Research Article

Lamellation Fractures in the Paleogene Continental Shale Oil Reservoirs in the Qianjiang Depression, Jiangnan Basin, China

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Based on the data of cores, thin sections, well logs, and test experiments, the characteristics and main controlling factors of lamellation fractures in continental shales of the third and fourth members of the Paleogene Qianjiang Formation in the Qianjiang Depression, Jiangnan Basin, are studied. Lamellation fractures mainly develop along laminae in shales. They have various morphological characteristics such as straightness, bending, discontinuity, bifurcation, pinching out, and merging. Lamellation fractures with high density show poor horizontal continuity and connectivity characteristics. The average linear density of the lamellation fractures is mainly between 20 m^{-1} and 110 m^{-1} , and the aperture is usually less than $160\text{ }\mu\text{m}$. The density of lamellation fractures is related to their apertures. The smaller the apertures of lamellation fractures are, the higher the density is. The development degree of lamellation fractures is mainly controlled by mineral composition, type, thickness, density of lamination, contents of organic matter and pyrite, lithofacies, structural position, etc. Lamellation fractures develop well, especially under the conditions of medium dolomite content, large lamination density, small lamination thickness, and high total organic carbon (TOC) and pyrite contents. The influences of lithofacies on the lamellation fractures are complex. The lamellation fractures are most developed in carbonaceous layered limestone dolomite and carbonaceous layered dolomite mudstone, followed by stromatolite dolomite filled with carbonaceous pyroxene. The fractures in the massive argillaceous dolomites and carbonaceous massive mudstones are poorly developed. No fractures can be found in the carbonaceous dolomitic, argillaceous glauconites or salt rocks with high glauconite content. Structure is also an important factor controlling lamination fractures. Tectonic uplifts are beneficial to the expansion and extension of lamellation fractures, which increases fracture density. Therefore, when other influence factors are similar, lamellation fractures develop better in the high part of the structure than in the low part.

1. Introduction

Shale oil refers to the petroleum resource contained in shale [1, 2]. Oil usually exists in shale pores and natural fractures in the form of adsorption and free states [3, 4]. Natural fractures in shales include structural fractures, lamellation fractures, and fractures related to abnormal high pressure [5, 6]. Among them, lamellation fractures distributed along lamellation provide important reservoir spaces and flow channels, influencing the enrichment, the productivity of a single well, and the development effects of shale oil [7–9].

The research on the distribution rules of lamellation fractures is of great significance for the exploration and development of shale oil.

Some scholars have studied natural fractures in shales [10–12]. Natural fractures in shales can be divided into structural and nonstructural fractures, in which nonstructural fractures are mainly lamellation fractures. The previous works have evaluated and predicted structural fractures in shales by using cores, well logs, seismic data, and finite element numerical simulation methods [13–15]. Lamellation fractures, bedding fractures, bedding parallel fractures, and

interlayer fractures are natural fractures resulting from the fracturing of shale along or approximately parallel to the direction of lamellations [16–18]. Compared with other rocks, shales have significant layered sedimentary characteristics [19]. These sedimentary interfaces are natural weak interfaces in shale [20]. Under the mechanical compaction, pressure dissolution, acid fluid intrusion, or formation uplift, the fractures are easy to follow along these interfaces [21–23]. Besides, the local abnormal high pressure formed in the process of mature hydrocarbon expulsion of organic matter causes the vertical maximum principal stress of the formation to change from compression to tension [24, 25]. When the pressure breaks through the shale fracture strength, the lamellation fractures can be formed [26]. Due to the small scale of lamellation fractures, the controlling factors of lamellation fractures are still unclear and the prediction of the distribution rule of lamellation fractures is very difficult. Therefore, the studies of the development characteristics and control factors of lamellation fractures are important.

By taking the third and fourth members of the Paleogene Qianjiang Formation in the Qianjiang Depression, Jiangnan Basin as the target, based on cores, thin sections, image logging, and testing experiment data, the characteristics and main control factors of lamellation fractures are analyzed, and the formation mechanism of lamellation fractures is discussed in the paper. This study can potentially provide guidelines for understanding the development rule of lamellation fractures in continental shale oil reservoirs.

2. Geological Setting

2.1. Structure. The Jiangnan Basin, located in the middle of the Yangtze Plate, is a faulted basin formed under the background of tectonic extensions from Cretaceous to Paleogene [27]. The Qianjiang Depression is in the middle of the Jiangnan Basin, with an area of 2530 km², which is the main depression generating hydrocarbon in the Jiangnan Basin [28, 29]. The northwest of the Qianjiang Depression is bounded by the Qianbei fault, and the other three directions of the Qianjiang Depression are uplift (Figure 1). The NE-SW normal faults are commonly developed in the Qianjiang Depression. In addition, a few small-scaled normal faults of E-W, N-S, and NW-SE directions exist.

2.2. Stratigraphy. The Cretaceous, Paleogene, Neogene, and Quaternary strata exist in the Jiangnan Basin (Figure 2). The Paleogene is a typical continental salt lake basin. The corresponding climate, lake level, and water salinity change rapidly and periodically, making a very thick salt layer deposited in the basin [30–33]. The Paleogene Qianjiang Formation is the main salt-bearing strata, which can be divided into four members and then further subdivided into 193 rhythmic salt layers whose thicknesses are from several meters to tens of meters [34].

The third and fourth members of the Qianjiang Formation are the main reservoirs of shale oil exploration due to the rich organic matters and high oil content. Hence, the

two members are selected as the key strata in this paper. In the third and fourth members, salt rocks and shales are well interbedded. Based on organic geochemical analyses, the intersalt shale has a good capacity to generate hydrocarbons, and the total oil production is more than 40×10^8 t [35].

The thickness of the fourth member is large, ranging from 178 m to 2218 m. The lithology of the fourth member of the Qianjiang Formation consists of dark grey oil shale, glauberite-filled dolomitic mudstone, salt rock, etc. In the lower part of the structure, the lithology is mainly shale. In the upper part, in addition to a large amount of shale, there are some siltstone and fine-grained sandstone.

The thickness of the third member of the Qianjiang Formation is between 150 m and 640 m. This member can be divided into 14 rhythmic layers. The main lithology is dark gray and brown gray intersalt shales. Siltstones and argillaceous limestones appear in the upper section of this member.

Due to the barrier of salt layer, it is difficult for oil and gas to migrate vertically but can migrate horizontally. After the migration, the remaining oil and gas are retained in shales, which results into a multilayered intersalt shale reservoir. This kind of reservoir is quite important for the oil and gas exploration in the Qianjiang Depression [36–39].

2.3. Reservoir. The Paleogene Qianjiang Formation is the main source rock of the Jiangnan Basin. Based on the core analysis of 256 samples, the lithology of intersalt reservoir mainly includes mudstones, shales, argillaceous dolomites, dolomitic mudstones, and glauberite-filled dolomitic mudstones. The X-ray diffraction (XRD) analysis of 315 samples indicates that minerals mainly include clastic minerals, carbonate minerals, and salt [35]. For clay mineral, illite is the main component with a content range from 60% to 82% and the average value of 72%. The illite/smectite mixed layer is the second major component in the clay minerals with a content range from 10% to 40% (average 27%). No kaolinite can be found in clay mineral. The ratio of clay minerals generally corresponds to the arid paleoclimate and the salt lake water rich in K⁺. For carbonate mineral, dolomite is the main component with an average content of 35%. The content of dolomite varies greatly in different depths due to the changes of sedimentary microfacies. For salt rock, glauberite is the main component with an average content of 25% [35]. Besides, the lithology also contains a small amount of quartz, feldspar, pyrite, and other clastic rock minerals and authigenic minerals.

The scanning electron microscope (SEM) analysis of 315 thin sections indicates that the reservoir space includes dolomite intergranular pore, glauberite intergranular pore, dolomite dissolution pore, glauberite dissolution pore, and fracture. Among them, the ratio of porous reservoir is about 36%, and that of fractured reservoir is 64%. This means that natural fractures provide the main reservoir space in shale reservoirs of the Qianjiang Formation. The core analysis of 256 samples shows that the range of porosity is between 8% and 18% in the third and fourth members of the Qianjiang Formation with the average value of 14.3%. Typically, porosity is directly positively proportional to dolomite content and

FIGURE 1: The structure of the Qianjiang Depression in the Jiangnan Basin. 1: Zhijiang Depression; 2: Yajiao Uplift; 3: Chentuokou Depression; 4: Tonghaikou Uplift; 5: Qianjiang Depression; 6: Chenhu Uplift; 7: Xiaoban Depression; 8: Tianmen Uplift; 9: Longsaihu Uplift.

inversely proportional to glauberite content. In the target formation, the permeability of the shale reservoir permeability ranges between 0.08 mD and 925 mD with the average value of 43.4 mD. The permeability varies widely due to natural fractures in reservoirs [4].

3. Characteristics of Lamellation Fractures

Lamellation fractures refer to the natural fracture formed during sedimentation and diagenesis, which are distributed along the lamellation planes [9]. Based on observations of 1300 m cores and 725 thin sections from 8 wells, the lamellation fractures are mainly developed along the shale laminae

and are nearly parallel to the arrangement direction of plastic minerals with the inclinations of the lamellation less than 10° . Lamellation fractures have various morphological characteristics such as straightness, bending, discontinuity, bifurcation, pinching out, and merging (Figure 3). The horizontal continuity and connectivity of lamellation fractures are usually poor. The margins of the most lamellation fractures are indistinct and have obvious dissolution. According to the core statistics, the linear density of the lamellation fractures mainly ranges between 30 m^{-1} and 110 m^{-1} (Figure 4) and about 27.2% of lamellation fractures are filled mainly by glauberite. The observation results of thin sections show the apertures of the lamellation fractures are generally less than

FIGURE 2: Stratigraphic column in the Qianjiang Depression (modified from Bai et al., 2014).

160 μm . The density of lamellation fractures shows a negative exponential function relation with the aperture. The larger the density of lamellation fractures have, the smaller the aperture is (Figure 5).

4. Influencing Factors of Lamellation Fractures

According to the analysis of cores, thin sections, and imaging log data, the development degree of lamellation fractures is

FIGURE 3: Distribution characteristics of lamellation fractures in the Paleogene shales in the Qianjiang Depression. (a) Casting thin section at depth of 1629.6 m from WY11 well. (b) Casting thin section at depth of 1559.3 m from WY11. (c) Scanning electron microscope at depth of 1491.2 m from WY10-6 well. (d) Scanning electron microscope at depth of 1746.7 m from WY11 well.

FIGURE 4: Density distribution of lamellation fractures in the Qianjiang Depression ($N = 828$).

related to organic content, mineral components, texture and structure of lamina and structural position, etc.

4.1. Organic Content. The development of lamellation fractures is closely related to organic matter [40]. The organic matter of the target layer has undergone sufficient evolution and is basically in the mature stage [41]. The vitrinite reflectance (R_o) of the third member of the Qianjiang Formation shales ranges from 0.50% to 0.88%, and the R_o of the fourth member is between 0.55% and 1.30%. The density of lamellation fractures in marine shales is closely related to the content

of organic carbon [9, 14]. Similarly, the density of lamellation fractures in continental shales is also positively correlated with the TOC content. The higher the TOC content is, the higher the density of lamellation fractures is (Figure 6).

In the process of organic matter maturation and hydrocarbon expulsion, the formation of a large number of hydrocarbons will increase the pore fluid pressure which leads to local abnormal high pressures [41–44]. These local abnormal high pressures can make the weak mechanical discontinuities preferentially crack to form lamellation fractures. The higher the TOC content in shales is, the more fluid is produced in

FIGURE 5: Relationship between density and aperture of lamellation fractures in the Qianjiang Depression.

FIGURE 6: Relationship between density of lamellation fractures and TOC content in the Qianjiang Depression.

FIGURE 7: Relationship between density of lamellation fractures and pyrite content in the Qianjiang Depression.

the hydrocarbon generation process, and subsequently, the higher the development degree of foliation fractures is. Therefore, the lamellation fractures often appear in areas with rich organic matters. The formation environment of lake facies rich in organic matters is similar to that of pyrite [45]. High organic matters could indicate high pyrite in the Qianjiang Formation [46]. From this study, Figure 7 shows that the density of the lamellation fractures increases with the increasing pyrite content, indicating that for the target area, pyrite can also be the indicator for the evaluation of the lamellation fractures.

FIGURE 8: Relationship between density of lamellation fractures and dolomite content in the Qianjiang Depression.

4.2. Mineral Components. The density of lamellation fractures is closely related to the mineral components in shales. Shales mainly consist of clastic minerals, salt rock minerals, and carbonate minerals. Among them, dolomite is the most important brittle mineral in shales. According to the statistics results from thin sections, the density of the lamellation fractures is related to the content of brittle minerals (e.g., dolomite). For example, the fracture density is the largest when dolomite content is about 50% in the study area. When focusing on the range of dolomite content between 0 and 50%, it is shown that the higher the dolomite content is, the more lamellation fractures develop. Due to the increase in dolomite content, the brittleness of shale is improved, and shale is more likely to fracture. When the content of the dolomite is greater than 50%, the degree of development of the lamellation fractures will decline accordingly. Higher dolomite content means a drier sedimentary environment, which is not conducive to the enrichment of organic matter. Even if the organic-poor shale formed in this sedimentary environment has high brittleness, it is not conducive to the formation of lamellation fractures (Figure 8). In the formations with a large amount of salt rocks (especially glauberite), the development of the lamellation fractures will be significantly reduced.

4.3. Texture and Structure of Lamina. The distribution of the lamellation fractures is related to the type, thickness, and

FIGURE 9: Relationship between density of lamellation fractures and thickness of lamina in the Qianjiang Depression ($N = 283$).

FIGURE 10: Relationship between density of lamellation fractures and lamina in the Qianjiang Depression ($N = 828$).

FIGURE 11: Relationship between density of lamellation fractures and thickness of glauberite lamina in the Qianjiang Depression ($N = 182$).

density of lamina. The third and fourth members of the Qianjiang Formation are rich in laminae which are composed of argillaceous, dolomitic, and glauberite lamination. Based on observations of lamellation fractures and laminae in rock cores, the lamellation fractures mainly develop around the lithologic change interfaces with frequent interbedding of

dolomitic and muddy laminations. On the contrary, due to the lack of these weak mechanical discontinuities in massive rocks, lamellation fractures usually do not develop well in massive rocks.

The statistical results of core observations also indicate that the development degree of lamellation fractures is related to the thickness of dolomitic and muddy laminations (Figure 9). As the thickness of lamina is distributed between 1 mm and 4 mm, the density of lamellation fractures is relatively high and the average density is more than 100 m^{-1} . As the thickness of the lamina is more than 4 mm, the density of the lamellation fractures is inversely proportional to lamina thickness. As lamina thickness is less than 1 mm, this relation will become proportional. Meanwhile, the density of the lamellation fractures is also related to the density of the dolomitic and muddy lamina (Figure 10). As the density of lamina is between 100 m^{-1} and 400 m^{-1} , the density of lamellation fractures is relatively high. As the lamina density is more than 400 m^{-1} or less than 100 m^{-1} , the density of the lamellation fractures decreases.

Unlike from dolomite and argillaceous laminations, glauberite laminations often fall into unconsolidated argillaceous deposits in the form of self-shaped snowflakes where

FIGURE 12: Density of lamellation fractures in different lithofacies in the Qianjiang Depression ($N = 829$). A: carbonaceous bedded argillaceous dolomite; B: carbonaceous laminated dolomite or calcareous mudstone; C: carbonaceous glauberite-filled laminated argillaceous dolomite; D: carbonaceous massive argillaceous dolomite; E: carbonaceous massive mudstone; F: carbonaceous dolomite or argillaceous glauberite; G: salt.

continuous weak mechanical discontinuities often do not appear. Therefore, in the shales with glauberite laminations, the density of lamellation fractures has negative correlations with both the thickness and the density of the glauberite laminations (Figure 11). As the density and thickness of glauberite lamination increase, the density of lamellation fractures decreases.

4.4. Lithofacies. Based on the mineral composition, bedding structure, and organic matter content, the salt rock can be divided into seven main lithofacies, i.e., argillaceous dolomite rich in laminated carbonaceous lamina, dolomitic or limy mudstone rich in laminated carbonaceous lamina, argillaceous dolomite rich in carbonaceous glauberite lamina, massive carbonaceous argillaceous dolomite, massive carbonaceous mudstone, carbonaceous dolomitic or argillaceous glauberite, and salt rock. Here, rocks with a TOC content of more than 2% are defined as carbon-rich rocks, those with a TOC content between 0.5% and 2% are carbon-containing rocks, and those with a TOC content of less than 0.5% are carbon-poor rocks [46]. Therefore, the comprehensive influences of mineral composition, bedding texture, structure, and organic matter content on the density of lamellation fractures can be summarized as the control of lithofacies on the development of lamellation fractures.

According to the statistics of lamellation fractures observed in cores (Figure 12), the density of lamellation fractures in the argillaceous dolomites rich in laminated carbonaceous lamina and dolomitic or limy mudstones rich in laminated carbonaceous lamina is the largest with the average density of more than 100 m^{-1} . In the argillaceous dolomite-rich carbonaceous glauberite lamina, the average density is more than 70 m^{-1} . The density of lamellation fractures in the carbonaceous massive argillaceous dolomites and carbonaceous massive mudstones is less than 40 m^{-1} . These differences indicate that densities of lamellation fractures in massive carbonaceous lithofacies are far lower than those in lithofacies rich in laminated carbonaceous lamina. The lamellation fractures are not developed in salt rocks, carbonaceous dolomitic or argillaceous glauberites.

4.5. Structural Position. The development degree of the lamellation fractures is also affected by structures. Different structural positions correspond to different density of the lamellation fractures. For example, W99 well at the high position of an anticline axis and BY2 well at the low position of depression are used for the comparison (Figure 1). The two wells have similar TOC content and lamina in shales. The TOC contents in the fourth section of the third member in the Qianjiang Formation in two wells are both in the range from 3.0% to 4.0%. The laminae are dolomitic lamina and muddy lamina with thickness between 1 mm and 4 mm in shales. However, the lamellation fracture densities of the two wells in the same layer are different. The average density of W99 and BY2 wells are 111 m^{-1} and 54 m^{-1} , respectively. The lamellation fracture density in the W99 well at the high structural position is higher than that in the BY2 well at the low structural position. The density difference of lamellation fracture results from their structural positions. Under the structural compression, the high position (W99) in the axis of anticline uplifted and eroded which leads to the overlying formation pressure reduced. The reduced overlying pressure will promote lamellation fractures, further expanding along the weak mechanical discontinuities and subsequently leading to high density of lamellation fractures, indicating that the development degree of the lamellation fractures at the high structural position is better than that at the low structural position.

5. Conclusion

Lamellation fractures mainly develop along lamellations in shales. They have various morphological characteristics such as straightness, bending, discontinuity, bifurcation, pinching out, and merging. The horizontal continuity and connectivity of the lamellation fractures are poor. The lamellation fractures are well developed in the Paleogene Qianjiang Formation shales, and the density of the lamellation fractures mainly lies between 20 m^{-1} and 110 m^{-1} . The aperture of lamellation fracture is generally less than $160 \mu\text{m}$. The density of lamellation fracture is related to its aperture; the

smaller the lamellation fracture apertures is, the higher the density is.

The development degree of the lamellation fractures is mainly controlled by mineral composition, texture type, quantity and density of lamina, organic matter content, pyrite content, and structural position. The densities of lamellation fractures in argillaceous dolomites rich in laminated carbonaceous lamina and dolomitic or limy mudstones rich in laminated carbonaceous lamina are the largest, followed by the density of the fractures in argillaceous dolomite-rich carbonaceous glauconitic lamina. In massive carbonaceous argillaceous dolomites and massive carbonaceous mudstones, the densities of lamellation fractures are low. The lamellation fractures are not developed in carbonaceous dolomitic or argillaceous glauconitic and salt rocks. The uplift of tectonic movement is conducive to the development degree of lamellation fractures. In the same lithofacies, the lamellation fractures in the high structural position are more developed than those in the low structural position.

Data Availability

The [data type] data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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