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Geochemical Analysis of a Multi-Layer Hydrocarbon Reservoir in the Wuerhe Area, Junggar Basin

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Abstract: From 5000 m underground to the surface, there is a multi-layer hydrocarbon reservoir under the Wuerhe nose uplift in the Junggar Basin. Light oil, heavy oil, oil sand, and solid bitumen are found in Permian to Cretaceous strata. The normal crude oil present under heavy oil and solid bitumen reservoir can easily ignored by explorers. To effectively exploit the petroleum and bitumen mineral resources in the Junggar Basin, geochemical characteristics of crude oils in the different layers were analyzed. It is concluded that the crude oils and bitumen minerals came from Permian source rocks of alkaline lacustrine facies. Combined with tectonic movement analysis, two stages of accumulation occurred in research area. During the Indosinian Tectonic movement, the crude oil generated from Permian source rocks first migrated upwards along large faults and then accumulated in the Permian, Triassic, and Jurassic reservoirs. The crude oil of the Jurassic reservoir was seriously biodegraded and a high abundance of 25-norhopane was detected. At the end of the Yanshan movement, small normal faults were developed to connect the oil in the Triassic reservoirs to the surface. The light components of the oil in the fault system quickly volatilized and left solid bitumen minerals in the faults. Due to the plugging effect of “bitumen plug”, the oil and gas in the lower part cannot migrate upward and be damaged. Therefore, light oil-heavy oil–oil sand and bitumen minerals were formed from the bottom to the top. The research result will also have a guiding significance for oil and gas exploration in the northwest margin of the Junggar Basin.

Keywords: biomarkers; crude oil alteration; oil-source correlation; multi-layer accumulation; geological movement

1. Introduction

A Permian-Triassic normal crude oils reservoir (normal crude oils reservoir include light oils reservoir and medium reservoir oils) has been found, and a Jurassic heavy oil reservoir and a bitumen mine have been discovered in the Wuerhe area of the Junggar Basin [1]. Heavy oil is an important resource for the development of world economy. In the northwest margin of the Junggar Basin, the proven accumulated heavy oil geological reserves are nearly $3 \times 10^8$ t, accounting for 97% of the total proven accumulated heavy oil geological reserves in the basin [2]. The main causes of heavy oil and bitumen in the Junggar Basin are the decomposition, consumption, and oxidation of hydrocarbon components in crude oil by biodegradation, water washing, and oxidation [2,3]. Most scholars use 3D static modeling to study multi-layer oil reservoirs by sedimentology and well log-based petrophysics [4–6]. They are usually not clear about the causes of multi-layer oil reservoir evaluation, because they lack a geochemical mechanism [7]. This study analyses the physicochemical properties of crude oil and geological evolution process. It reveals the oil alteration process and the formation process of light oil-heavy oil–oil sand and bitumen multilayers. This research also provides theoretical guidance for the exploration and development of oil reservoirs.
2. Geological Setting and Petroleum Background

2.1. Geological Setting

The Wuerhe area is located in Karamay City, Xinjiang Uygur Autonomous Region. It is located in the Wuxia fault zone of the northwest margin of the Junggar Basin, adjacent to the Mahu oil-rich depression in the South (Figure 1).

Figure 1. Structural location map of the research area, northwestern Junggar Basin.

The clastic sediments in the basin were mainly deposited after the Carboniferous [8]. The vertical sequence of strata encountered during drilling primarily includes the Tugulu group of the Cretaceous system; the Qigu, Sangonghe and Badaowan Formations of the Jurassic system; the Baijiantan, Karamay, and Baikouquan Formations of the Triassic system; and the lower Wuerhe, Xiazijie, and Fengcheng Formations of the Permian system. Among them, Cretaceous and Jurassic, Jurassic and Triassic, and Triassic and Permian are regional unconformity contacts (Figure 2).

The late Hercynian tectonic movement formed the basic outline of the Junggar Basin, including large uplift, depression, and large-scale fault zone in Permian. The Karamay-Wuerhe fault zone was formed in this period. Early strong tectonic activity accompanied by a volcanic eruption resulted in the deposition of extremely thick sandy conglomerate and volcanic rock of the Jiamuhe Formation. During the sedimentary period of the Fengcheng Formation, volcanic activity decreased gradually, the climate became dry, and evaporation began, forming an alkaline lake sedimentary environment. The Fengcheng Formation, composed of high-quality source rocks, was formed by the lithologic combination of marginal conglomerate, middle dolomite, and local volcanic rocks [9].
Figure 2. Comprehensive stratigraphic column of Wuerhe area, showing the stratigraphic conditions.

The intensity and scope of the Triassic Indosinian tectonic movement was smaller than that of the previous Permian movement. It inherited the previous tectonic movement and formed some nose structures and reverse faults [8]. The whole Triassic is a normal cycle terrigenous coarse clastic deposit with lithology from coarse to fine and water body from shallow to deep. From bottom to top, the lithologic combination of sandstone and...
mudstone interbedding was formed. Under the influence of the Late Triassic tectonic movement, the strata were uplifted, and the lake water retreated.

The intensity of the Yanshanian movement in Jurassic was much weaker than that of the Carboniferous–Permian movement and only inherited activity in the Wuxia fault zone. In the late Yanshanian movement, the main faults and folds in the Wuxia fault zone stopped, and the tectonic movement was mainly characterized by intermittent subsidence. The Cretaceous and Later Cenozoic strata were filled steadily and overlapped with low angle from southeast to northwest [10]. On the underlying paleotectonic background, the stratum was thick in the south and thin in the north, which gradually thinned out.

2.2. Structural Characteristics

In the Permian–Triassic era, the research area developed a large nose-shaped structural belt with a 10 km width and a 20 km length horizontally and two sets of deep and shallow fault systems longitudinally. The deep large-scale reverse fault was formed in the Hercynian Indosinian movement. Five reverse faults were developed from the Halalarte mountain to the Mahu depression. Among them, F3 and F5 faults control the boundary of the Wuerhe nose uplift; F4 fault is located in the middle of the nose uplift, and the deep fault section breaks upward from the Carboniferous system to the top of the Jurassic system (Figure 3c).

Figure 3. Structural characteristics of Wuerhe nose uplift, showing the two sets of deep and shallow faults are connected with each other on the profile, forming a “Y” type combination, which provides a channel for oil migration (a–c).
Small scale positive faults and strike-slip fault systems formed by the Yanshanian movement are developed in the shallow layer, with the characteristics of “flower structure” in their profile. The faults are broken upward to the ground surface and downward to the Jurassic and Triassic strata. The two sets of fault systems show a “Y” type combination on the section and nearly parallel extension in the plane, both striking near northeast. The interpretation scheme of shallow faults can be accurately determined through satellite photos, field observations, and wave group variation characteristics of the seismic profile in the Wuerhe bitumen vein area (Figure 3a,b). The inherited nose uplift structure and the relay communication of deep and shallow fault systems provide conditions for oil accumulation and vertical migration channel for multi-layer reservoir formation.

2.3. Petroleum Background

In the center of nose uplift, normal oil reservoirs in the 11 blocks of the Wuerhe oilfield have been found to have Permian–Triassic strata, with reserves of approximately 230 million tons of oil having a density of 0.863–0.904 t/m$^3$ (API gravity values is 25.0–32.5). The reservoir types are mainly structural or lithologic with a structural background (Table 1). Heavy oil reservoirs in six blocks of Fengcheng oilfield have been found to have Jurassic strata in the northwest wing of nose uplift, with reserves of approximately 372 million tons and density of 0.958 t/m$^3$. Through conventional thermal recovery, superheated steam huff and puff and Steam Assisted Gravity Drainage (SAGD) development tests [11], it has been determined that the Fengcheng heavy oil has entered the stage of large-scale development, with an annual production of more than 2 million tons.

Compared with other areas, in the north of the Fengcheng oilfield, the depth of buried strata is shallower, and the physical properties of its Jurassic and Cretaceous reservoirs are better. After the migration of deep oil and gas, oil sand may be formed through oxidation, water washing, and light component volatilization. Some oil sands are exposed on the surface, forming the largest oil sandhill and residual hill in China [2].

<table>
<thead>
<tr>
<th>Name</th>
<th>Block Description</th>
<th>Middle Buried Depth (m)</th>
<th>Reservoir Lithology</th>
<th>Reservoir Type</th>
<th>Crude Oil Density (t/m$^3$)</th>
<th>Gas Oil Ratio (m$^3$/m$^3$)</th>
<th>Geological Reserves (10$^4$ t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wuerhe Oilfield</td>
<td>Feng 3, Feng 5, Feng 1 well blocks</td>
<td>P1f</td>
<td>Dolomitic siltstone</td>
<td>Structure, structure-lithology</td>
<td>0.898</td>
<td>116</td>
<td>4682</td>
</tr>
<tr>
<td></td>
<td>Fengnan 5 well block</td>
<td>P1f</td>
<td>Dolomitic siltstone</td>
<td>Lithology, structure</td>
<td>0.904</td>
<td>75</td>
<td>3346</td>
</tr>
<tr>
<td></td>
<td>Wu 35, Fengnan 2 well blocks</td>
<td>P2x</td>
<td>Glutenite</td>
<td>Fault nose, structure-lithology</td>
<td>0.863</td>
<td>27</td>
<td>5608</td>
</tr>
<tr>
<td></td>
<td>Wu 27 well block</td>
<td>P2w</td>
<td>Glutenite</td>
<td>Structure, lithology</td>
<td>0.871</td>
<td>80</td>
<td>912</td>
</tr>
<tr>
<td></td>
<td>Wu 33, Wu 36, Wu 5 well blocks</td>
<td>T1b, T2k</td>
<td>Glutenite</td>
<td>Structure, lithology</td>
<td>0.863</td>
<td>30</td>
<td>7665</td>
</tr>
<tr>
<td></td>
<td>Wu 16 well block</td>
<td>T2k</td>
<td>Glutenite</td>
<td>Structure-lithology</td>
<td>0.877</td>
<td>9</td>
<td>723</td>
</tr>
<tr>
<td></td>
<td>Zhong 18, Zhong 32, Zhong 5, Zhong 59,</td>
<td>J1b, J3f</td>
<td>Sandstone</td>
<td>Structure-lithology</td>
<td>0.958</td>
<td>0</td>
<td>37,200</td>
</tr>
<tr>
<td></td>
<td>Zhong 010 well blocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fengcheng Oilfield</td>
<td>Zhong 37, Zhong 59, Zhong 010 well blocks</td>
<td>J1q</td>
<td>Sandstone</td>
<td>Exist in fault fractures</td>
<td>-</td>
<td>0.982</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Oil sand deposits</td>
<td>J1q</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>5017</td>
</tr>
<tr>
<td></td>
<td>Bitumen mine</td>
<td>K1g</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>12–15</td>
</tr>
</tbody>
</table>

In the main part of the nose uplift, the fault system connects with a deep reservoir; oil and gas migrate to the surface via the fault system and forms bitumen through secondary action. The distribution of veins is controlled by the fault system, and it reflects the spatial distribution characteristics of faults (Figure 4). Eighteen main faults can be seen in the outcrop, forming a broom-like fault zone spreading in the southwest and converging in the northwest. The width of the bitumen vein (horizontal fault distance) generally ranges from
0.05 m to 0.5 m, the maximum being about 1.2 m. The sandstone on both sides of the vein is black owing to bitumen impregnation; it has a width of 0.5–1.5 m, forming black oil sand deposit. The mine is the only natural bitumen mine for large-scale mining in China. The proven mineral reserves are about 120,000–150,000 tons. Bitumen production began in 1958, and the maximum annual production of bitumen can reach 8000 tons. After more than 60 years of mining, only 110 m of the upper part of the ore vein has been excavated, and the lower part of the bitumen vein, that is nearly 250 m deep, is yet to be mined. The bitumen produced by the ore vein is rare, high-quality, and hard bitumen which is an important raw material for special paint and ink.

Figure 4. Normal fault characteristics of Wuerhe asphalt vein, showing the sandstone on both sides of the fault with a width of 0.5–1.5 m, forming a black asphalt vein due to bitumen impregnation.

3. Experimental Methods

The samples used in the experiment were obtained from the Wuerhe oilfield, Wuerhe bitumen vein, Fengcheng oil field, and oil sand deposits in the Wuerhe area, northwest Junggar Basin. Moreover, 5 Permian source rocks, 5 Permian light oil, 5 Triassic medium oil, 5 Jurassic heavy oil, and 2 Cretaceous solid bitumen were collected for experimental analysis.

3.1. Separation of Organic Matter

The Permian source rock samples were first crushed to 100 mesh (0.177 mm), and Soxhlet extraction was carried out with chloroform (chloroform) as solvent for 72 h to obtain the soluble organic matter. The organic matter in the rock and crude oil are separated by chromatographic column. To precipitate the asphaltene with n-hexane, deasphalting was carried out by silica gel/alumina (2:1, volume ratio) chromatographic column. The qualitative components are separated into saturated hydrocarbons, aromatic hydrocarbons, and non-hydrocarbon fractions.
3.2. GC Analysis

For GC analysis, we used an Agilent 7890A gas chromatographic instrument equipped with a HP-5 column (30 m × 0.32 mm inner diameter × 0.25 µm film thickness) and a flame ionization detector (FID). The temperature of the GC oven was maintained at 60 °C for 2 min, then increased to 290 °C at the rate of 4 °C/min, and finally maintained at 290 °C for 30 min. Nitrogen was used as a carrier gas at a constant flow rate of 1.2 mL/min.

3.3. GC-MS Analysis

For gas chromatography-mass spectrometry (GC-MS) analysis, the following conditions were implemented: The ion source temperature was 250 °C, and the ionization energy was 70 eV. The chromatographic column was a HP-5 elastic quartz capillary column (30 m × 0.32 mm × 0.25 µm film thickness). The carrier gas was 99.999% helium. The initial temperature was 80 °C. The temperature was raised to 300 °C at 4 °C/min, and then it was kept constant for 30 min. Data during the experiment were recorded by the full scan and selected ion monitoring (SIM) modes.

4. Results and Discussion

4.1. Group Composition

The composition of crude oil changes greatly from bottom to top (Figure 5). In Permian source rocks, saturated hydrocarbons make up 75.6~90.4%, while non-hydrocarbons and asphaltenes make up 6.1~13.7%. In Permian–Triassic normal oil, 0.8400~0.8809 g/cm³ for oil density (Table 2), saturated hydrocarbons make up 63.8~85.2% of its contents while non-hydrocarbons and asphaltenes make up 6.2~20.4%. In Jurassic heavy oil, 0.9270~0.9564 g/cm³ for oil density, saturated hydrocarbons make up 31.8%~57.1% of its contents while non-hydrocarbons and asphaltenes make up 27.1~40.1%. Cretaceous solid bitumen density is greater than 1 g/cm³, average 1.1245 g/cm³. In the solid bitumen, saturated hydrocarbons make up on average 13.5% while non-hydrocarbon and asphaltenes make up on average 80.1%. From Permian to Cretaceous, the saturated hydrocarbon content of crude oil decreases, while the content of non-hydrocarbons and asphaltenes increases. Thus, it may be concluded that the group composition of crude oil is altered by secondary actions such as biodegradation, water washing, and oxidation. The content of each component in the source rock is similar to that in the normal oil, indicating that the Permian–Triassic oil is from the Permian source rock. The decrease in the content of light components (such as saturated hydrocarbons) and the increase in the contents of heavy components (such as non-hydrocarbons and asphaltene) increases the density and viscosity of crude oil.

Table 2. Density and viscosity data of crude oil samples in Wuerhe area.

<table>
<thead>
<tr>
<th>Number</th>
<th>Horizon</th>
<th>Density (g/cm³)</th>
<th>Viscosity (Pa.s 20 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P_1_w</td>
<td>0.8513</td>
<td>18.77</td>
</tr>
<tr>
<td>2</td>
<td>P_2_w</td>
<td>0.8809</td>
<td>63.10</td>
</tr>
<tr>
<td>3</td>
<td>P_3_w</td>
<td>0.8517</td>
<td>19.69</td>
</tr>
<tr>
<td>4</td>
<td>P_4_w</td>
<td>0.8542</td>
<td>20.17</td>
</tr>
<tr>
<td>5</td>
<td>T_1_b</td>
<td>0.8400</td>
<td>9.74</td>
</tr>
<tr>
<td>6</td>
<td>T_2_b</td>
<td>0.8654</td>
<td>28.25</td>
</tr>
<tr>
<td>7</td>
<td>J_3_q</td>
<td>0.9270</td>
<td>2779.70</td>
</tr>
<tr>
<td>8</td>
<td>J_3_q</td>
<td>0.9564</td>
<td>4847.00</td>
</tr>
<tr>
<td>9</td>
<td>J_3_q</td>
<td>0.9564</td>
<td>4712.00</td>
</tr>
<tr>
<td>10</td>
<td>K_1_h</td>
<td>1.1300</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>K_1_l</td>
<td>1.1190</td>
<td>-</td>
</tr>
</tbody>
</table>

4.2. N-Alkanes

Saturated n-alkanes are one of the most compounds in source rocks, and their carbon composition and distribution is mainly affected by sedimentary environment and thermal evolution [12]. Odd–Even Predominance (OEP) is 1.01~1.16, consistent with odd carbon
number predominance. It indicates that the source rocks and crude oil in the study area were highly mature.

![Figure 5. Triangles of group composition contents of crude oil samples in Wuerhe area, showing a decrease of the saturated hydrocarbon content and an increase of non-hydrocarbons and asphaltene contents from Permian source rocks to Cretaceous bitumen.](image)

Pristane/Phytane (Pr/Ph) is an important index for judging the redox conditions of the depositional environment [2]. The ratios of the samples are 0.36–0.96, all less than 1 (Table 3). The values of Pr/ n-C<sub>17</sub> and Ph/ n-C<sub>18</sub> can also reflect redox conditions and their oil source correlation. The ratios of Ph/nC<sub>18</sub> and Pr/nC<sub>17</sub> in source rocks, crude oil, and bitumen are deposited in the reducing environment and may be related to each other (Figure 6).

**Table 3. Biomarker parameters of source rocks and crude oil samples in Wuerhe area.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Permian Source Rocks</th>
<th>Light Oil</th>
<th>Normal Oil</th>
<th>Heavy Oil</th>
<th>Bitumen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO. 1 2 3 4 5 6 7 8 9</td>
<td>A 0.45 0.36 0.65 0.75 0.73 0.68 0.66 0.66 0.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B 1.13 1.05 1.05 1.03 1.09 1.09 1.05 1.01 1.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C 0.24 0.28 0.18 0.38 0.35 0.31 0.29 0.20 0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D 1.11 0.66 0.74 0.39 0.29 0.36 0.39 0.39 0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E 0.59 0.54 0.56 0.53 0.52 0.53 0.54 0.49 0.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: A: Pristane/Phytane (Pr/Ph); B: Odd–Even Predominance (OEP); C: Ts/(Ts + Tm); D: gammacerane/C<sub>30</sub>-hopane; E: C<sub>31</sub>-hopane 22S/(22S + 22R).

4.3. Steranes

The different content of sterane in crude oil may be related to its sedimentary environment [13]. During the deposition period of the Fengcheng Formation in the Wuerhe area, the climate became dry, and evaporation began, forming an alkaline lake sedimentary environment, and therefore, the content of C<sub>29</sub> steranes in crude oil increased. In addition, the distribution of regular steranes of C<sub>29</sub> and C<sub>30</sub> compounds became relatively concentrated (see triangle diagram; Figure 7). This indicates that the crude oils in this area originated from the source rocks of Permian Fengcheng Formation with the abundance of algae in the parent materials.
Figure 6. Pr/nC_{17} vs. Ph/nC_{18} diagram of source rocks and crude oil samples in Wuerhe area, showing most of the samples are distributed in the range of type I. (I: Organic matter produced by algae; II: Organic matter produced by algae and terrestrial; III: Organic matter produced by terrestrial).

4.3. Steranes

The different content of sterane in crude oil may be related to its sedimentary environment [13]. During the deposition period of the Fengcheng Formation in the Wuerhe area, the climate became dry, and evaporation began, forming an alkaline lake sedimentary environment, and therefore, the content of C_{29} steranes in crude oil increased. In addition, the distribution of regular steranes of C_{29} and C_{30} compounds became relatively concentrated (see triangle diagram; Figure 7). This indicates that the crude oils in this area originated from the source rocks of Permian Fengcheng Formation with the abundance of algae in the parent materials.

4.4. Hopanes

Hopanes are the most widely distributed complex biomarkers in sediments. Gammarocene is an important biomarker compound in saline water environments. A high content of gammarocene is often used as an indicator of a strongly reducing high salt environment [14]. It can be seen from Table 3 that in the source rocks and crude oil samples, the gammacerane index is greater than 0.14, indicating a high salinity environment. The C_{31}-hopane 22S/(22 S + 22 R) value are greater than 0.50, indicating high maturity of the source rock and crude oil. A small amount of Ts was detected in all samples, and the Ts/(Ts + Tm) value is less than 0.38. Thus, it can be inferred that the crude oil in the Wuerhe area all comes from Permian source rocks. The mass of the source rocks and crude oil samples is provided in Figure 8. The C_{19} and C_{21} peaks of tricyclic terpanes are higher than those of the rest; the Tm peaks are higher than the Ts peaks, and the peaks of C_{30} to C_{35}-hopanes decrease in turn and contain higher gammacerane alkanes and have similar characteristics. It can be proved that all crude oils come from Permian source rocks.

4.5. Reservoir Formation Model

Based on the comprehensive analysis of geological tectonic movement and reservoir geochemical characteristics, two stages of tectonic movement occurred in the Wuerhe area, resulting in two stages of reservoir formation.

During the Late Permian Jurassic, the thrust folds and large-scale faults formed by the Hercynian Indosinian movement in the Wuerhe area determined the accumulation of oil and gas in later stages. The folds provided certain conditions for the accumulation of oil and gas in later stages. The large fault connecting the Permian, Triassic, and Jurassic strata enabled the oil and gas produced by the source rocks of the Permian Fengcheng Formation to migrate upward form three sets of reservoirs. At the time of migration, the
three reservoirs were all light oil reservoirs; then, their strata denuded. Being the uplift wall of the fault, the northern strata suffered from serious denudation. As a result, the original light oil reservoir was exposed to the surface and suffered from biodegradation, oxidation, and other secondary effects, forming an oil sand deposit. In total ion chromatograms (TIC) of Jurassic heavy oil, the content of n-alkanes is very small, and the baseline is higher (Figure 9 TIC). When a “baseline bulge” of biodegradation markers occurs, it forms certain compounds, the mixture of which is collectively termed as “unknown complex mixture” [15]. As shown in Figure 9, the peaks of pristane and phytane are similar to the main peaks of C\textsubscript{17} and C\textsubscript{18} n-alkanes, which indicates that the biological activity is strong. The nC\textsubscript{17} and nC\textsubscript{18} concentrations are greatly reduced by strong biodegradation of crude oil. Meanwhile, 25-norhopane, considered as the biodegradation product of crude oil, was also detected in heavy oil (Figure 9 m/z191); 25-norhopane is also known as 10-demethylhopane or demethylated hopane or degraded hopane. In the process of degradation, bacteria first consume light components such as n-alkanes, which lead to the enrichment of oil with heavy components and increases the oil density and viscosity. In the weak denudation nose bulge, the depth, temperature, and other conditions are suitable for the survival of microorganisms. The original light oil reservoir must have been seriously biodegraded and washed out to form a heavy oil reservoir.

Figure 7. Diagram of C\textsubscript{27}-C\textsubscript{28}-C\textsubscript{29} regular sterane content of source rocks and crude oil samples in Wuerhe area, showing a high content of C\textsubscript{29} regular steranes.

Figure 7. Diagram of C\textsubscript{27}-C\textsubscript{28}-C\textsubscript{29} regular sterane content of source rocks and crude oil samples in Wuerhe area, showing a high content of C\textsubscript{29} regular steranes.

During the Yanshanian movement in the Cretaceous, the development of the main faults and folds in the Wuxia fault zone practically ceased, and only small normal faults and strike-slip fault systems developed in the shallow part of the uplifted nose. The fault system broke up to the surface and down to Jurassic and Triassic, forming a “Y” shape with large deep faults. In the Cretaceous solid bitumen within the fault, 25-norhopane was not detected, and the distribution of saturated hydrocarbons was relatively even, indicating that the asphaltene was not formed by biodegradation. The crude oil probably reached near to the surface through the fault. Low temperatures and pressure might have led to the rapid loss of the light components in the oil; the remaining heavy components enabled the
density and viscosity of the crude oil to increase continuously. Finally, the Cretaceous solid bitumen mine was formed, and the fault was closed [16].

Figure 8. Mass chromatogram of hopanes of source rocks and crude oil samples in Wuerhe area, showing the C\textsubscript{19}, C\textsubscript{21}, and C\textsubscript{23} peaks of tricyclic terpanes are higher than those of the rest; the Ts peaks are higher than the Tm peaks, and the peaks of C\textsubscript{30}-C\textsubscript{35} hopanes decrease in turn and contain high gammacerane alkanes.
part could not move upward, and therefore, they were preserved. A multi-layer reservoir formation model has been analyzed depicting entire strata of the study region, i.e., the Permian–Triassic light oil reservoir, the Jurassic heavy oil reservoir, the Cretaceous oil sand, and the bitumen (Figure 10).

Figure 9. Total ion chromatograms (TIC) and Mass chromatogram of hopane of Jurassic heavy oil samples in Wuerhe area, showing the “baseline bulge” and high content of 25-norhopane.

Like a plug, the Cretaceous bitumen deposits block the migration of oil and gas to the part. Owing to the plugging effect of the “bitumen plug”, the oil and gas in the lower part could not move upward, and therefore, they were preserved. A multi-layer reservoir formation model has been analyzed depicting entire strata of the study region, i.e., the Permian–Triassic light oil reservoir, the Jurassic heavy oil reservoir, the Cretaceous oil sand, and the bitumen (Figure 10).

Figure 10. Multi-layer reservoir formation model in Wuerhe area, showing the Permian source rocks, the Permian–Triassic light oil reservoir, the Jurassic heavy oil reservoir, the Cretaceous oil sand, and the bitumen from bottom to top. Five reverse faults (F1–F5) were developed from the Halalarte mountain to the Mahu depression.
5. Conclusions

The fault system controls the distribution of oil reservoirs in the study area. Deep large faults connect the Permian reservoir to the upper stratum for oil storage. The crude oil buried at shallow depths or exposed to the surface is subject to biodegradation or oxidation to form oil sand or heavy oil resources. The small-scale fault system is filled with solid bitumen blocking the upward migration of lower lodged crude oil and protects it from damage. Therefore, there may be normal oil reservoirs in the lower part of heavy oil reservoirs or bitumen deposits by geochemical biomarker analysis, which have not been explored. The geochemical characteristics of light oil-heavy oil–oil sand and bitumen in the Wuerhe area are very rare in oil fields. Understanding the change process of crude oil, we can predict the next exploration area. Our model not only provides a theoretical basis for oilfield exploration but also provides typical analysis cases for Petroleum Universities.

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