Hydrocarbon Accumulation Process and Mode in Proterozoic Reservoir of Western Depression in Liaohe Basin, Northeast China: A Case Study of the Shuguang Oil Reservoir

Guangjie Zhao 1,2, Fujie Jiang 1,2,*, Qiang Zhang 3,*, Hong Pang 1, Shipeng Zhang 1, Xingzhou Liu 4 and Di Chen 1,2

Abstract: The Shuguang area has great oil and gas potential in the Proterozoic and it is a major exploration target in the Western Depression. However, controlling factors and a reservoir-forming model of the Shuguang reservoir need further development. The characteristics of the reservoir formation in this area were discussed by means of a geochemical technique, and the controlling factors of the oil reservoir were summarized. The oil generation intensity of Es4 source rock was 25 × 10^6–500 × 10^6 t/km², indicating that the source rocks could provide enough oil for the reservoir. The physical property of the quartz sandstone reservoir was improved by fractures and faults, which provided a good condition for the oil reservoir. Two periods of oil charging existed in the reservoir, with peaks of 38 Ma and 28 Ma, respectively. A continuous discharge of oil is favorable for oil accumulation. Oil could migrate through faults and fractures. In addition, the conditions of source–reservoir–cap assemblage in the Shuguang area well preserved the oil reservoir. The lower part of the Shuguang reservoir was source rock, the upper part was reservoir, and it was a structure-lithologic oil reservoir. These results are crucial for further oil exploration.

Keywords: accumulation process; controlling factors; accumulation mode; Shuguang oil reservoir; Liaohe Basin

1. Introduction

The revolutionary success of tight oil in the USA has reversed the downward trend of oil production in North America at one stroke [1,2] and changed the world’s traditional energy pattern to some extent. As a result, through active exploration, tight oil areas with large-scale reserves have been explored in several basins in China, such as the eastern Bohai Bay Basin [3,4], Ordos Basin [5,6], Sichuan Basin [7], and western Junggar Basin [8]. Therefore, tight oil has become a critical field.

Tight oil refers to oil in tight reservoirs with a low overburden matrix permeability (less than 0.1 mD) and low porosity (less than 10%) [9]. Previous researchers focused on porosity [10] and permeability [11], diagenesis [12,13], fractures [14], migration [15], accumulation mechanism [16], and charging period [17]. However, research about the accumulation process and mode of tight reservoirs is not sufficient, and the comprehensive understanding of tight reservoirs needs further exploration. And, it has guiding significance for oil exploration.

The oil and gas in the Liaohe Basin have attracted extensive attention [18–20]. The Shuguang oilfield is in the north of the Western Depression of the Liaohe Basin. Previous
studies mainly focused on reservoirs [21], favorable zone prediction [22], dynamic characteristics of accumulation [23], conditions for accumulation [24], evaluation of crude oil [25], and origin of crude oil [26]. However, the controlling factors of the Shuguang oilfield have not been comprehensively researched, which seriously hindered the pace of oil exploration in the Western Depression in the past two decades. Therefore, it is significant to reveal the main controlling factors of the Shuguang oilfield and point out its accumulation mode. The objectives of the study were to point out the controlling factors and accumulation mode of the Shuguang reservoir. The result has reference significance for the exploration of other similar oil reservoirs.

2. Geological Setting

The Liaohe Basin is a rift basin of Liaoning Province in the northeast of China (Figure 1a). Panjin city is in the southwest of the basin. The basin is composed of the Eastern Depression, Damintun Depression, and Western Depression; the Western Depression was mainly studied for this study. To the northwest of the basin are the Yanshanian Mountains and to the southeast are the Jiaoliao Mountains (Figure 1b). The east–west span of the basin is about 65 km, and the north–south span is about 470 km. The basin was formed in three rifting cycles starting from the early Jurassic [27]. The second rift cycle of the Cretaceous increased the kinds of volcanic rocks and sediments. The present basin resulted from the third rifting cycle caused by subduction [28].

Figure 1. Location and sampling sites of the Shuguang oilfield. (a) Location map of the Liaohe Basin. (b) Selected profiles and division of main structural units. (c) Faults and wells in the Western Depression [19]. The sample wells are marked. A–A’ line shows the profile position of Figure 3. B’–B line shows the profile position of Figure 14.
The Shuguang ancient buried hill belt is located in the western slope of the Western Depression, which is controlled by NE-trending faults. Due to the influence of NE-trending and near-EW-trending faults, the whole buried hill belt is divided into multiple buried hill fault blocks, and the long axis direction of each buried hill is mainly eastward. The strata in this area are in turn the Neozoic Guantao Formation, Dongying Formation, Shahejie Formation, Fangshenpao Formation, Mesozoic, Paleozoic, Proterozoic (Pt), and Archaean (Ar) from top to bottom (Figure 2). The main reservoirs in this area are the Pt and Archean reservoirs in Qianshan (Figure 1c). In this paper, the main target layers are the buried hill strata of Paleozoic, Pt, and Archaean.

**Figure 2.** Generalized geological histogram indicating the structural events and source–reservoir–cap combination of the Shuguang area (modified from reference [19]).

The Shuguang oilfield is in the middle and northern section of the Western Depression, with several oil-generating depressions around it, including the Chenjia and Fanshan sags in the east and the Qingshui Sag in the south, which are very rich in
hydrocarbon resources. Normal faults and reverse faults are relatively developed, providing a good channel for regional oil migration (Figure 3). The Pt is the main reservoir, while some reserves also exist in the Paleozoic (Pz) and Archean. The mudstone of the Mesozoic and Fangshenpao Formation, the mudstone of the Paleozoic Cambrian, and the Slate of the Proterozoic Qingbaikou are good cap beds.

![Figure 3](image-url) Profile map (geological section A-A’ is from Figure 1b) indicating a common mode of accumulations in different tectonic zones in the Liaohe Basin (modified from reference [19]).

3. Samples and Methods

3.1. Samples

To characterize the Shuguang oil reservoir, samples were collected (Table 1). The geochemical characteristics of source rock, reservoir quality, and charging period of the samples were analyzed. The data of crude oil were provided by the Research Institute of Exploration and Development of Liaohe Oilfield.

Table 1. The data of the samples from Shuguang area.

<table>
<thead>
<tr>
<th>Well</th>
<th>Layer</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Rock Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG183</td>
<td>Es4</td>
<td>2911</td>
<td>Mudstone</td>
<td>Source rocks</td>
</tr>
<tr>
<td>Shu103</td>
<td>Es4</td>
<td>3102</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG184</td>
<td>Es4</td>
<td>3030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shu111</td>
<td>Es4</td>
<td>3276</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG169</td>
<td>Es4</td>
<td>2910</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shu102</td>
<td>Es4</td>
<td>2301</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CG6</td>
<td>Es3</td>
<td>3181</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XX2</td>
<td>Es4</td>
<td>3710</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shu103</td>
<td>Pt</td>
<td>3404.7</td>
<td>Dolomite limestone</td>
<td></td>
</tr>
<tr>
<td>SG184</td>
<td>Pz</td>
<td>3180</td>
<td>Dolomite limestone</td>
<td></td>
</tr>
<tr>
<td>SG189</td>
<td>Pt</td>
<td>4169</td>
<td>Quartzite</td>
<td></td>
</tr>
<tr>
<td>SG183</td>
<td>Pz</td>
<td>3157</td>
<td>Dolomite limestone</td>
<td></td>
</tr>
<tr>
<td>SG98</td>
<td>Pt</td>
<td>1750</td>
<td>Quartzite</td>
<td>Reservoir rocks</td>
</tr>
<tr>
<td>SG169</td>
<td>Pt</td>
<td>3398</td>
<td>Quartzite</td>
<td></td>
</tr>
<tr>
<td>SG195</td>
<td>Pz</td>
<td>2255</td>
<td>Quartz sandstone</td>
<td></td>
</tr>
<tr>
<td>Shu116</td>
<td>Pt</td>
<td>4005.6</td>
<td>Dolomite limestone</td>
<td></td>
</tr>
<tr>
<td>Shu125</td>
<td>Pt</td>
<td>3788</td>
<td>Limestone</td>
<td></td>
</tr>
<tr>
<td>SG172</td>
<td>Pz</td>
<td>4138</td>
<td>Calcite dolomite</td>
<td></td>
</tr>
</tbody>
</table>
3.2. Methods

3.2.1. Geochemical Analyses

TOC (total organic carbon) and rock pyrolysis were measured by a Rock-Eval 6 pyrolysis analyzer. Pyrolysis includes two parameters: S₁ + S₂ (potential hydrocarbon generation from rock pyrolysis, mg/g) and Tmax (temperature of maximum rate of hydrocarbon generation from source rock, °C). Ro is the reflected light test by a Leica DM4500P polarizing microscope under the condition of sample fragmentation and oil immersion. The chloroform asphalt “A” was determined by a traditional fast Soxhlet extraction method.

3.2.2. Reservoir Characteristics

The blue dyed resin or liquid glue was poured into the pore space of the rock under a vacuum, so that the resin or liquid glue was consolidated, and then the rock was ground into thin slices. SEM images were produced at the China University of Petroleum (Beijing). The diameter of samples was 0.5–3.0 cm and the thickness were 0.2–1.0 cm. The observation instrument was a Zeiss SUPRA 55 Sapphire SEM. A sample of quartz sandstone was cut into sheets and then observed through an instrument. The helium expansion method was used to measure the porosity and permeability using an ultrapore–200A porometer. The diameter of the experimental reservoir core sample for porosity and permeability was 2.5 cm. The features of fractures were depicted by core description.

3.2.3. Fluid Inclusion

Petrographic observation was made by a NIKON-LV100 double-channel fluorescence, reflected light, and transmission light microscope. Micro thermometry was performed on a 300 µm thick, double-sided polished sheet on a LinkamTHMSG600 cooling and hot station. In the process of temperature measurement, the temperature rise rate of the hot and cold stations was controlled to within 0.1–5.0 °C/min and the correction test error was ±0.1 °C.

Moreover, BasinMod 1D software was utilized to construct burial history and thermal history by collecting data such as the strata thickness of single well, lithology, erosion thickness, Ro, geothermal gradient, and absolute age.

4. Results

4.1. Geochemical Features of Oil

The fluid physical properties reflect the preservation conditions and migration direction of crude oil to some extent. In this article, the oil test data of eight industrial oil flow wells in the Shuguang area in the Proterozoic and Archean oil groups were sorted out and analyzed, and the density of crude oil at 20 °C and the viscosity of crude oil at 50 °C were statistically analyzed so as to have a better understanding of the properties of Shuguang crude oil. At 20 °C, the density of crude oil basically ranged from 0.83 g/cm³ to 0.97 g/cm³ and light oil was generally less than 0.90 g/cm³, while heavy oil was more than 0.90 g/cm³. As can be seen from the table, the Shuguang area was dominated by light oil and the oil properties of the wells at the structural high point were obviously different from those of other wells, mainly due to the distribution of heavy crude oil in the top part of the early structure, which may be caused by the destruction of the crude oil formed in the early stage. Viscosity values ranged from 4.55 to 1256 mPa·s (Table 2).

Normal-density oil and heavy oil were mainly found in the Shuguang oilfield. Most of the normal-density oil was in the southeast of the Shuguang oilfield. The thermal cracking and migration fractionation were the critical factors controlling the physical properties of crude oil. Heavy oil was concentrated in the northwest of the Shuguang oilfield.
Table 2. Data of crude oil in Shuguang oilfield.

<table>
<thead>
<tr>
<th>Area</th>
<th>Well</th>
<th>Depth (m)</th>
<th>Density/g·cm$^{-3}$ (@20 °C)</th>
<th>Viscosity/mPa·s (@50 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shuguang oilfield</td>
<td>SG183</td>
<td>3185.0</td>
<td>0.87</td>
<td>57.6</td>
</tr>
<tr>
<td></td>
<td>Shu103</td>
<td>3392.5</td>
<td>0.84</td>
<td>8.73</td>
</tr>
<tr>
<td></td>
<td>Shu111</td>
<td>3755.42</td>
<td>0.83</td>
<td>7.33</td>
</tr>
<tr>
<td></td>
<td>SG98</td>
<td>1633.3</td>
<td>0.93</td>
<td>438</td>
</tr>
<tr>
<td></td>
<td>Shu116</td>
<td>4023</td>
<td>0.88</td>
<td>31.2</td>
</tr>
<tr>
<td></td>
<td>Shu125</td>
<td>3358.71</td>
<td>0.86</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>Shu110</td>
<td>3734.48</td>
<td>0.84</td>
<td>10.88</td>
</tr>
<tr>
<td></td>
<td>Shu107</td>
<td>3491.89</td>
<td>0.88</td>
<td>33.99</td>
</tr>
<tr>
<td></td>
<td>Shu112</td>
<td>2824.03</td>
<td>0.87</td>
<td>28.6</td>
</tr>
<tr>
<td></td>
<td>Shu123</td>
<td>3834.49</td>
<td>0.94</td>
<td>4.55</td>
</tr>
<tr>
<td></td>
<td>SG175</td>
<td>3993.29</td>
<td>0.83</td>
<td>9.12</td>
</tr>
<tr>
<td></td>
<td>SG100</td>
<td>1604.5</td>
<td>0.93</td>
<td>496.6</td>
</tr>
<tr>
<td></td>
<td>SG103</td>
<td>1933.50</td>
<td>0.85</td>
<td>19.91</td>
</tr>
<tr>
<td></td>
<td>SG104</td>
<td>1944.8</td>
<td>0.87</td>
<td>87.07</td>
</tr>
<tr>
<td></td>
<td>SG105</td>
<td>1917.50</td>
<td>0.86</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>SG106</td>
<td>1885.5</td>
<td>0.86</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>SG11</td>
<td>1791.83</td>
<td>0.85</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td>SG112</td>
<td>1555.5</td>
<td>0.93</td>
<td>441</td>
</tr>
<tr>
<td></td>
<td>SG26</td>
<td>1652.77</td>
<td>0.93</td>
<td>1256</td>
</tr>
<tr>
<td></td>
<td>SG32</td>
<td>1588.8</td>
<td>0.93</td>
<td>449.26</td>
</tr>
<tr>
<td></td>
<td>SG158</td>
<td>1134.66</td>
<td>0.97</td>
<td>7953</td>
</tr>
</tbody>
</table>

4.2. Condition of Source Rocks

Based on the research result, the source rocks in the Western Depression were thick and mainly in the Es4 Formation (Figure 4) [29]. Therefore, this paper focuses on evaluating the oil generation intensity of the Es4 Formation.

Figure 4. Thickness map of source rock of the Es4 Formation in Liaohe Basin.

The main indexes to evaluate the abundance of source rocks were TOC, PG, and chloroform asphalt “A” [30]. TOC content of mudstone ranged from 0.43% to 21.5% (average 4.42%). The PG of mudstone (S1 + S2, i.e., gas production) ranged from 0.49 to 62.31 mg HC/rock (average 19.4). According to the evaluation reference [31], the potential generation of mudstone was classified into non, poor, fair, good, and excellent grades. The mean value of chloroform asphalt “A” was 0.76%. The main types of the Shuguang reservoir were of a fair–good grade (Table 3, Figure 5a).
Table 3. The pyrolysis data of source rocks for the Shuguang area.

<table>
<thead>
<tr>
<th>Area</th>
<th>Rock Stratum</th>
<th>TOC (%)</th>
<th>PG (mg/g)</th>
<th>“A” (%)</th>
<th>Tmax (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shuguang area</td>
<td>Es4</td>
<td>0.43–21.5/4.42 (25)</td>
<td>0.49–62.31/19.4 (16)</td>
<td>0.25–1.34/0.76 (19)</td>
<td>420–458</td>
</tr>
</tbody>
</table>

Note: The number before ‘/’ is the data range; the number after ‘/’ is the mean value; the number in ‘( )’ is the quantity of samples. TOC: total organic carbon; PG: potential generation; “A”: chloroform bitumen “A”; Tmax: pyrolysis peak temperature.

Figure 5. Identification chart of generation potential (a) and organic matter types (b) of source rocks.

The oil index (HI) of mudstone ranged from 3.20 to 290.00 mg HC/g TOC. Most of the Tmax values of the source rocks ranged from 420 °C to 448 °C (Figure 5b). As can be seen from the relationship between the two parameters in Figure 5b, the main types of kerogens were II–II [31]. The Ro values of the samples ranged from 0.62% to 1.73%, and the main range was between 0.60% and 0.90%, indicating that source rocks had high hydrocarbon generation potential (Table 4).
Table 4. The vitrinite reflectance test data of the Shuguang oilfield.

<table>
<thead>
<tr>
<th>Well</th>
<th>Layer</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Ro (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG183</td>
<td>Es4</td>
<td>2911</td>
<td>Mudstone</td>
<td>0.82</td>
<td>This study</td>
</tr>
<tr>
<td>Shu103</td>
<td>Es4</td>
<td>3102</td>
<td>Mudstone</td>
<td>1.73</td>
<td>PLOEDRI</td>
</tr>
<tr>
<td>SG184</td>
<td>Es4</td>
<td>3030</td>
<td>Mudstone</td>
<td>0.84</td>
<td>This study</td>
</tr>
<tr>
<td>Shu111</td>
<td>Es4</td>
<td>3276</td>
<td>Mudstone</td>
<td>1.04</td>
<td>This study</td>
</tr>
<tr>
<td>SG169</td>
<td>Es4</td>
<td>2910</td>
<td>Mudstone</td>
<td>0.78</td>
<td>This study</td>
</tr>
<tr>
<td>Shu102</td>
<td>Es4</td>
<td>2301</td>
<td>Mudstone</td>
<td>0.85</td>
<td>This study</td>
</tr>
<tr>
<td>XX2</td>
<td>Es4</td>
<td>3710</td>
<td>Mudstone</td>
<td>1.58</td>
<td>This study</td>
</tr>
</tbody>
</table>

Note: PLOEDRI = PetroChina Liaohe Oilfield Exploration and Development Research Institute; Ro: vitrinite reflectance of source rock.

When organic matter entered the oil window, it produced a lot of oil. In conclusion, when the Ro value was 0.60%~0.90% (within the oil generation window), the source rocks could produce more oil. In a word, the source rocks in the Shuguang area had the conditions for forming industrial gas reservoirs [19].

4.3. Characteristics of Reservoir

The thin section test (Figure 6) showed that the Proterozoic lithology was mainly quartz sandstone. Rock fragment is a sedimentary rock formed by the weathering, migration, and deposition of rock debris. The particles of debris were from particulate to coarse medium; the sorting was generally good and the roundness was mainly subroundness. The main sandstones were quartz arenite (Figure 6) [32], which differed from the Middle Jurassic Ravenscar sandstones of North America.

![Figure 6. The Pt quartz sandstone compositional data in the Shuguang oilfield (the Miocene data are cited from Okunuwadje [33]).](image)

Figure 7 shows that intergranular pores, intergranular dissolution pores, and fractures formed the major space of the Proterozoic reservoir. However, primary pores were rare. Unstable rock dissolved, leading to the formation of intragranular pores (Figure 7a). The different shapes of the intergranular pores were caused by the dissolution of calcite...
(Figure 7b,c), and some of the intergranular pores were due to the formation of quartz particles (Figure 7d). Part of the fractures existed in the core, showing the development of sandstone fractures (Figure 7e,f). To sum up, a comprehensive analysis was suitable to characterize the different pore structures of the reservoir.

Figure 8 indicates there was no obvious change trend between the porosity and permeability of Pt sandstone. More than 55% of Pt sandstones had porosity less than 10%. The porosity distribution ranged from 0.65% to 19.6%, and the 55% of the permeability was from 0.04 to 13.2 mD. To sum up, the Pt reservoir porosity was generally low. However, fractures and dissolution could make local physical properties better [20].

**Figure 7.** Main reservoir space types of sandstones in the Shuguang oilfield. Note: Intragenular dissolution pore (cast thin section), well Shugu175 (Pt), 3986.63 m (a); intergranular dissolved pore, (cast thin section), well Shugu175 (Pt), 3989.13 m (b); intergranular dissolved pore (SEM), well Shugu175 (Pt), 3987.83 m (c); intergranular pores (SEM), well Shugu169, (Pt) 3396.10 m (d); fracture (SEM), well Shugu172 (Pt), 3983.49 m (e); fracture (SEM), well Shugu173 (Pt), 4137.08 m (f).
4.4. Oil Charging Periods

The homogenization temperature (HT) of inclusions and the burial history could determine the hydrocarbon charging period of the reservoir [34]. Fluid inclusions developed well in the Pt reservoir, which were divided into oil and brine inclusions.

The fluid inclusions in this area could be divided into two phases according to the formation period and inclusions’ characteristics of the main minerals.

(1) The first phase of inclusions: oil inclusions (Figure 9a,b) and the host minerals were mainly quartz, followed by calcite and feldspar. The size of the inclusions ranged from 1 to 70 µm, the HT of the brine inclusions were symbiotic, and the organic inclusions ranged from 100 to 110 °C. Under a polarizing microscope, it was gray-black, black, and brown-black, and fluorescence showed a dark-brown fluorescence. It may be formed mainly in the low-maturity stage and mainly in heavy oil.

Figure 8. The relationship between porosity and permeability of the Pt sandstone reservoir from the Shuguang oilfield (N = 102).

Figure 9. Photomicrographs of inclusions from for the Proterozoic strata. Note: well Shugu169, 3398.1 m, Pt, quartz sandstone, oil inclusions under transmitted light (a); well Shugu169, 3398.1 m, Pt, quartz sandstone, oil inclusions are yellow-green under UV light (b); well Shugu172, 4138.3 m, Pt, quartz sandstone, oil inclusions under transmitted light (c); well Shugu172, 4138.3 m, Pt, quartz sandstone, oil inclusions are yellow-green and blue-green under UV light (d).
(2) The second phase of inclusions: mainly oil inclusions (Figure 9c,d). The host minerals were mainly quartz followed by calcite. The size of the inclusions was 1–9 μm and they were grayish-brown, light grayish-brown, brown, etc. The fluorescence of blue-white, dark blue-white, or dark blue was displayed under UV excitation. The HT of the brine inclusions was 125–140 °C. They may be formed in the mature stage and mainly in mature oil [35].

Figure 10 and Figure 11 show the oil charging periods were 38 Ma and 28 Ma, respectively, corresponding to the result of a previous study [36].

![Figure 10. Homogenization temperature of oil inclusions in well Shugu169 in Shuguang area.](image)

![Figure 11. The timing of hydrocarbon filling by using homogenization temperatures of fluid inclusions and thermal history modeling for well Shugu169 in Shuguang area.](image)

5. Discussion

5.1. Controlling Factors of Oil Accumulation

5.1.1. High-Quality Source Rocks in Organic Matter

Source rocks have a critical influence on the location of oil accumulation. Due to a large unconformity surface and fractures, oil accumulated near traps after hydrocarbon expulsion from source rocks. The analysis of Section 4.2 indicates that high-quality source rocks exist in Es4 with a thickness of 100–400 m (Figure 4). According to Section 4.2, the quality of source rocks was good; a previous study showed that the Es4 source rocks were good and the oil generation intensity was high [37]. The oil production intensity in the Shuguang area is about $25 \times 10^6$–$500 \times 10^6$ t/km² (Figure 12). This result indicates that the source rocks can provide enough oil for a large accumulation of oil.
5.1.2. Oil Charging Characteristics

According to the analysis results in Section 4.4, oil charging periods were 38 Ma and 28 Ma, respectively (Figure 11). Tectonic activity is the key factor influencing the accumulation process of the Shuguang oil reservoir. On this basis, it can be concluded that there were two oil charging periods in the Shuguang reservoir.

From the Yanshanian movement period to the Himalayan orogeny period, the strata deformation was strong and developed from northeast to southwest. The tectonic deformation of this time had a dual function. First, it matched the major oil expulsion stage and caused late accumulation. Second, it disrupted and adjusted an early reservoir.

In general, the Pt reservoirs had different accumulation periods (Figure 13).

(1) Es stage (45–36 Ma): In the late Yanshanian movement, tectonic traps formed in the Pt strata, and the faults were still active at this time, with transport characteristics. The Es4 source rocks were less mature, and the heavy oil and low-maturity oil migrated to the middle and high buried hills along the active faults and accumulated in the traps of the Pt strata. The peak period of oil charging was 38 million years ago.

(2) Ed period (35–23 Ma): This period was the key period of reservoir formation. The traps were basically established. The Es source rocks gradually developed and matured. A large amount of mature oil was generated and then moved along the faults to the traps of the Pt strata in the low buried hill to form reservoirs. The peak of oil charging was 28 million years ago. It is worth mentioning that the late Himalayan movement may have damaged and adjusted the reservoir at that time.

<table>
<thead>
<tr>
<th>3000</th>
<th>1800</th>
<th>570</th>
<th>100</th>
<th>65</th>
<th>50</th>
<th>23</th>
<th>Geological time (Ma)</th>
<th>Geological era</th>
</tr>
</thead>
<tbody>
<tr>
<td>Es</td>
<td>Pt</td>
<td>Ps</td>
<td>Ma</td>
<td>E</td>
<td>N</td>
<td></td>
<td>Source rock</td>
<td>Reservoir rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Trap formation</td>
<td>Oil generation period</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Early oil generation period</td>
<td>Late oil generation period</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Oil charge time</td>
<td>Destruction and modification of hydrocarbon reservoir</td>
</tr>
</tbody>
</table>

**Figure 12.** Accumulating oil generation intensity of Es4 source rocks from the Shuguang area (modified according to the data from PLOEDRI).

**Figure 13.** Comparison diagram of oil accumulation events in the Shuguang oil reservoir, including the reservoir-forming element and the oil charging period.

In conclusion, oil accumulation in the Shuguang oil reservoir is a continuous process. However, a previous scholar considered that three charge periods happened in the oil
reservoir [38], which does not correspond to this study. It may have been caused by the
difference in the selected inclusions.

5.1.3. Fracture Influencing the Distribution of Oil Reservoir

The pore structure of a reservoir affects the formation mechanism of that reservoir
[39]. The major migration of reservoir formation is the pore, fracture, and the fault. The
permeability of quartz sandstone in the Shuguang oilfield is low. Therefore, improving
permeability through fractures is key to local fluid migration [40]. The linear fracture density
(LFD) was used to study the fractures in the Pt reservoir [41]. Take the Dibei oil and
gas reservoir in the Kuqa Depression as an example. Industrial oil flow from well YN2
was found in the Jia Formation. The LFD of the strata is 4.18/m [42]. In contrast, the Jiy
unit has no industrial oil and gas, and the LFD is 1.56/m. The result shows that LFD is
critical to improve oil and gas production. Due to the structural extrusion in the Shuguang
area, the LFD of the formation improved the porosity and permeability of the reservoir
and controlled the distribution of the reservoir. Core and thin section results showed that
the number of formation fractures was large in the Shuguang area (Figure 7e,f) and pro-
vide a good condition for oil accumulation. The analysis showed that fractures affect the
distribution of oil, which corresponds to the result of the Dibei reservoir [39].

5.1.4. Preservation Condition

Good conditions for the preservation of a cap layer are conducive to the formation of
large oil and gas reservoirs [43,44]. The combination of source, reservoir, cap, and fault in
the Shuguang area is conducive to oil preservation. The main source rock is Es4 mudstone.
Pt quartz sandstone is rich in fractures and is a good reservoir. The sealing ability of the
overlying Fangshenpao Formation and the Mesozoic cap layer is better, which can pre-
vent vertical oil loss [45]. Oil migrates along faults and fractures and accumulates in
nearby reservoirs.

5.2. Accumulation Mode

Oil generation intensity is high in the Shuguang area, indicating it can produce a
large amount of an oil resource (Figure 12). Quartz sandstone is favorable for the for-
mation of an oil reservoir. From the perspective of longitudinal sedimentary assemblage,
the reservoir-forming mode of the Shuguang oil reservoir is of a lower generation and
upper reservoir. Due to the differences in the source rocks, the oil accumulation mode
differs from some scholars’ conclusion [46].

Based on the above analysis, the Shuguang reservoir was confirmed as a structure-
lithologic mode (Figure 14) with the following reservoir-forming characteristics:

1. In the early stage, the source rock produced oil and migrated upward along the fault
connecting the source rock to the reservoir. Some oil migrated laterally to the reser-
voir traps in the middle buried hill and high submerged hill. This situation applies
to heavy oil and low-maturity oil charging in the early period.

2. In the late period, mature oil from the source rocks moved along faults and fractures
to the reservoirs in the low buried hill and accumulated under the cover of the cap.
5.3. Implications for Development

Reservoir physical properties control reservoir production. Oil migrates upward and along fractures and faults. If upper rock blocks the upward path, oil migrates laterally and gathers in the trap. A structural trap and stratigraphic trap are key to oil accumulation. A large number of thrust faults play a key role in oil migration and oil reservoir [14,47].

The fractures in the Shuguang reservoir mainly developed due to a strong structural extrusion. Fractures have a certain influence on the reservoir. If the fracture occurs at the top of the oil reservoir, it can reduce the sealing capacity of the cap layer, resulting in oil leakage. On the contrary, if fractures develop within the reservoir, the sandstone physical properties are optimized and the reservoir is adjusted, which is favorable for the formation of a “sweet spot” (a relatively oil- and gas-rich region) [39]. Well Shugu 169 has an LFD of 4.12/m with the highest daily energy, while wells Shugu175 and Shugu183 have a lower LFD and lower production. The reason for this phenomenon is that the development of fractures optimizes the physical properties of the reservoir. Such fractures can increase commercial production of oil and gas reservoirs in the United States [48] and China [14].

In addition, the Shuguang area is a potential area with a lot of oil. This point should be the critical focus of future work: by revealing the coupling relationship of key control factors, a new “sweet spot” of oil resources in the Shuguang area should be further determined.

6. Conclusions

(1) The source rocks in the Shuguang area were mainly developed in the Es4 Formation and have a strong oil generation intensity, which produces a lot of oil for the oil reservoir.

(2) During the Es stage (45–36 Ma), oil migrated along the active faults and accumulated in the tectonic traps of the Pt strata. During the Ed period (35–23 Ma), a lot of mature oil moved along the faults to the traps of the Pt strata to form reservoirs. The late Himalayan movement might have adjusted the reservoir at that time. The faults and fractures provide a good path for oil migration.

(3) The relationship between the source–reservoir–cap assemblage and trap and the fracture in the Shuguang area is favorable for oil accumulation. It is a structure-lithologic oil reservoir with lower generation and an upper reservoir. The “sweet spot” associated with fracture is the critical focus of future work.

Author Contributions: Conceptualization, G.Z. and F.J.; methodology, Q.Z.; software, H.P.; validation, S.Z., Q.Z., and X.L.; formal analysis, D.C.; investigation, X.L.; resources, D.C.; data curation, S.Z.; writing—original draft preparation, G.Z.; writing—review and editing, F.J.; supervision, H.P.
project administration, F.J.; funding acquisition, D.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was financially funded by the Science Foundation of China University of Petroleum, Beijing (2462022XKB1005), and China Postdoctoral Science Foundation (2022M723487).

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Acknowledgments:** We appreciate Yanmin Guo and Zhi Tian for their help in collecting the data. Their insightful suggestions were also helpful for the manuscript.

**Conflicts of Interest:** The authors declare no conflicts of interest.

**References**


29. Ge, W. Study on Tight Oil Accumulation Characteristics of the Fourth Member of Shahejie Formation in Western Liaohe Depression. Master’s Thesis, Southwest Petroleum University, Chengdu, China, 2018. (In Chinese with English Abstract)


34. Lisk, M.; Brincat, M.; Gartrell, A. An integrated evaluation of hydrocarbon charge and retention at the Griffin, Chinook, and Scindian oil and gas fields, Barrow Subbasin, North West Shelf, Australia. AAPG Bull. 2006, 90, 1399–1380.


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.