favorable to become new targets of shale oil exploration, with a preliminary prediction of recoverable oil of about 4.48×10^9 t (Zou et al., 2013). Shale reservoirs are characterized by low porosity and ultra-low permeability. Moreover, natural fractures are widely developed in shale plays, representing essential storage spaces and flow

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pathways (Li et al., 2022a). In addition, the enrichment of the play requires appropriate deposition, preservation, and maturation conditions, which are important geological factors. These shale formations can become commercially viable when fracturing stimulation and horizontal drilling are used (Gale et al., 2014).

Although hydraulic fracturing enhances the oil and gas production of shale plays, the presence of natural fractures is vital for tight formations. Hence, fracture identification based on outcrops, cores, and thin sections is the primary approach to understanding fracture occurrence, mode, scale, filling degree, and other mechanical properties of the formation. Additionally, this approach enables the identification and measurement of the fractures in outcrops and the comparison of the results to the macroscopic fracture network on a smaller scale (Engelder et al., 2009; Olson et al., 2009; Evans et al., 2014; Laubach et al., 2018; Hooker et al., 2020). However, fracture development in shale is unique and is controlled by several geological factors, such as the in-situ stress field and rock strength. Unlike marine reservoirs, lacustrine shale reservoirs have thinner single layers, frequent interbedding, a small extent, and strong heterogeneity (Ju et al., 2016; Tian et al., 2019). Various sedimentary structures, such as laminae, bedding, and cleavages, are prevalent, exacerbating the heterogeneity and anisotropy of the formation. Furthermore, the spatial distribution, type, and other characteristics of fractures in lacustrine shale can vary significantly in different basins. For example, the density of bed-parallel fractures in the Qingshankou Formation in the Liaoning Basin is 1300/m (He et al., 2022), whereas that in the Chang 7 Formation in the southern Ordos Basin ranges from several to dozens of fractures per meter (Li et al., 2022b). Additionally, the Permian Lucaogou Formation in the Jimusar Sag of the Junggar Basin is generally horizontal with limited structural fractures but has an abundance of bed-parallel fractures and micro-fractures (Liang et al., 2021).

It is important to note that lacustrine and marine shales differ significantly in their depositional environment, lithofacies type, and mineral composition. The density and pattern of fractures in interbedded reservoirs, such as lacustrine shale, are generally affected by the lithology (a combination of lithology and lithofacies) (Laubach, 2003; Tavani et al., 2015; Zhao et al., 2015; Gong et al., 2018, 2021). Furthermore, many scholars have conducted numerous studies on the formation mechanisms and main controlling factors of natural fractures in marine shale. They have concluded that geological factors, such as mineral composition, formation thickness, organic matter content, and formation pressure, influence the development degree of fractures in shale formations, affecting their productivity (Ding et al., 2012; Gale et al., 2014; Gale and Holder, 2015; Tian et al., 2020; Meng et al., 2021).

We have limited information on the characteristics and mechanisms of fracture development and the main controlling factors in lacustrine shale reservoirs, in contrast to marine shales. Previous studies have primarily focused on structural fractures, whereas we have a limited understanding of bed-parallel fractures (Wu et al., 2003; Gale and Holder, 2015; Zanella et al., 2015; Huang et al., 2016) and their influencing factors, although bed-parallel fractures are critical. Therefore, further studies are necessary to understand the importance of those fractures and their role in the exploration and development of lacustrine shale.

This paper focuses on the analysis of the lacustrine shale of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin. We study the genetic types, development characteristics, and main controlling factors of natural fractures. We conduct an in-depth analysis and observation of cores, thin sections, and other relevant data to provide information for the exploration and development of shale oil in the Bohai Bay Basin and similar lacustrine shale plays around the globe.

2. Geological overview

The Qikou Sag is located in the central part of the Bohai Bay Basin in eastern China, with an exploration area of nearly 6000 km^2. It is one of the largest oil and gas-rich sags in the Bohai Bay Basin (Ma et al., 2020). It is surrounded by the Cangxian uplift, Chengning uplift, and Shaleitian uplift. The west side is bounded by the Cangdong fault, which is connected to the Cangxian uplift. The southwest Kongdian uplift is connected to the Cangdong sag and overlays the Chengning uplift to the south. The Shaleitian uplift is located in the east, and the Shaleitian uplift is located in the north, with the Hangu fault as the boundary (Wang et al., 2020) (Fig. 1). The Qikou Sag is a pan-like, faulted basin composed of a main sag and four sub-sags, with a north fault, a southern superstructure, and a half-graben structure. It is a sedimentary sag that has geologically evolved since the Oligocene epoch.

The shale oil exploration in the Qikou Sag is concentrated in the Paleogene strata. Significant shale oil exploration is being conducted in the Qibei sub-sag, with estimated resources of 6.5×10^8 t (Zhao et al., 2021). The Qibei slope is located at the southwestern margin of the Qikou Sag, which is sandwiched between the Binhai fault in the north and the Nandagang fault in the south. The tectonic evolution is characterized by strong subsidence in the early stages and depression in the late stage. The Qibei Sag was impacted by the Yanshan movement, and the Nandagang fault and the Binhai fault started to move at the end of the Mesozoic. The NW-SE trending extension changed the sag structurally during the deposition of the third member of the Shahejie Formation. Large-scale and intense rifting occurred (Li et al., 2011), and several NE-NNE trending faults began to form.

Simultaneously, a number of positive structures, such as the Beidagang and Nandagang buried hills and the Yangsanmu uplift, were formed at the periphery of the sub-sag. Affected by the positive structure and early synsedimentary faults, a dustpan-shaped fault depression was formed at the base of the coastal fault. A multi-level sedimentary slope-break belt was created from the Yangsanmu uplift to the northeast Qibei Sag-Qikou main Sag, and there are few secondary faults and fold structures in the sub-sag (Miao et al., 2022). The first sub-member and the first member of the Shahejie are comprised of fine-grained sedimentary rocks composed of dark mudstone, oil shale, and organic-rich shale. The target layer of this study is the first sub-member of the third member of the Shahejie Formation; the thickness of the target layer in the study area is 200–350 m (Fig. 1). The overall lithology is relatively fine and is dominated by black shale and black-dark gray massive mudstone, with thin layers of gray dolomite and dark-gray to gray siltstone. The semi-deep to deep water depositional environment has been relatively stable (Han et al., 2021).

3. Samples and methods

A vertical well (F39x1) drilled through the third member of the Shahejie Formation in the Qikou sub-sag was selected for sampling and cored. We analyzed the 29-m long core to observe and describe the natural fractures in detail. We considered four aspects in the characterization of the fractures, focusing on bed-parallel fractures: fracture density, aperture, morphology, and filling. The shale in this section is characterized by bedding planes. The number of fractures (ratio of the matrix to the fracture) was measured by counting and averaging the number of different fracture types intersecting two parallel lines running through the core in the longitudinal direction. The length of the section was 1 m, and we measured the number of bed-parallel fractures in each lithology interval. The ratio of these two was defined as the bedding fracture density (Fig. 2).

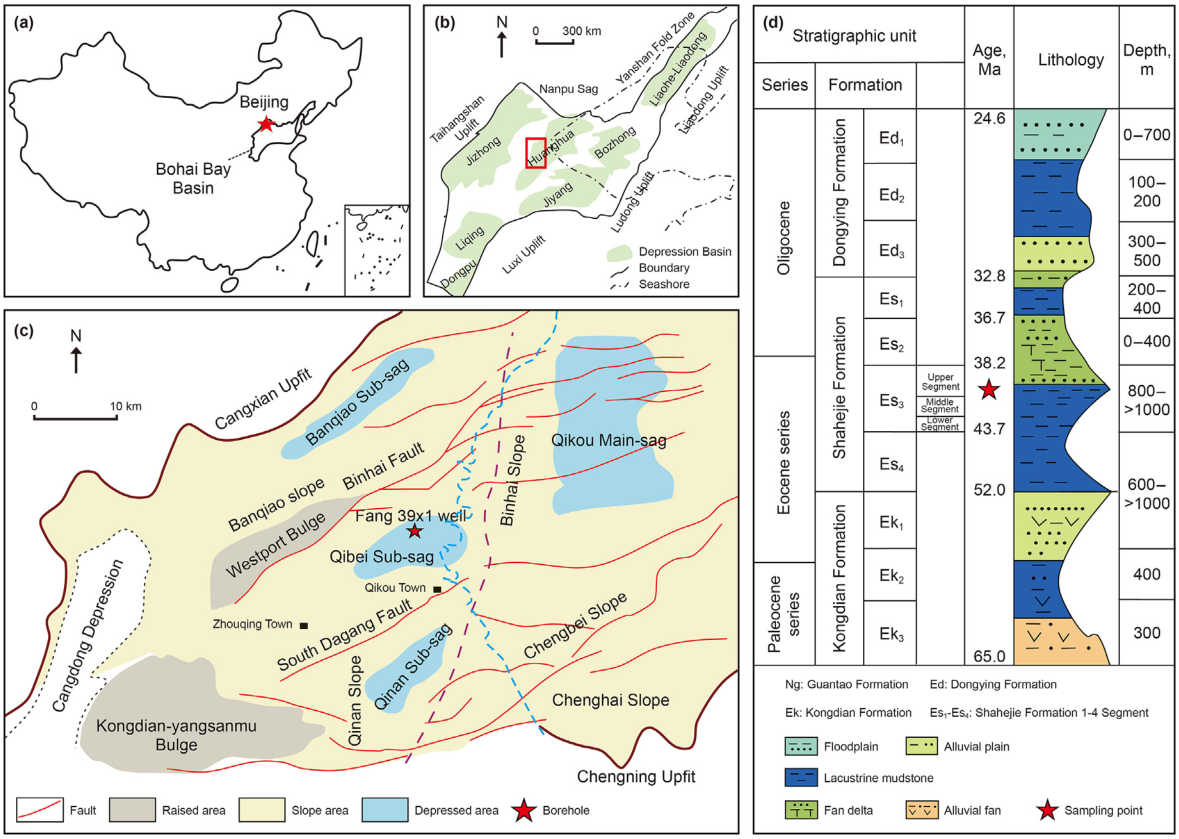


Fig. 1. Regional geological overview of the study area. (a) Regional tectonic location of the Bohai Bay Basin. (b) The distribution of sags in the Bohai Bay Basin. (c) Structural outline of the Qikou Sag. (d) Stratigraphic column of the Qikou Sag.

A feeler gauge was used to measure the fracture aperture in the core on a macroscopic level, and software was used to measure the microscopic fracture aperture based on the thin-section observation. The fracture morphology and filling materials observed in the cores and thin sections were recorded to determine the discontinuity, branching, bending, filling, and dissolution state of the bed-parallel fractures (Cobbold and Rodrigues, 2007; Bons et al., 2012; Cobbold et al., 2013; Lander and Laubach, 2015; Zeng et al., 2022). It should be noted that, as the fracture aperture increases, the core is retrieved from the well due to the unloading of the overburden pressure. However, we believe our results can reflect the development degree of the subsurface fractures (Lyu et al., 2017; Gong et al., 2019; Gasparrini et al., 2021).

We performed X-ray diffraction (XRD), micro-computed tomography (CT), and scanning electron microscopy (SEM) and measured the total organic carbon (TOC) content. A total of 55 samples were collected from the core that was retrieved from Well Fang 38X1 for the analysis. A total of 20 samples were used for XRD analysis and the TOC measurement. The samples covered the entire interval. They were numbered sequentially from the bottom to the top, and the sampling interval was about 0.3 m. The XRD results were used to examine the lithology in the well. Another 20 samples were selected from the JY-A well at a depth of about 10,000 m for thin section preparation perpendicular to the bedding plane. The thin sections (2 cm × 2 cm) were stained with a blue resin. Three samples were used for SEM, and four samples with different lithofacies were used for micro-CT.

We identified the sedimentary structures in the coring section to determine the controlling factors of fracturing. Bedding layers visible to the naked eye and smaller than 1 cm are generally referred to as laminae; however, we did not observe any bedding structure larger than 3 cm. The combination of the XRD data and core observations enabled us to identify and separate the core into different lithofacies.

4. Results

4.1. Types of shale lithofacies

There is a negligible difference in the shale lithofacies deposited in the deep to semi-deep lacustrine environment in the entire interval. However, scholars have developed different methods to identify these differences (Loucks and Ruppel, 2007; Liang et al., 2018), including the rock composition, structural features, organic matter abundance, and carbonate lithofacies and their origins (Lazar et al., 2015; Ran et al., 2016; Liu et al., 2017). However, we consider two major factors to separate the lithofacies and determine the relationship between the lithofacies and the fractures: the fracture aperture, the lithofacies type, and their interactions. Hence, the fine-grained diamictite in the Es_3 Formation can be categorized into 5 types: laminated shale, layered shale, massive mudstone, massive calcareous mudstone, and massive siltstone (Fig. 3).

4.2. Mineralogical characteristics of shale

The mineral components of the shale samples from Well F39x1 are mainly siliceous minerals, clay minerals, and calcareous minerals; their amounts differ for different lithofacies. The quartz + feldspar content is less than 50 wt%, the calcium mineral

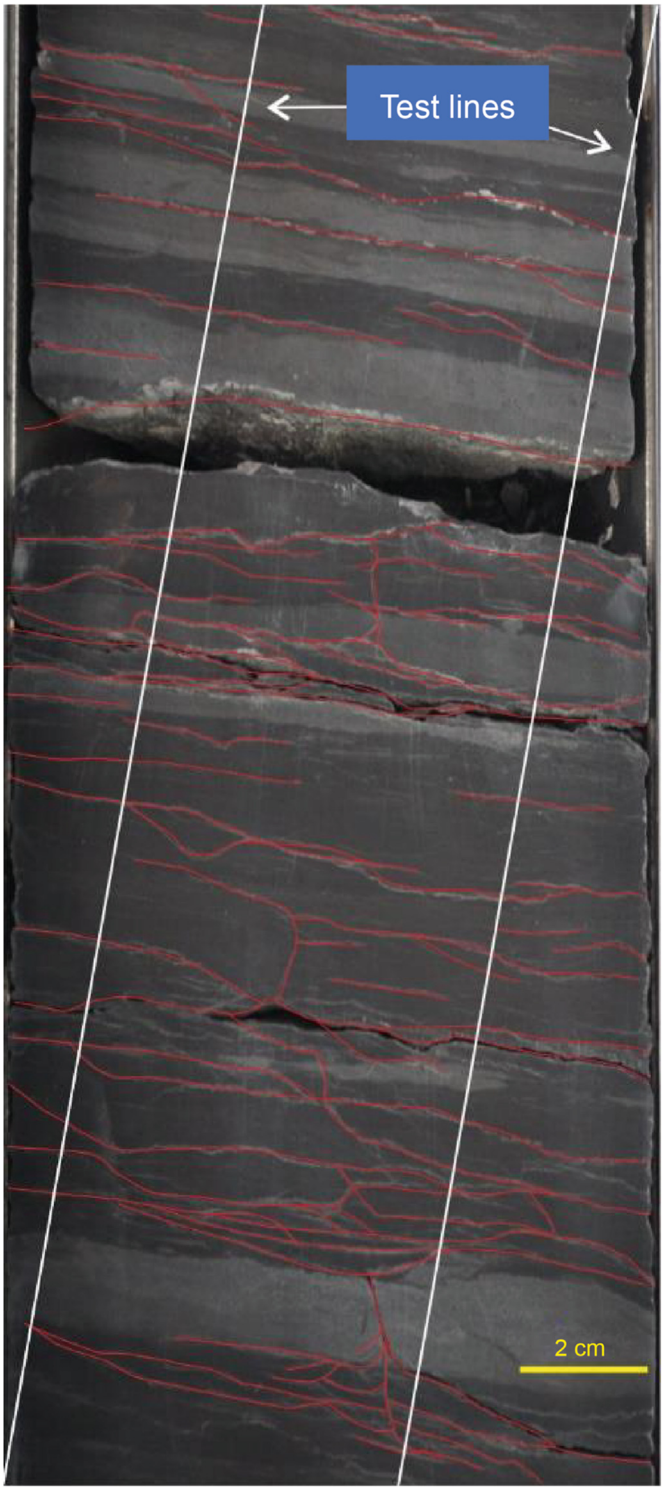


Fig. 2. Fracture description method.

content is less than 25 wt%, and the clay mineral content is in the range of 20–40 wt%. The mineral composition of the layered shale facies is dominated by quartz + feldspar, whose content is 40–50 wt%. The content of calcium and clay minerals is higher than 50 wt %, and that of clay minerals is 30–40 wt%. The mineral composition is dominated by quartz + feldspar, followed by clay minerals and carbonate minerals. The massive mudstone is abundant in quartz + feldspar minerals with more than 50 wt%, followed by the clay minerals and carbonate minerals. Finally, the massive calcareous mudstone minerals are low in quartz, mainly carbonate with more than 30 wt% and more than 50 wt%. Next is the massive siltstone facies with >50 wt% of quartz + feldspar content and low contents of clay minerals and carbonates (Fig. 3). The average content of quartz and feldspar shale in the upper part of Es_3 in the entire well section is 44.3 wt%; the highest content is 56.9 wt%, and the lowest is 34.4 wt%. The average clay content is 32.2 wt%, with the highest value of 40.7 wt% and the lowest value of 16.8 wt%. Finally, the average carbonate content is 21.3 wt% with the highest value of 59.4 wt% and the lowest value of 7 wt% (Figs. 7 and 8).

4.3. TOC content

All shale samples have a high TOC content, with an average value of 1.05 wt%. Among all lithofacies, the TOC content of the lamellar shale is the highest, ranging from 0.9 to 2.5 wt%, with an average value of 1.5 wt%. The overall TOC content of the layered mudstone is 0.5–2.4 wt%, with an average of 1.2 wt%. The TOC content of the massive mudstone is relatively low at 0.2–1.2 wt%, with an average of 0.76%, and the organic carbon content of the massive carbonate lithofacies is similar to the massive mudstone: 0.2–1.0 wt% with an average of 0.68 wt%. The siliceous lithofacies have a low organic carbon content of 0.4–1.0 wt%, with an average of 0.65 wt% (Figs. 7 and 8).

4.4. Types and characteristics of natural fractures

Most fractures in the reservoir are naturally occurring and discontinuous. They formed due to structural deformation or stress perturbation (Nelson, 2001). The main natural fractures of the Bohai Basin are high-angle structural and bed-parallel fractures; the former group can be separated into shear and tensile fractures depending on the development mechanism and features.

(1) Structural fractures

Structural fractures refer to natural fractures formed due to structural deformations (Zeng et al., 2008, 2020; Nelson, 2001). The statistical results from the core samples show that the fractures in the study area are primarily shear fractures. These fractures are smooth and widely distributed. The shear fractures have large angles (60°–80°) and are 10–20 cm long (Fig. 4a). The filling degree of the fractures is low with a large aperture (>100 μm), serving as major flow conduits for the vertical migration of hydrocarbons.

It is easy to distinguish between tensile and shear fractures based on their characteristics. The tensile fractures are less developed and nearly vertical, with inclination angles of 70°–90°. The fracture length is significantly lower than that of the shear fractures (3–10 cm), and the crack opening is typically larger than 100 μm (Fig. 4b). Moreover, tensile fractures are small and attributed to the enrichment (generation and expulsion) of shale oil.

(2) Bed-parallel fractures

Bed-parallel fractures refer to fractures formed by the separation of layers along the lamination and weak planes during various diagenetic processes. Diagenesis includes mechanical compaction, water loss shrinkage, dissolution, organic matter thermal maturation, and fracturing (Tian et al., 2020). The core observations show that the bed-parallel fractures are generally parallel or approximately parallel to the layers and exhibit bending, discontinuity, branching, and pinching along the bedding planes. Based on the length of the bed-parallel fractures, those that developed between the calcareous laminae and the clay and silt layers are large (cm-

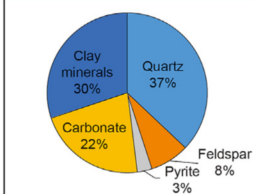
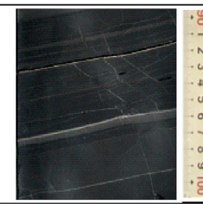
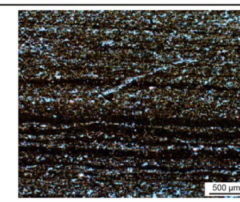
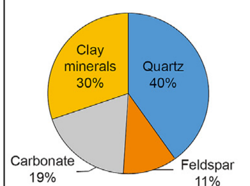
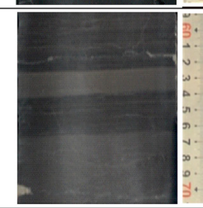
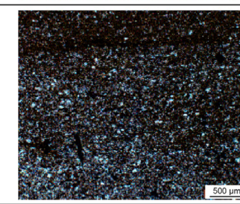
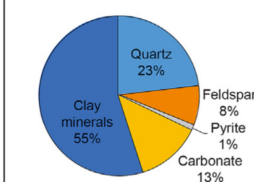
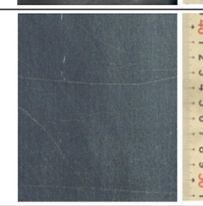
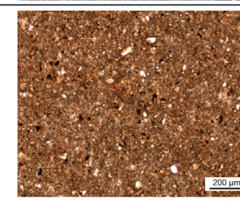
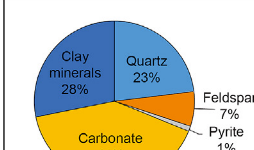
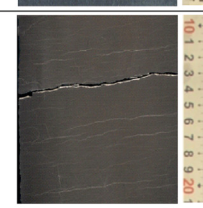
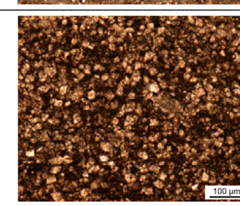
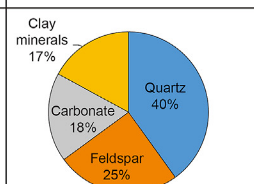
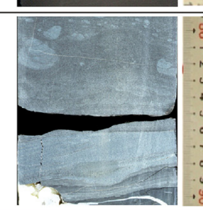
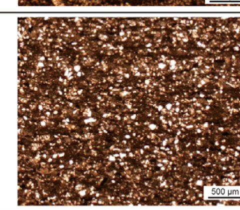
Lithofacies	Characteristics	Pie chart	Core photo	Photo under the microscope (single polarized light)
Laminated shale	Dark organic matter and clay laminae are well developed, thickness<1 cm, felsic>40%, clay<30%			
Layered shale	Interbedded light gray mudstone and dark gray shale, single layer thickness greater than 1 cm, felsic >50%, clay<30%			
Massive mudstone	Light grey-grey block, laminae not developed, felsic content⩾50%			
Massive argillaceous carbonate rock	Yellow-gray massive, undeveloped laminae, carbonate rock content >25%, developed micrite powder crystal dolomite			
Massive siltstone	Dark gray layered, felsic content>50%, low clay content			

Fig. 3. Lithofacies division method of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin.

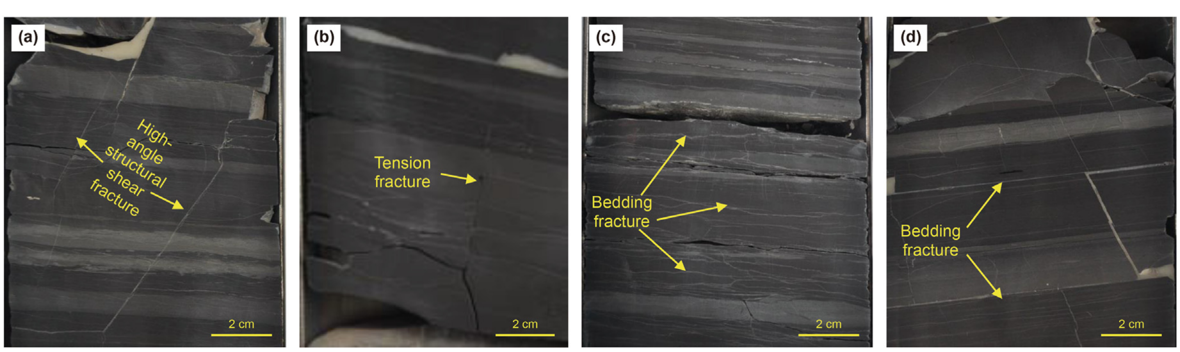


Fig. 4. Photos of fractures in shale cores of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin; (a) High-angle structural shear fracture (Well Fang39x1, Sha3 Member, 3897.4 m); (b) Tension fracture (Well Fang39x1, Sha3 Member, 3898.1 m); (c) Densely developed bedding fractures, with calcite full filling (Well Fang39x1, Sha3 Member, 3989.5 m); (d) The bedding fracture intersects with the high-angle structural fracture (Well Fang39x1, Sha3 Member, 3989.5 m).

decimeter), continuous, and have a large aperture of tens of microns (40–100 μm). In contrast, the bed-parallel fractures inside the organic laminae are generally short (10–40 μm), discontinuous, and not straight (Figs. 4c,4d,5a–5d,6). The development of bed-parallel fractures provides large amounts of space for the enrichment of the shale and improves the lateral permeability of the shale

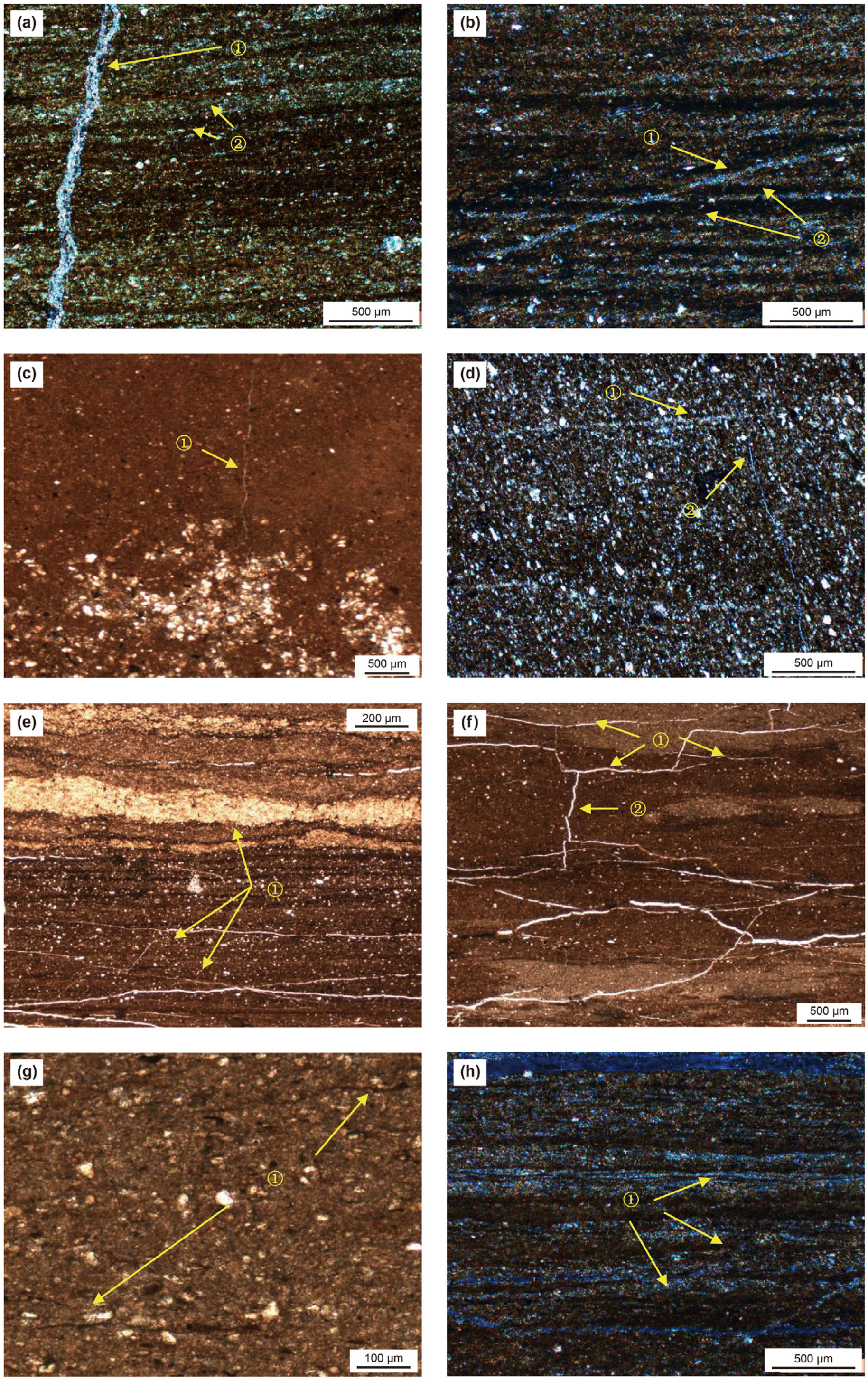


Fig. 5. Photographs of fractures in the shale thin section of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin. (a) High-angle structural fracture, single polarized light (Well Fang39x1 3898.83 m). ①Structural fractures intersecting with bedding fractures at a high angle, unfilled. ②Dedding fracture. (b) Intersecting bedding fracture, crossed polarized light (Well Fang39x1 3898.02 m). ①Structural fractures intersecting with bedding fractures at low angles. ②Dedding fracture. (c) High-angle structural fracture, single polarized light (Well Fang39x1 3892.5 m). ①Structural fractures intersecting with bedding fractures at a high angle, unfilled. (d) Intersection of bedding fractures and high-angle structural fractures, single polarized light (Well Fang39x1 3895.02 m). ①Bedding fracture. ②Structural fractures intersecting with bedding fractures at a high angle, unfilled. (e) Bedding fracture, single polarized light (Well Fang39x1 4381.5 m). ①Bedding fracture (Well Fang39x1 4381.5 m). (f) Complex fracture networks (Well Fang39x1 4379.45 m). ①Bedding fracture, single polarized light. ②Tension fracture. (g) Bedding fracture, single polarized light (Well Fang39x1 3899 m). ①Bedding fracture. (h) Bedding fracture, single polarized light (Well Fang39x1 3897.2 m). ①Bedding fracture unfilled.

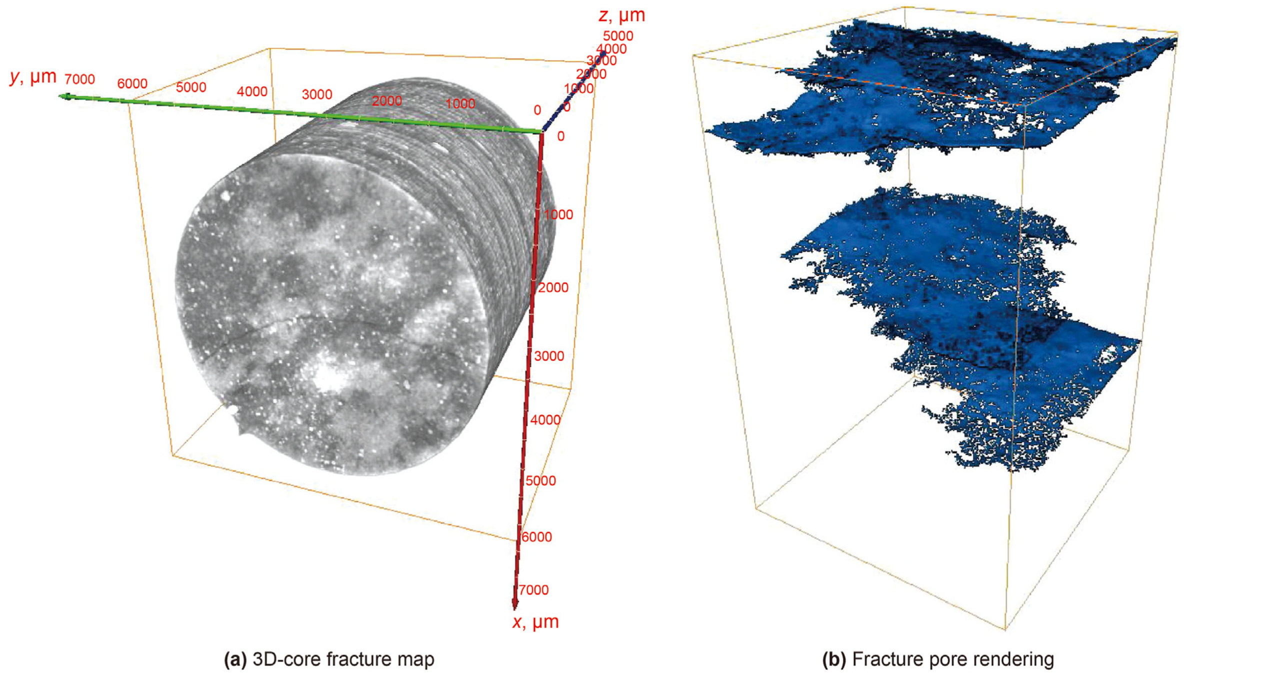


Fig. 6. Shale of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin. (a) Core column sample; (b) 3D distribution characteristics of bed-parallel fractures.

reservoirs. In addition, bed-parallel fractures can also intersect with high-angle structural fractures to form a fracture network (Fig. 5e–h), substantially enhancing the connectivity of the shale reservoirs.

4.5. Fracture density

We conducted core observations and descriptions at depths of 3890~3900 m and 3982–3999 m in the Well Fang 39X1 to understand the density and other characteristics of the structural and bed-parallel fractures in the study area. The statistical results show that the development degree of the natural fractures increases with the depth. i.e., they are less developed at the shallower strata. The bed-parallel fractures are more developed than the structural fractures, and their development degree increases with an increase in depth. The 3890–3900 m section has a fracture density of 20–80/m, with an average of 57.81/m. The bedding fracture density is 10–75/m, with an average of 46.72/m. It should be noted that structural fractures are also well-developed in this section. The development degree is significantly lower than that of the bed-parallel fractures, and the fracture density is between 5 and 25/m, with an average of 12.95/m (Fig. 7). The fractures in the 3982–3999 m section are more developed than those in the 3890–3900 m section, and the fracture density increases from 20/m at the bottom to 250/m at the top, with an average value of 46.72/m. The structural fractures are less developed than the bed-parallel fractures, and their average density of 14.14/m (Fig. 8).

4.6. The main controlling factors of shale fractures

The observation of fractures in the cores of the third member of the Shahejie Formation in the Qikou Sag confirms that the fractures exhibited high heterogeneity, with different development characteristics in different parts. We observe large differences in the development degree of fractures, even in the same well. These differences are attributed to the above-mentioned factors, such as lithofacies, mineral composition, organic matter content, and the number of laminae. However, the dominant factors differ for individual fractures.

4.6.1. Lithofacies

The mechanical property and strength of the lithofacies influence the development degree of fractures. Under the same stress conditions, a shale with a low Poisson's ratio and a high Young's modulus is more brittle and more likely to form structural fractures. The number of structural fractures is higher in sandstone than in shale (Zeng et al., 2020). The shale in the Es_3 Formation in the Qikou Sag of the study area is comprised of five different lithofacies: massive dolomite, massive siltstone, massive mudstone, layered shale, and laminated shale. The results demonstrate that the fracture density is the highest in the laminated shale (122.72/m), followed by the layered shale (110.75/m), siltstone (113.43/m), dolomite (100.49/m), and massive mudstone (88.44/m). The core observations show that bed-parallel fractures occur dominantly in the laminated shale. The average fracture density of the laminated shale is 124.78/m, that of the layered shale is 96.25/m, and that of the siltstone is 109.9/m. Moreover, the average fracture density of dolomite is 85.91/m, and that of the massive mudstone is 80.25/m on average (Fig. 9a). It is important to note that structural fractures are prevalent in siltstone. The average fracture density of the siltstone, layered mudstone, laminated mudstone, dolomitic shale, and massive mudstone is 23.97/m, 19.08/m, 16.82/m, 16.82/m, and 16.14/m, respectively (Fig. 9b).

4.6.2. Mineral composition

The mineral composition of the shale affects the mechanical properties and strength of the rock. The XRD data revealed that the shale of the third member of the Shahejie Formation in Qikou Sag is comprised of clay minerals, quartz, calcite, feldspar, pyrite and other minerals. We established a relationship between the mineral content and the natural fracture density in the well based on different lithofacies. The results show that the number of bed-parallel fractures and the quartz + feldspar content in the study area are generally positively correlated. The development degree of

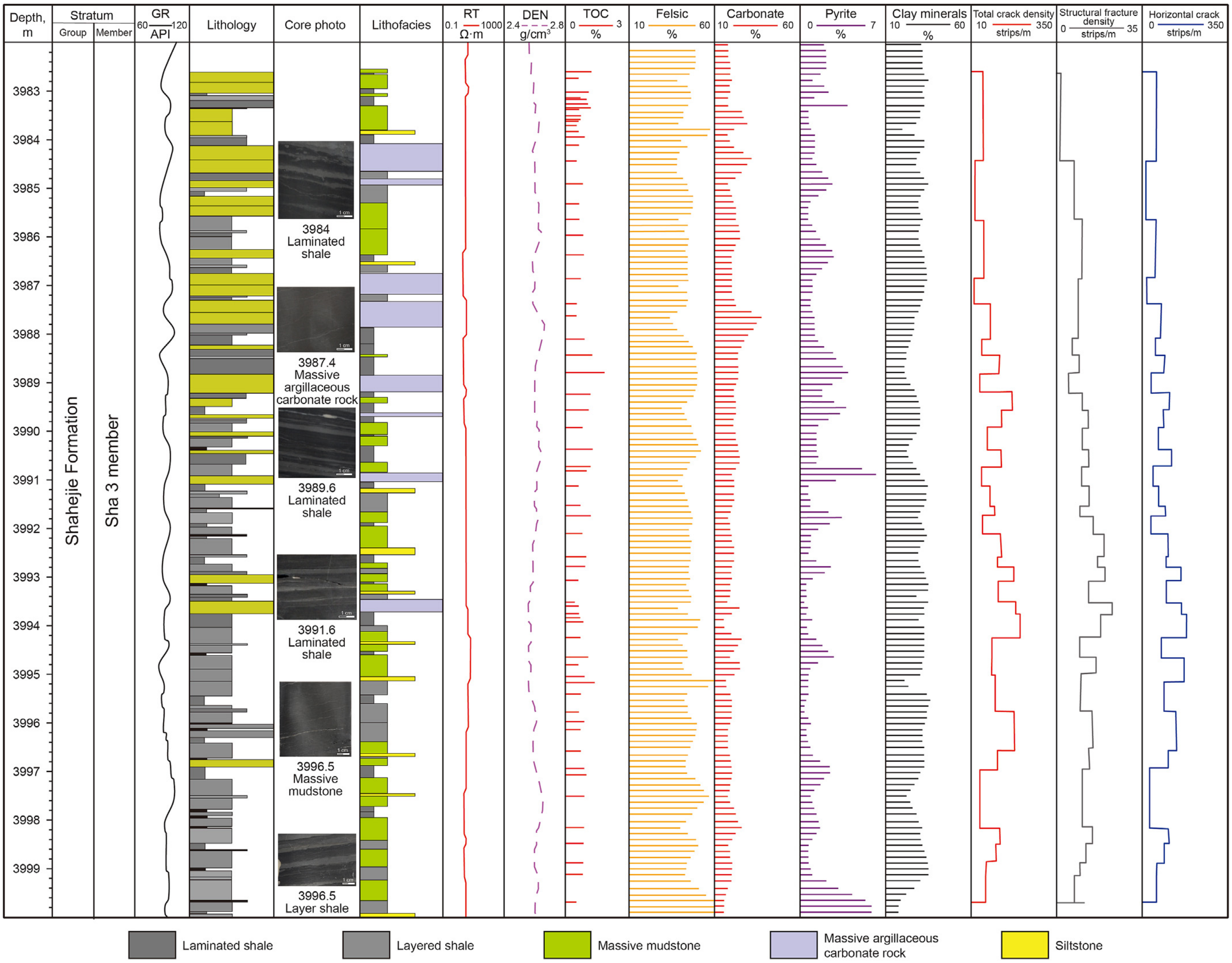


Fig. 7. Vertical distribution of lithology, TOC, mineral composition and fracture density in the 3890–3900 m depth section of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin.

the bed-parallel fractures is significantly higher when the quartz + feldspar content exceeds 35 wt%. Furthermore, the number of structural fractures is also positively correlated with the quartz + feldspar content at a content greater than 40 wt%, and the development degree is significantly higher at this content. Additionally, the structural fracture density is the largest (78/m) at a quartz + feldspar content of 45 wt% (Figs. 7,8,10a,10b). The quartz + feldspar content decreases with an increase in the depth from 3890 m to 3900 m, resulting in a significantly higher fracture density in the upper parts than in the lower parts of the formation (Fig. 7). In contrast, the quartz content in the 3982–3999 m depth range does not show any particular trend (Fig. 8).

The clay mineral content significantly affects the formation of bed-parallel fractures. Micro-fractures are formed when montmorillonite is transformed into illite during diagenesis, promoting the development of bed-parallel fractures (Li et al., 2022b). Our results indicate a positive correlation between the number of bed-parallel fractures and the clay mineral content in the study area. The number of bed-parallel fractures is significantly higher when the clay mineral content exceeds 25 wt% and reaches 330/m at a clay mineral content of 35 wt%. In contrast, the number of structural fractures in the study area is negatively correlated with the clay mineral content. It is significantly lower when the clay mineral content exceeds 25 wt% (Figs. 7, 8,10c,10d). The reason is that an increase in the clay content decreases Young's modulus and increases the Poisson's ratio, decreasing shale brittleness. It is well-documented that this change hinders the formation of structural fractures.

In general, higher pyrite and carbonate mineral contents promote fracturing in shale (Long et al., 2011; Ding et al., 2012). However, the comparison of the fracture parameters obtained from the core of the Es_3 shale in Qikou Sag shows that the degree of fracture development is not highly correlated with the pyrite and carbon mineral contents. The pyrite content in the study area is generally lower than 3 wt%, resulting in a negligible influence of the pyrite content on the fracture density (Fig. 10e and f). The thin section analysis (Fig. 5g) shows a low abundance of carbonate minerals. Areas with higher amounts of this mineral formed during the salinization period of the paleoenvironment. Thus, the lack of carbonate minerals has had a negligible effect on rock brittleness in the study area (Fig. 10g and h).

4.6.3. Organic matter content

The organic carbon content determines the hydrocarbon generation capacity of shale and controls the fracture developments.

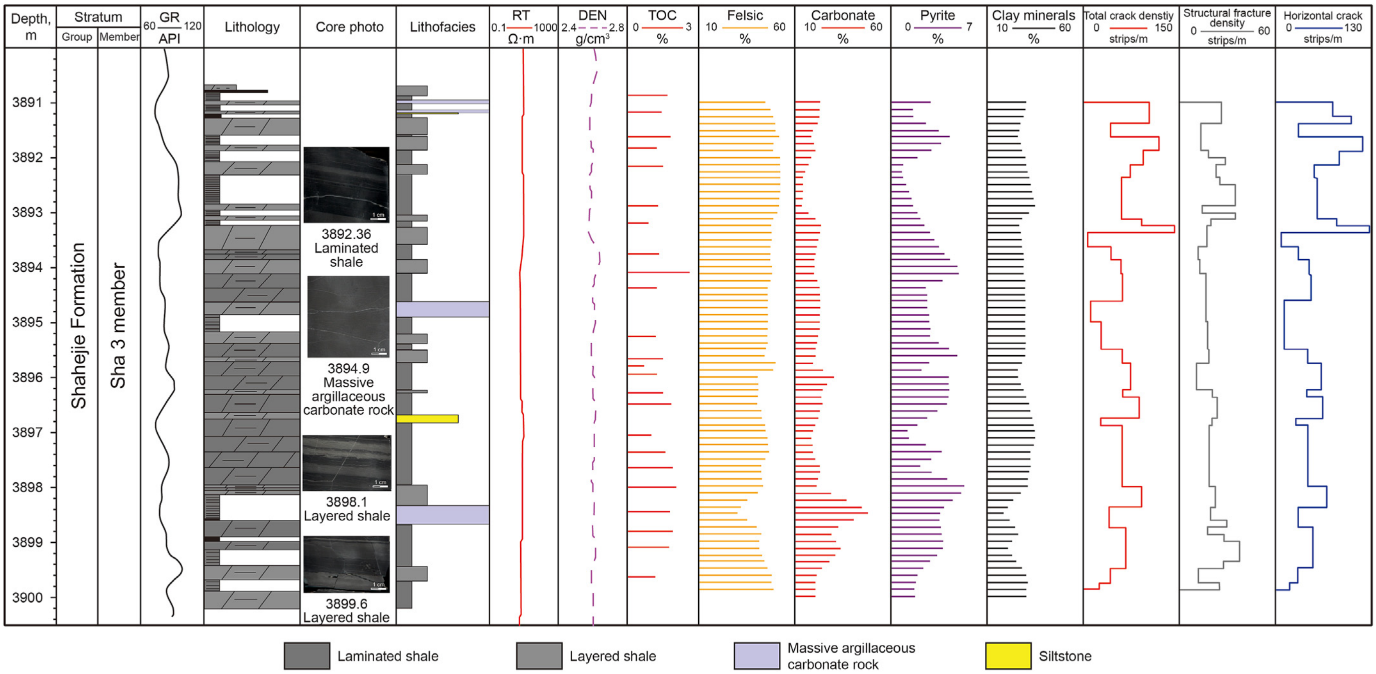


Fig. 8. Vertical distribution of lithology, TOC, mineral composition, and fracture density in the 3982–3999 m depth section of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin.

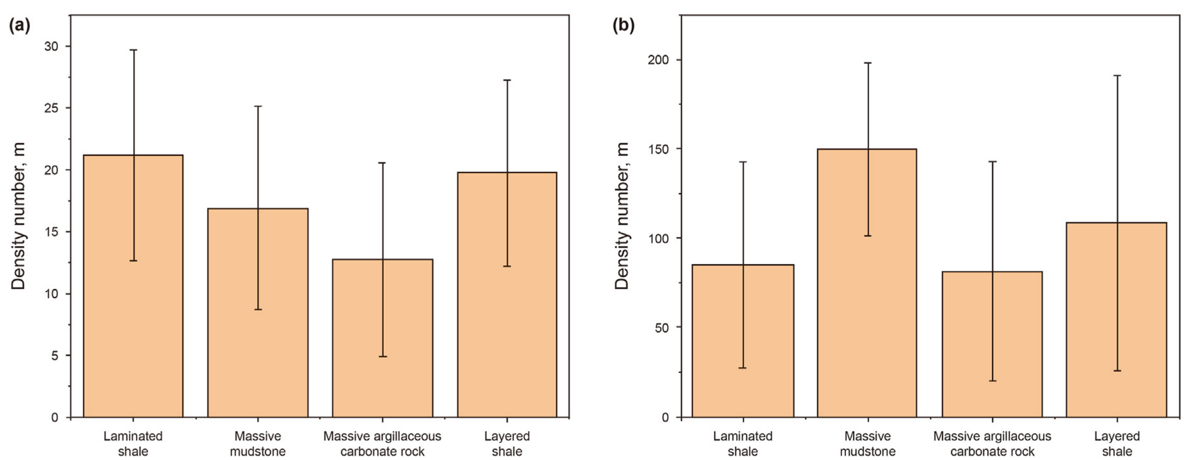


Fig. 9. Relationship between shale fractures and lithofacies in the third member of the Shahejie Formation in the Qikou Sag. (a) bed-parallel fractures; (b) Structural fractures.

Under the same geologic conditions, the mineralogical composition, mechanical properties, and organic carbon content substantially affect the fracture development in shale (Ding et al., 2012). During thermal evolution, organic matter generates large quantities of hydrocarbons, causing high fluid pressure. As the thermal evolution continues, a transformation occurs from oil generation to gas generation, and the effects of overpressure become more significant (Gao et al., 2005; Tian et al., 2020). Therefore, an increase in the fluid pressure can cause the Mohr circles to shift to the left, causing fracture initiation.

On the other hand, acid dissolution during organic matter maturation causes an increase in the bed-parallel fractures' aperture and improved connectivity. Therefore, the bed-parallel fractures are more developed in shale with a high organic matter content and a high degree of thermal maturation. A positive correlation is observed between the TOC content and the density of bed-parallel fractures at a TOC content of 0.5–1.2 wt%. The fracture density is significantly higher at a TOC content greater than 0.75 wt%. In contrast, the TOC content has a negligible effect on the number of structural fractures (Fig. 11).

4.6.4. The number of layers

Lamination refers to the smallest or thinnest layers that can be distinguished in sedimentary rocks. They formed during sediment deposition. A lamina is the smallest unit of bedding, and the thickness of a single layer is generally less than 10 mm. A large number of laminae exist in the lacustrine shale of the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin. Generally, the lamination has low mechanical strength and easily breaks and forms cracks when subjected to an external force. We observe a relationship between the number of laminae and the number of fractures. As the number of laminae increases, the density of the bed-parallel fractures and structural fractures increases, but the bed-parallel fractures are more sensitive to the

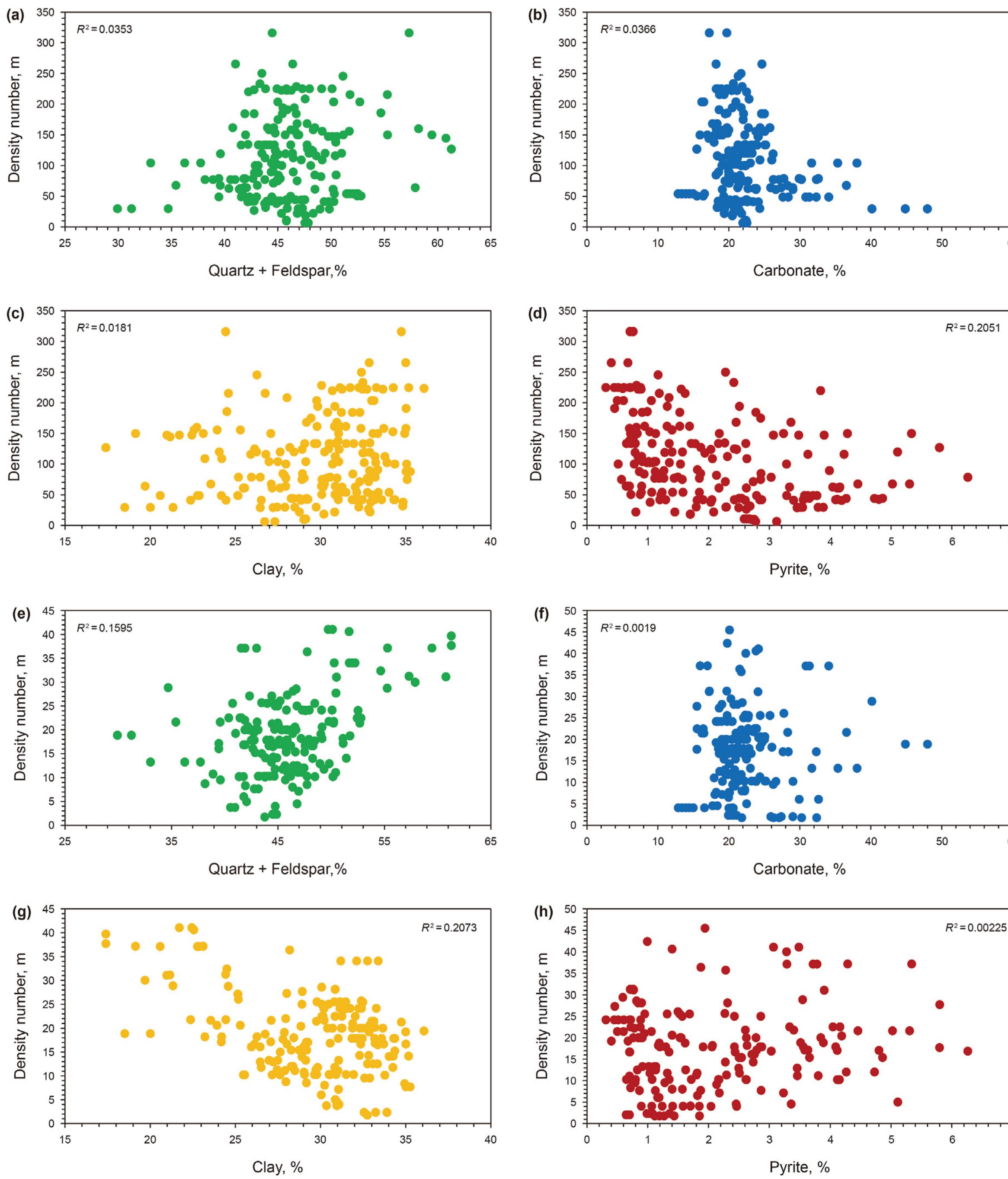


Fig. 10. Relationship between structural fractures and mineral composition of shale in the third member of the Shahejie Formation in the Qikou Sag (a, b, c, d are for bed-parallel fractures, e, f, g, h are for structural fractures).

number of laminae (the coefficient in the fitting equation is large) (Fig. 12).

5. Discussion

5.1. Influence of natural fractures on shale plays

Shale play exploration and development has confirmed that the enrichment and high production of plays is not only related to geological (high TOC content, high brittle mineral content, and high porosity) and engineering factors but also to the development degree of natural fractures (Guo et al., 2016; Liang et al., 2017). Adsorbed and free gas occur in the pores of lacustrine shale plays. Most of the gas in the organic, pyrite intercrystalline, and clay mineral intercrystalline pores is adsorbed, whereas free gas occurs in the other pore types in the matrix, including the bedding and structural fractures (Guo et al., 2016). Lacustrine shale has low permeability due to the low formation pressure and geothermal gradient and the high viscosity and density of adsorbed hydrocarbon fluids in the pores. Moreover, bed-parallel fractures and high-angle structural fractures represent connections, forming a fracture-pore network that substantially improves the storage capacity of shale and affects shale oil enrichment and shale permeability. Thus, the fractures enable the adsorbed fluids to move

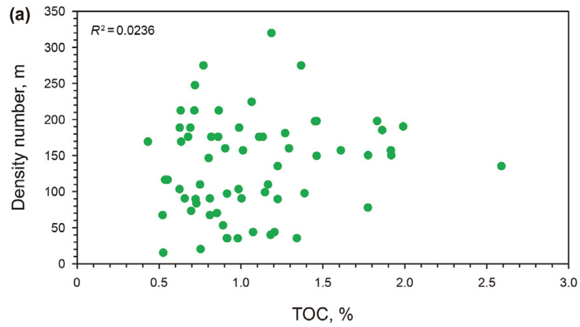


Fig. 11. Relationship between shale fractures and TOC in the third member of the Shahejie Formation in the Qikou Sag. (a) bed-parallel fractures; (b) Structural fractures.

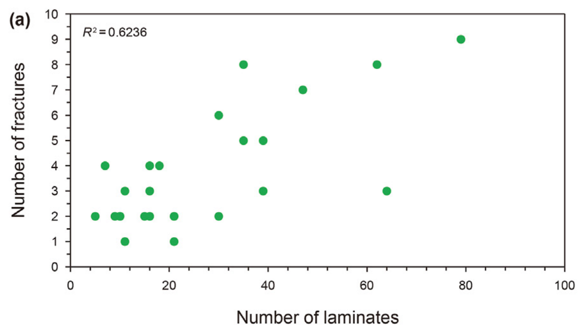


Fig. 12. Relationship between shale fractures and the number of laminae in the third member of the Shahejie Formation in the Qikou Sag. (a) Bed-parallel fractures; (b) Structural fractures.

freely, improving the flow and mobility of shale oil and its productivity. Therefore, natural fractures are critical for identifying sweet spots in lacustrine shale.

The mineral composition and structural features of the lacustrine shale strata are more complex in this study area than the marine shale in North America and the Upper Ordovician Wufeng Formation-Lower Silurian Longmaxi Formation (Long et al., 2017; Wang et al., 2017b; Jin et al., 2021) in the Sichuan Basin, China. The lacustrine shale originated from sediments moving from different directions into the lake, resulting in complex sedimentology. Furthermore, the lateral movement of the basin depocenter in different periods has resulted in frequent changes in the shale strata and rapid spatial changes in the lithofacies (Liu et al., 2019). In addition, the bedding fracture density differs significantly for different lithofacies and is the highest for the bedded shale (Fig. 13). The development of laminae and bedding increases the anisotropy of the shale, and the lowest tensile strength occurs in the vertical direction (Cosgrove, 1995, 2001; Lash and Engelder, 2005). Under the same external force, a shale with well-developed laminae and bedding is more likely to rupture and form bed-parallel fractures.

The main fractures in the laminated shale in the research area are bedding fractures occurring between the bedding interface or between minerals with significant differences in mechanical properties (such as the contact surface between organic matter and the surrounding rock). Layered shale has a lower bedding density than laminated shale, resulting in a lower density of bedding fractures and a higher density of structural fractures. The massive mudstone and massive calcareous mudstone do not exhibit extensive bedding, and the clay mineral content is high. The development density of fractures is low, and the development scale is small. They have the lowest fracture density of the five rock facies. The contents of brittle minerals (feldspar + quartz) in the massive siltstone and the number of structural fractures are high. Since the bedding is not well-developed, the mineral composition is relatively homogeneous, and the density of bedding fractures is low.

In addition, the organic matter content of the laminated shale and layered shale is generally greater than 1 wt%. The organic matter generates large quantities of hydrocarbons during the thermal evolution, which cannot be discharged in the shale system with low porosity and low permeability, causing excess fluid pressure. Studies have shown that the rock fails and fractures are formed along the shale's laminar interface or pre-existing micro-fractures and other weak planes when the pore fluid pressure exceeds 1.5 times the hydrostatic pressure (Kalani et al., 2015; Teixeira et al., 2017). Therefore, excess pore pressure during organic matter maturation promotes the formation of bed-parallel fractures in laminar and layered shales. In addition, laminar shale is well-developed in the horizontal direction. Laminae and high-angle fractures are created during hydraulic fracturing and connect to form a complex fracture network system. This process can free the adsorbed gas in the shale, improving the production of shale gas plays. In summary, shales with a high organic matter content and layered laminae have strong hydrocarbon generation and storage capacities; thus, they are self-sourced reservoirs. However, the organic matter content of massive shale is typically less than 0.75 wt%, and the density of bed-parallel fractures is low (< 50/m). Thus, the hydrocarbon generation and storage capacities of this shale type are generally low, and the structural fractures are the key factor influencing its storage capacity. Therefore, when structural fractures are well-developed, massive shale can be considered a good reservoir in laminar shale lithofacies. In this scenario, the hydrocarbons can migrate to the nearby massive shale lithofacies with relatively good reservoir properties, creating a relatively rich and prolific series of reservoirs. This type of shale oil is often considered a conventional reservoir or a source-reservoir separated type (Li and Zhu, 2020; Zhao et al., 2020).

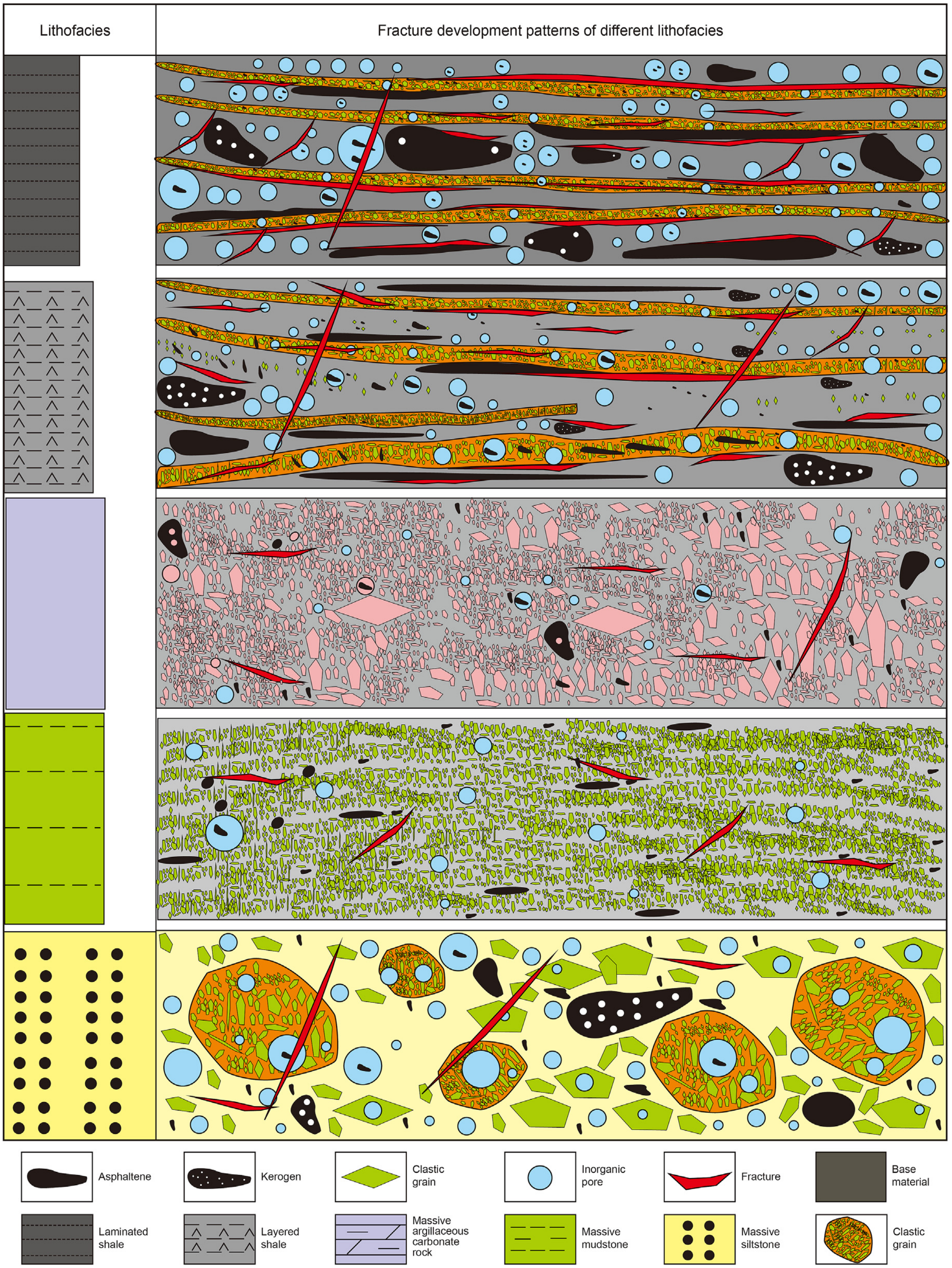


Fig. 13. The pore types in different lithofacies.

5.2. Effect of carbonate minerals on fractures

The brittle mineral content directly affects the mechanical properties of shale. Under the same external force, a higher content of brittle minerals promotes shale fracturing (Zeng et al., 2016). Minerals in shale include quartz, feldspar, calcite, dolomite, pyrite and clay, although there is no consensus on the definition of brittle minerals. Jarvie et al. (2007) considered quartz the only brittle component in shale in their study of the Barnett shale in North America. Rickman et al. (2008) analyzed statistical data of the

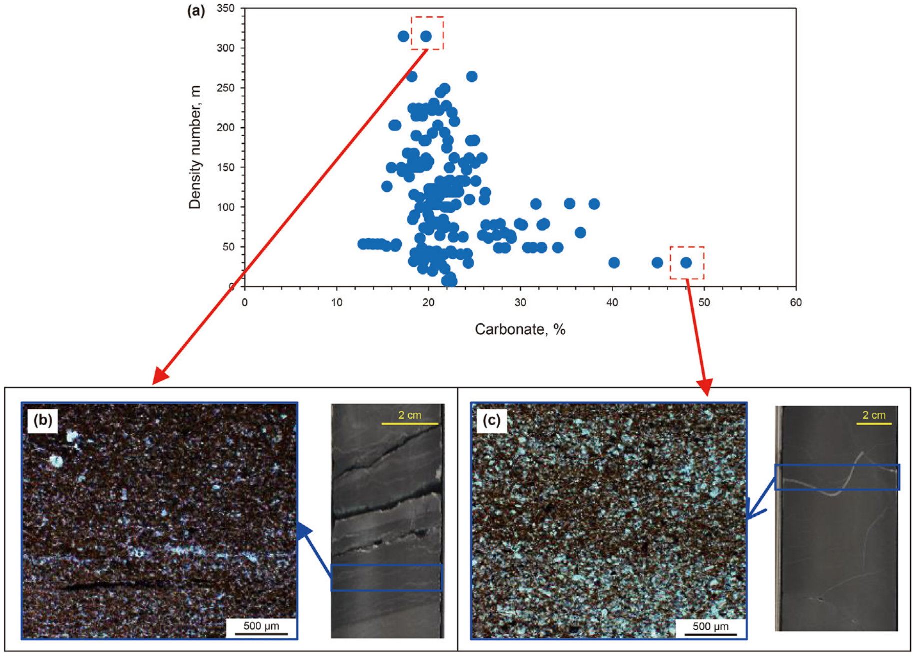


Fig. 14. Relationship between bedding fracture carbonate rock and bed-parallel fracture density (a); 3995.31 m optical thin film photo of Well Fang 39X1 (b); 3987.62 m optical thin film photo of Well Fang 39X1 (c).

Barnett shale and found that the brittleness increased with an increase in the quartz content and decreased with an increase in the clay content. The shale rich in carbonate minerals was moderately brittle. Matthews et al. (2007) summarized typical shale gas plays in North America and observed that carbonate rocks were more brittle than clay and quartz, which are brittle minerals. Scholars have concluded that quartz and carbonate minerals are the most important minerals affecting the brittleness of marine shale (Chen and Xiao, 2013; Li, 2013; Zeng et al., 2013; Labani and Rezaee, 2015; Rybacki et al., 2015, 2016; Lai et al., 2016; Wang et al., 2017a). However, the fracture parameters obtained from the core observations in this study indicate that the effects of the carbonate content on the number of fractures differ significantly for the lacustrine shale and the marine shale. Few bed-parallel fractures occur when the carbonate mineral content exceeds 35 wt%. The core data and thin section results show that massive mudstone has a high carbonate mineral content and low density of bed-parallel fractures. Thus, the effect of the carbonate mineral content on shale fracturing should be considered when evaluating brittle minerals in lacustrine shale (Fig. 14).

6. Conclusion

The third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin, contains many natural fractures in the lacustrine shale, including high-angle structural fractures and bed-parallel fractures. The shear fractures are long (10–20 cm), have a high dip angle and a low filling degree, and are generally open and conducive to fluid flow. They are critical channels for the vertical migration of shale oil and gas in the study area. The near-vertical fractures in the layers and the migration distance of the shale oil and gas along the fractures are short. Thus, the oil and gas enrichment of the shale occurs close to the source. A large number of bed-parallel fractures are parallel or approximately parallel to the layers and provide an adequate reservoir space for the enrichment of shale oil and gas, improving the lateral permeability of the formation.

The lithofacies, mineral composition, organic matter content, and the number of laminae affect the fracture density in the lacustrine shale in the third member of the Shahejie Formation in the Qikou Sag, Bohai Bay Basin. Structural fractures occur predominantly in siltstone, whereas bed-parallel fractures are more common in laminated shale. A higher quartz content corresponds to a higher content of brittle minerals, promoting fracture formation. In contrast, a higher clay mineral content results in a reduction in shale brittleness, which is not favorable for the formation of structural fractures. However, the clay mineral transformation contributes to the formation of bed-parallel fractures. A low content of pyrite and carbonate minerals in the study area has a negligible effect on the degree of fracture development. Excess pressure due to hydrocarbon generation in conjunction with acid dissolution can stimulate the formation of bed-parallel fractures. The number of bed-parallel fractures is significantly higher when the TOC content exceeds 0.75 wt%. In addition, as the density of laminae increases, the density of bed-parallel and structural fractures increases. Overall, the bed-parallel fractures are more sensitive to the number of laminae.

The organic matter content of the laminated shale and layered shale in the Qikou Sag, Bohai Bay Basin, is generally higher than 1 wt%, and bedding and structural fractures are well-developed. Overall, the shale play in the study area has high hydrocarbon generation and storage potential and can be considered a self-sourced reservoir. The organic matter content of siltstone, massive argillaceous carbonate rock, and massive mudstone is usually less than 1 wt%, and the hydrocarbon generation capacity of the shale is relatively low.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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