Research Article

Densification and Fracture Type of Desert in Tight Oil Reservoirs: A Case Study of the Fuyu Tight Oil Reservoir in the Sanzhao Depression, Songliao Basin

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The exploration of unconventional oil and gas, especially the exploration process of tight oil, is closely related to the evolution of tight reservoirs and the accumulation process. In order to investigate the densification and accumulation process of the Fuyu tight oil reservoir in the Sanzhao depression, Songliao Basin, through the new understanding of reservoir petrological characteristics, diagenesis and diagenetic sequence are combined with a large number of inclusions: temperature measurement, spectral energy measurement, and single-well burial history analysis, and then contrastive analysis with current reservoir conditions. The results prove that diagenesis is dominated by compaction and cementation, and the restoration of paleoporosity shows that its porosity reduction rate reached 67% and the densification process started in the early Nenjiang Formation and was finalized at the end of the Nenjiang Formation. The accumulation of the Fuyu oil layer generally has the characteristics of two stages and multiple episodes, and the main accumulation period is the end of the Mingshui Formation. The end of the Nenjiang Formation, where the main body of the reservoir is densified, is just a prelude to the massive expulsion of hydrocarbons in the Songliao Basin, which makes the Fuyu oil layer have the characteristics of first compacting and then accumulating. Through the above analysis, it can be seen that the accumulation of oil and gas in the Fuyu oil layer, Sanzhao depression, is more dependent on the fault-dominated transport system. In addition, it is believed that tight oil accumulation should have the characteristics of short-distance oil enrichment around the fault, and the development area of fracture deserts near the fault sand body should be the key area for further exploration.

1. Introduction

The Fuyu oil layer in the Sanzhao depression is located in the northern Songliao Basin, which is close to the source rock of the Qingshankou Formation, and its own reservoir is relatively tight. Therefore, it has become typical tight oil under source in China. The Fuyu oil layer not only has some typical characteristics of tight oil within the source, such as poor reservoir physical properties, large distribution area, low resource abundance, locally developed sweet spots, and incomplete reservoir distribution controlled by traps [1–7] but also has the characteristics such as the reservoir pressure different from the characteristics of in-source tight oil [8]. The Fuyu oil layer has experienced many years of continuous exploration and practice, and predecessors have done a lot of research on its source rock conditions, sedimentary environment, preservation conditions, and other petroleum geological conditions [9–12], which has been clear that it has a
potential scale of tight oil resources of nearly two billion tons, but there is still a lack of in-depth discussion and research on the relationship between the evolution of the reservoir and the process of accumulation. From the perspective of tight oil, the relative sequence between the densification time of the reservoir and the main accumulation period directly affects the oil and gas abundance and enrichment zones of the Fuyu oil layer. If the reservoir is tight first and then accumulates, then for the already densified reservoir, the reservoir has basically lost its ability to transport oil and gas, and under the control of the fault-dominated transport system, exploration should be given priority to high-quality sweet spots near faults. On the contrary, exploration can be carried out in areas rich in sand bodies with far faults. Therefore, research on the reservoir densification and accumulation process is of great practical significance for releasing tight oil resources in the Songliao Basin and further realizing the potential of tight oil.

2. Geological Background

The Songliao Basin is a large-scale Mesozoic-Cenozoic composite sedimentary basin with a faulted depression double structure, which has developed the Sanzhao depression, Qijia-Gulong depression, Heiyupao depression, Changyuan anticline, Mingshui terrace, Chaoyanggou anticline, and other multiple tectonic units. The Sanzhao depression is located in the middle-eastern part of the Songliao Basin, and the middle-shallow exploration strata above 2000 meters are developed with the Fuyang oil layer (FY), Gaotaiyi oil layer (G), Putaohua oil layer (P), Saertu oil layer (S), and other sets of oil-bearing layers from bottom to top, and the main source rock is the high-quality dark rock of the Qingshankou Formation (K2Qn). The structural diagram of the Songliao Basin is shown in Figure 1. During the Quantou Formation period when the Fuyang oil layer was developed, the Sanzhao depression has the sedimentary characteristics of multiple sources and multiple water catchment centers. As a whole, it was dominated by delta front and plain deposits. The river is small in scale and changeable in direction, with the average width being generally less than 800 meters, the thickness of the sand body is thin, and the average thickness of a single sand body is generally less than 4 meters. The overlying Qing 1st member source rock has a relatively high abundance of organic matter, mainly type I kerogen, with an average organic carbon of 3.14% and the average of chloroform bitumen A of 0.62%. The average of total hydrocarbons is up to 4290×10^{-6} ppm, and the average value of the sum of S1 and S2 is as high as 29.27 mg/g. Under the influence of compression and overturning of multiple tectonic stresses, the top surface of the Quantou Formation has a complex structure with alternating uplifts and depressions and developed nearly 4000 dense faults; the average length is less than 2 km, the vertical fault distance is distributed in 20 to 60 meter, and the direction is mainly north-northwest and north-northeast. Exploration practice has confirmed that the Fuyang oil layer has relatively poor physical properties, with porosity generally ranging from 8% to 12% and permeability ranging from 0.2 to 1.2 mD, which was dominated by fault-lithologic reservoirs. In the past three years, nearly 150 million tons of tight oil reserves have been submitted, demonstrating good exploration potential.

3. Lithological Features of the Reservoir

3.1. Rock Types and Composition Characteristics. The lithology of the Fuyu oil layer mainly includes fine sandstone, siltstone, silt-bearing fine sandstone, rare medium-fine sandstone, and medium sandstone. The rock types are mainly...
feldspar lithic sandstone and lithic feldspar sandstone. Quartz content distribution is in the range of 16.06% to 64.29%, with an average of 28.2%, and feldspar content ranges from 16.28% to 53.45%, with an average of 34.22%. The content of lithic fragment is from 3.45% to 57.89%, with an average of 37.59%, mainly igneous rock cutting, followed by metamorphic rock cuttings, containing a small amount of sedimentary rock cuttings. The type of cement is mainly carbonate, clay mineral, and siliceous, and the carbonate is mainly calcite, with the content distribution range of 1.0% to 55.0%, with the average value of 9.99%. The clay mineral content in descending order is illite with an average of 3.35%, kaolinite with an average of 0.14%, and siliceous cement ranging from 1.0% to 5.0%, with an average of 2.3%.

3.2. Rock Fabric. The Fuyu oil layer is mostly fine sandstone with an average content of 52.61%, followed by siltstone with an average content of 46.26%. The maturity of the sandstone structure is moderate, and the particles experienced mostly point-line contact, followed by line contact, accompanied by a small amount of bump contact and suture line contact. The main types of cementation are porous type, contact type, mosaic type, and base type (Figure 2).

4. Reservoir Diagenesis and Diagenetic Sequence

4.1. Diagenesis. Microscopic observations of rock thin slices and cast thin slices, scanning electron microscopy, and cathode luminescence [13, 14] show that the diagenesis experienced by the tight sandstone reservoirs in the research area mainly includes compaction, cementation, metasomatism, and dissolution. The diagenesis has an important influence on the pore development of the reservoir [15].

4.1.1. Compaction. During the diagenesis process of the Fuyu oil layer, it has experienced medium-strength compaction, common line contact, and point-line contact under the microscope, as well as a small amount of concavo-convex contact (Figure 2). Brittle minerals, such as feldspar and quartz, are crushed, while plastic minerals, such as lithic mica, are commonly deformed. The particle contact relationship indicates that after the Fuyu oil layer experienced uplift at the end of the Mingshui Formation deposition, the later subsidence did not reach the maximum burial depth stage, and the sandstone particles did not reach the maximum degree of compaction.

Figure 2: Particle contact relation of the compact reservoir in the Fuyu Formation: (a) Shuang 51, the casting thin sections, 1724.09 m, plane-polarized light, ×100; (b) Fang 51, the casting thin sections, 1888.57 m, orthogonal light, ×200; (c) Fang 50, the casting thin sections, 1810.22 m, orthogonal light, ×100; (d) Zhao 26, the casting thin sections, 1886.86 m, orthogonal light, ×100.
4.1.2. Cementation. The results of casting thin sections, scanning electron microscopy, and cathode luminescence observations show that the cementation mainly includes calcareous cementation, siliceous cementation, and clay mineral cementation. Calcareous cementation is dominated by calcite cementation, while siliceous cementation is mainly manifested in the secondary enlargement of quartz and feldspar particles. Calcite cementation is the most common, mainly including the early-formed continuous crystal calcite and the late-formed splendid calcite, which is orange under cathode luminescence, and the morphological characteristics are mainly porous, continuous crystal cementation, blocking the pores and reducing the physical properties of the reservoir. In the samples with strong local cementation, even basal cementation is formed, and the particles are floating and form a dense layer (Figures 3(a) and 3(b)). Siliceous cements are widely distributed in sandstone in the study area, mainly appearing on the surface of detrital quartz particles in the form of secondary quartz enlarged edges (Figures 3(c) and 3(d)). The secondary increase in quartz in the Fuyu oil layer is more common, but the total amount is relatively low. The identified content under the microscope ranges from 1.0% to 5.0%, most of which is 2.0% to 3.0%.

4.1.3. Metasomatism. The metasomatism in the study area is mainly the calcite of feldspar. After the feldspar is replaced by calcite, it forms metasomatism phantom and residual structure, and the edge of feldspar presents irregular shape such as tooth shape (Figure 4).

4.1.4. Dissolution. Dissolution refers to the process of dissolving part or all of the soluble parts in the surrounding rock when the acid fluid in the reservoir migrates in the channel, which is the main reason for the formation of secondary pores in the reservoir rock and increases the pore space and is an important diagenesis to improve the physical properties of sandstone reservoirs [16]. The main acidic medium for the dissolution in the study area is the organic acid produced by the decarboxylation of the organic matter in the mud during the thermal evolution of the organic matter, the carbonic acid...
formed by the transformation of CO$_2$ and smectite, and the acidic water formed by the transformation of clay minerals. The main corroded particles are acidic unstable aluminosilicate mineral feldspar, soluble rock cuttings, and carbonate cements. Various types of secondary pores formed by dissolution in the study area are the main types of the reservoir space in this area.

4.2. Diagenetic Sequences. Through the analysis of the relationship between the following five minerals under a microscope, the diagenetic sequence of the Fuyu oil layer in the Sanzhao area is determined.

4.2.1. Quartz Secondary Growth Occurred Earlier Than Late Calcite Cementation. The content of quartz secondary augmentation is obviously lower than that of carbonate cements. Two stages of quartz enlargement can be seen in the secondary enlargement. Calcite is developed outside the quartz enlargement, and the calcite fills the intergranular pores and the metasomatism quartz grains and their enlargement edges (Figure 5). Therefore, the occurrence time of quartz secondary growth is generally earlier than that of late calcite.

4.2.2. Quartz Secondary Growth Occurred Earlier Than or at the Same Time as Dissolution. Silica is one of the main products of feldspar dissolution. Smectite can expel Si$^{4+}$ in the process of transforming into clay minerals, forming siliceous cement in sandstone. Therefore, the quartz level I increase can occur in the early diagenetic stage, which is earlier than the occurrence time of the dissolution of feldspar minerals. In addition, the early hydration of feldspar also provided a material source for the early secondary growth of quartz. In

Figure 4: Typical metasomatism of the Fuyu Formation in the Sanzhao depression: (a) Shuang 51, 1724.09 m, the fourth member of the Quantou Formation, calcite metasomatic feldspar, rock cutting and quartz, ×100; (b) Zhou 182, 1828.89 m, the fourth member of the Quantou Formation, calcite continuous crystal cementation, metasomatic feldspar, feldspar metasomatism residual, local metasomatism quartz, ×100.

Figure 5: Secondary enlargement of quartz and calcite cement: (a) Fang 162, 1923.04 m, the fourth member of the Quantou Formation, quartz secondary growth in two stages, calcite is later than the second phase of quartz, ×200; (b) Pu 53, 1681.83 m, the fourth member of the Quantou Formation, calcite continuous crystal cementation, calcite metasomatic feldspar, ×100.
this case, the time of secondary growth of quartz is earlier than that of the corrosion of organic acid (Figure 6). Microscopic observation shows that dissolution pores are usually developed outside the quartz secondary enlargement edge, and dissolution remnants of feldspar can be seen in the dissolution pores. The analysis shows that the quartz secondary enlargement occurs before the dissolution, and the original feldspar particles occupy part of the pore space, inhibiting the process of quartz secondary enlargement.

4.2.3. Late Calcite Was Formed Later Than Dissolution or Occurred at the Same Time as Dissolution. Except for the early continuous crystal calcite, most of them are splendid calcite filling the intergranular pores and underwent the phenomenon of replacing feldspar or even quartz (Figure 5). The phenomenon of splendid calcite associated with dissolution pores is very common, and the calcite beside the dissolution pores has no obvious dissolution phenomenon, indicating that the formation time of calcite is later than the time when the dissolution occurs, or the acidic fluid can only dissolve the feldspar but not enough to dissolve the calcite, and the products formed by the dissolution of feldspar also provide a material source for calcite.

4.2.4. Late Calcite Cementation Occurred Earlier Than Oil Charging. It is generally believed that hydrocarbon charging can change the original fluid environment in the pores, thereby affecting the process of diagenesis. Observation under a thin-slice microscope and scanning electron microscope observation show that the hydrocarbon residual calcite crystal form was intact in the dissolution pores on the outside of the calcite cement, indicating that it did not suffer from the dissolution transformation caused by the change of the fluid environment owing to the oil charging, and its formation time should be earlier than that of oil charging. In addition to the above phenomena, the symbiosis of calcite and hydrocarbon residual asphaltenes can also be seen, indicating that the hydrocarbon residual asphaltenes prevent the continued growth of calcite or are located in the remaining intergranular pores after calcite filling, which means that the hydrocarbon charging time is later than the calcite cement formation time (Figure 7).

Through the statistics of the relationship between the content of calcite cement and the oil-bearing grade, it can be seen that the content of calcite cement and the oil-bearing grade are negatively correlated; that is, the content of calcite cement in the oil-free samples is the highest, up to 60%. Oil immersion—the oil trace level is the second—reduced to about 40%, and the content of calcite cement in the oil-saturated to oil-rich samples is the lowest, generally below 25%. There is no obvious difference between the oil-bearing grades of quartz secondary enlargement content, which indicates that the influence of hydrocarbon charging on the quartz secondary enlargement is not obvious.

Through synthesizing the above analysis, the reservoir compaction of the Fuyu oil layer runs through the entire diagenesis process, and compaction is the strongest in the early diagenetic period. In the early diagenesis stage, the feldspar experienced hydration in the shallow burial stage, which provided a material source for the early secondary growth of quartz. In the middle diagenetic stage, with the increase in the thermal evolution degree of organic matter, organic matter enters the low-mature stage, generating a large amount of organic acids, dissolving soluble minerals such as feldspar, and forming secondary pores, which to a certain extent provide space and material sources for the cementation of late calcite. At the same time, the dissolution of feldspar consumed organic acids, which also created suitable alkaline conditions and material sources for calcite and illite precipitation. Organic matter enters the oil generation threshold, a large amount of hydrocarbons are expelled from the source layer, and hydrocarbons enter the pores of the reservoir, which changes the original fluid environment and inhibits cementation to a certain extent [17, 18]. Cementation may continue in areas not affected by hydrocarbon charging. Compaction, calcite cementation, siliceous cementation, and illite filling are the main causes of reservoir deterioration (Figure 8).
5. Reservoir Pore Evolution and Compaction History

In the process of subsidence or uplift, the reservoir has undergone various effects of diagenesis. Although the secondary pores can be formed under the influence of dissolution, it is inevitable that the pores become smaller and the porosity decreases. The study of pore evolution is the key problem to determine the tight time of the reservoir [19, 20].

5.1. Reservoir Paleoporosity Restoration. In the process of stratum subsidence, the porosity continues to decrease under the influence of compaction and cementation. Athy proposed the classic Athy model for mudstone and believed that porosity and burial depth are exponentially related. Nowadays, when analyzing the degree of compaction of mudstone and sandstone, this exponential relationship is used to express the quantitative relationship of porosity and burial depth of clastic rocks [21–24].

The paleoporosity restoration method adopted in this study is as follows: based on the measured sandstone porosity, the sandstone porosity is calculated by using the time difference of acoustic waves, and the measured porosity is corrected to calculate the calculation formula, so as to obtain the logging interpreted porosity that is consistent with the measured porosity and then obtain the variation curve of the average porosity with depth. This curve is the variation curve of present-day porosity with depth, and the variation curve of paleoporosity with depth can be approximated by considering the denudation thickness. It can be seen from the porosity evolution curve that the burial depth of the same formation in the same period is not consistent; that is, the subsidence rate and the amount of subsidence are different in the same period, indicating that the burial time actually has an effect on the porosity. The comprehensive equation of the measured porosity data and logging calculation data of 5 wells, using paleoburial depth ($H$) and geological time ($t$) as independent variables and paleoporosity ($\Phi$) as dependent variables, to establish the binary function of porosity, burial depth, and geological time is as follows:

$$\Phi = 41.7494 - 0.00984H - 0.3222 \times 10^{-4}Ht - 0.06928t.$$  \hspace{1cm} (1)

Since the ancient porosity cannot be accurately measured, in order to verify the reliability of the porosity recovery model, the measured porosity of exploratory wells in the area not involved in the model establishment was selected as the calibration and compared with the porosity calculated by this model (Table 1). The analysis results show that the error between the calculated porosity of this model and the measured porosity is in the range from -0.7 to 1.4. The reasons for the error are the following three points. First of all, the porosity calculated by the model mainly depends on the fitting between the porosity and the logging curve, and this fitting relationship usually has some fitting accuracy error. Secondly, the measured porosity is artificially sampled for data measurement, which invisibly includes whether the sampling position can replace the physical properties of the
Table 1: Comparison between the calculated porosity model and present measured porosity of the Fuyu oil field.

| Well no. | Present porosity measured (%) | Computed porosity (%) | Absolute error | Well no. | Present porosity measured (%) | Computed porosity (%) | Absolute error |
|----------|-------------------------------|-----------------------|----------------|----------|-------------------------------|-----------------------|----------------|
| Z1       | 9.8                           | 10.3                  | -0.5           | Z16      | 7.4                           | 7.9                   | -0.5           |
| Z2       | 10.2                          | 10.1                  | 0.1            | Z17      | 8.2                           | 8.9                   | -0.7           |
| Z3       | 10.0                          | 9.6                   | 0.4            | Z18      | 11.4                          | 11.0                  | 0.4            |
| Z4       | 11.4                          | 11.9                  | -0.5           | Z19      | 9.6                           | 9.5                   | 0.1            |
| Z5       | 12.0                          | 10.6                  | 1.4            | Z20      | 10.5                          | 10.9                  | -0.4           |
| Z6       | 9.0                           | 9.6                   | -0.6           | Z21      | 11.3                          | 11.0                  | 0.3            |
| Z7       | 8.6                           | 8.5                   | 0.1            | Z22      | 12.1                          | 12.5                  | -0.4           |
| Z8       | 13.4                          | 12.2                  | 1.2            | Z23      | 8.8                           | 8.4                   | 0.4            |
| Z9       | 10.6                          | 10.3                  | 0.3            | Z24      | 9.6                           | 10.1                  | -0.5           |
| Z10      | 9.7                           | 9.2                   | 0.5            | Z25      | 7.8                           | 7.6                   | 0.2            |
| Z11      | 7.2                           | 7.8                   | -0.6           | Z26      | 11.2                          | 11.5                  | -0.3           |
| Z12      | 10.8                          | 10.4                  | 0.4            | Z27      | 10.4                          | 10.0                  | 0.4            |
| Z13      | 11.4                          | 11.2                  | 0.2            | Z28      | 8.8                           | 9.0                   | -0.2           |
| Z14      | 9.8                           | 9.3                   | 0.5            | Z29      | 9.2                           | 8.5                   | 0.7            |
| Z15      | 11.0                          | 10.5                  | 0.5            | Z30      | 11.4                          | 10.0                  | 1.4            |
sand layer and the systematic error caused by the instrument measurement. Finally, the porosity parameters calculated by the model are mainly burial depth and burial time. There is a certain measurement error between the depth calculated by the model and the actual burial depth of the sand body, and the burial time error is relatively large. The burial time calculated this time is based on the burial time of the top surface of Qingshankou, and the burial time of a specific sand group cannot be accurately given. Combined with the above-mentioned reservoir classification standards, the error of this range should be able to meet the application of reservoir classification of the Fuyu oil layer group.

According to the actual calculation of the recovery model, firstly analyze the corresponding relationship between the porosity recovery of a single well and the burial depth and geological time. Taking Xushen 7 and Chang 102 as an example, the reservoir of Xushen 7 gradually entered the densification stage when the burial depth of Chang 102 was 1700 m and the burial depth of Chang 102 was 1200 m, which corresponds to the early and middle stages of the Nenjiang Formation, while the burial depth of large-scale densification was 2100 m and 1700 m, respectively, and the geological period was the late stage of the Nenjiang Formation (Figure 9).

Based on the current stratum thickness, combined with compaction correction and denudation thickness recovery, obtain the paleoburial depth data of the end of the Nenjiang Formation and the end of the Mingshui Formation, and compile the paleoporosity plan of the top of the fourth member of the two periods. In general, at the end of the Nenjiang Formation, the main body of the Sanzhao depression entered the compact stage, and the porosity in most areas was below 14%, which was close to the compact stage. At the end of the Mingshui Formation, the range of densification further expanded, further extending westward to the Changyuan area and gradually southward, including Chaoyanggou terraces and other higher structures (Figure 10).

5.2. Duration of Reservoir Tightness. According to the analysis of porosity evolution and burial history of the Fuyu oil layer in the Sanzhao area, this area has gradually entered the tight stage with porosity lower than 12.0% at the end of the Nenjiang River (Figure 11). In the early burial stage of the Fuyu oil layer, the average initial porosity was about 36.0%. Before the Nenjiang Formation, the Fuyu oil layer experienced an early diagenetic stage, and the porosity dropped from 36.0% to 25.0%. The diagenesis experienced at this stage mainly includes compaction, secondary enlargement of quartz, and chlorite membrane. The total amount of quartz and chlorite membranes is about 2.7%, the porosity reduction rate is about 7.5%, the compaction reduction is 8.3%, and the porosity reduction rate is about 23.0%.

Figure 9: Paleoporosity recovery curve. (a) Well Xushen 7 and (b) Well Chang 102.
In the middle of the Nenjiang Formation, the Fuyu oil layer entered the middle diagenetic A2 stage, and by the late Nenjiang Formation, the porosity decreased from 21% to 12%. This stage has undergone compaction, illite cementation, and hydrocarbon charging. Hydrocarbon charging inhibited the growth of calcite and illite. Through calculating the pore-reducing effects of illite cementation and compaction, respectively, the pore reduction amount of illite at this stage can be estimated.

Figure 10: Upper Quantou Formation paleoporosity plan of the Sanzhao depression. (a) The end of the Nenjiang formation and (b) The end of the Mingshui formation.

Figure 11: Comprehensive model of pore evolution, diagenetic sequence, and burial history of the Fuyu oil layer in the Sanzhao depression.
stage was about 4.05%, and the porosity reduction rate was about 11.25%. The amount of pore reduction by compaction is about 4.95%, and the reduction rate is about 13.75%.

In the early diagenesis period, the pore reduction is dominated by compaction, followed by quartz secondary growth and chlorite membrane. In the mid-diagenesis stage A₁, the pore reduction is dominated by the late calcite cementation, followed by compaction, and the dissolution pore increase is offset by the first two effects. In the mid-diagenesis stage A₂, the pore reduction is dominated by compaction, followed by illite cementation. Throughout the evolution process, the compaction porosity reduction rate is about 46.22%, the cementation porosity reduction rate is about 31.97%, the dissolution porosity enhancement rate is about 11.58%, and the total porosity reduction rate is about 67%. In summary, it is concluded that the densification degree of tight sandstone of the Fuyu oil layer should have been maximized in the late Nenjiang Formation, and the tight reservoirs have basically been formed.

### 6. Analysis of the Main Accumulation Period of the Fuyu Oil Layer

The Songliao Basin has experienced multiperiod tectonic movement and formed a multicycle basin. The source rocks of the first member of the Qingyi formation expelled hydrocarbon for many times in the basin, resulting in a single-stage or multistage upflow to the Gaotaizi tight reservoir and down to the Fuyu tight reservoir. In order to determine the history of hydrocarbon accumulation in the Fuyu oil layer, this study is mainly based on a large amount of microscopic hydrocarbon migration and accumulation information obtained from the systematic analysis of fluid inclusion samples and analyzes the accumulation period of tight reservoirs. Taking Zhou 165 as an example, blue-white and blue-green fluorescent oil inclusions were detected in two siltstone samples from the depth of 1839.69 m and 1842.37 m in the Fuyu oil layer, indicating at least two episodes of oil charging. The results of microscopic temperature measurement show that the uniform temperature of the salt water inclusions in the first scene is 95.1~109.4°C, with an average value of 102.5°C. The homogenization temperature of the salt water inclusions in the second scene is 110.1~129.8°C, with an average of 117.8°C, and the homogenization temperature of oil inclusions is 91.5~110.7°C, with an average value of 102.7°C. The homogenization temperature of salt water inclusions in the third scene is 135.2~153.9°C, and the average value is 145.6°C; the homogenization temperature of oil inclusions is 129.1~135.1°C, and the average value is 132.8°C (Figure 12).

In this research, the uniform temperature of brine obtained in the same period of oil inclusions in the Sanzhao area was used to project on the single-well burial history map to determine the period of oil and gas accumulation (Figure 13). It can be seen that the Fuyu oil layer has two stages of accumulation. The first stage occurred during the 75~73 Ma of the late period of the Mingshui Formation deposition, which corresponds to the first scene of charging. The second stage occurred during the 67~65 Ma of the late Mingshui Formation, which corresponds to second and third scene. In other words, the late period of the Mingshui Formation deposition should be the main accumulation period of the Fuyu oil layer, while the late period of the Nenjiang Formation is only a small-scale oil and gas discharge, which is the prelude to large-scale hydrocarbon migration and accumulation.

### 7. Relationship between Reservoir Densification and Accumulation Period and Its Significance

The above research shows that the study of accumulation history indicates that the study area has experienced two stages of accumulation, the late Nenjiang Formation (77~73 Ma) and the late Mingshui Formation (67~65 Ma), of which the late Mingshui Formation is the main accumulation period. According to the analysis of the corresponding relationship between the maturity of the regional source rock and the paleoporosity plane, at the end of the Nenjiang Formation, the range of oil and gas maturity and accumulation is roughly consistent with the tight range at the end of the Mingshui Formation deposition. At the end of the Mingshui Formation, the Sanzhao area has entered the source rocks to generate a large amount of mature hydrocarbons, which is basically consistent with the distribution range of tight

![Figure 12: Histogram of homogenization temperature of fluid inclusions in silty sandstone in well Zhou 165.](image-url)
reservoirs at the end of the Mingshui Formation (Figure 14). Therefore, the Fuyu oil layer has the characteristics of first being tight and then accumulating.

The purpose and significance of studying the relationship between reservoir tightness history and accumulation period are to analyze the differences in the process of oil and gas
accumulation, so as to more accurately find favorable oil and gas enrichment zones. In the tight reservoir of the Fuyu oil layer, if the accumulation period is earlier than the time when the reservoir is densified, then the method of comparing the past with the present is adopted. In the accumulation stage, the reservoir is still a conventional reservoir, and the oil and gas can migrate downward to the Fuyu oil layer through the intensive faults at the top of the Quantou Formation. With the cooperation of lateral transport of the sand body, the oil and gas can be transported to a relatively far trap for accumulation, and such oil and gas area will form a large area of a continuous distribution pattern. However, in fact, the densification time of the Fuyu oil layer was earlier than the main accumulation period. A large amount of oil and gas discharged from the overlying Qingshankou source rock was displaced downward through the fault. In tight reservoirs with underground porosity less than 12% and permeability generally less than 0.1 mD, long-distance migration and accumulation cannot be as smooth as conventional reservoir sand bodies. Past exploration practices have also confirmed that the types of traps discovered are mainly fault traps and fault-lithological traps. The oil reservoirs are characterized by multilayer superposition on the plane and section, forming the characteristics of contiguous distribution after superposition. These oil reservoirs are communicated by widely developed fault facies and exhibit the characteristics of quasi-continuous distribution in space, which are jointly controlled by the fault and its adjacent high-quality sand bodies (Figure 15).

What needs to be clarified and emphasized here is that the so-called reservoir densification does not mean that conventional high-quality reservoirs are transformed into very tight sand bodies with extremely low porosity without storage capacity but refers to the process of reservoir densification, and this process is also significantly different for different sand bodies, and the result of densification is generally maintained at porosity above 8.0%. Therefore, the free fluid field still exists, but it is weaker and more selective than conventional reservoirs. Under the influence of various diagenesis, the vertical sand bodies are becoming denser. In practice, it can often be found that the physical properties of the sand bodies dispersed vertically in the Fuyu oil layer are quite different, as well as the phenomenon of oil-dry interbeds. The densification degree is also reduced in the high part of the structure or the relatively shallow burial part, which forms the sweet sand body of the tight reservoir in the common sense. Under the communication of faults, such sand body can still form the lateral migration and accumulation of a certain distance laterally. Therefore, tight oil reservoirs often have the characteristics of strong heterogeneity, no uniform oil-water interface, and relatively high-quality sand bodies around faults that are relatively enriched in oil and gas. Hence, according to the actual characteristics of the Fuyu oil layer in the Sanzhao area, which is tight first and then accumulates, the sweet spot development area of the sand body near the fault should be a hydrocarbon enrichment area and should become the main exploration target.

8. Conclusions

(1) The Fuyu oil layer in the Sanzhao depression is dominated by fine sandstone and siltstone. The diageneis is dominated by mechanical compaction and cementation, and the dissolution and pore-enhancing effect are not obvious. The paleoporosity recovery show that the total porosity reduction rate can reach 67%, the porosity reduction rate of mechanical compaction is about 46.22%, and that of cementation is about 31.97%, and layer densification has been basically completed at the end of the Nenjiang Formation.

(2) The Fuyu oil layer expulsion began at the end of the Nenjiang Formation and reached the peak at the end of the Mingshui Formation, each stage has 2-3 episodes of hydrocarbon expulsion history, and the most important accumulation period should be at the end of the Mingshui Formation.

(3) Combined with the analysis of reservoir tight history and accumulation history, it shows that the Fuyu oil
reservoir has the characteristics of first being dense and then accumulation, and the tight reservoir is not conducive to the long-distance lateral migration and accumulation of oil reservoirs.

(4) The accumulation process of the first densification and then accumulation leads to the hydrocarbon accumulation of the Fuyu reservoir which largely depends on the transport system dominated by dense faults. It is considered that near-fault fracture-type deserts and sand body development area should be an oil-gas area, which should be the main exploration target.

Data Availability

No additional data are available.

Conflicts of Interest

The authors declare no conflict of interest.

Authors’ Contributions

Binchi Zhang performed the experiment and wrote the manuscript. Dejiang Kang contributed to the conception of the study. Shizhong Ma contributed significantly to the analysis. Wenzhe Duan performed the data analysis. Yue Zhang helped perform the analysis with constructive discussions.

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