Hydrocarbon resource evaluation of deep Paleogene source rock in Dongying Sag

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Abstract. The exploration breakthrough of well Fengshenxie 101 once again shows the great potential of sandy conglomerate in deep northern belt of Dongying sag. Based on the oil source correlation, it is confirmed that the condensate oil in this well mainly sourced from the lower part of Es4. The resource of the source rocks are the key factors affecting the exploration of this hydrocarbon system. Based on restoration of original organic matter abundance, the hydrocarbon resources are calculated using genetic method. The total are $4.67 \times 10^8 \text{t}$, indicating that the deep layers of the Dongying sag still have great exploration potential.

Keywords: Dongying Sag, the lower part of Es4, oil source correlation, total hydrocarbon resources

1. Introduction

Along with the development of exploration, the exploration target of Dongying sag has gradually changed from medium shallow layer to deep layer with buried depth greater than 3500m[1]. So far, the exploration and recognition of the lower part of the fourth member of the Shahejie Formation (Es4) are still limited. After the breakthrough of well Fengshen 1 block in 2005, the exploration of glutenite body was stagnant. Recently, well fengshenxie 101 has obtained high-yield oil and gas flow in the deep sandy conglomerate of the lower part of Es4. The success of this well not only opens a new prospect in the northern Dongying belt, but also indicates the huge exploration potential in the deep reservoirs of Dongying sag and even the whole Jiyang depression. However, there is no unified conclusion on the source of oil and gas and its resource potential in the deep reservoirs of the lower Es4, which limits the further exploration. Therefore, a systematic study of the source of oil and gas and its resource potential can provide a scientific basis for deep-seated oil and gas exploration in the northern Dongying belt, and have important significance for the deep-seated exploration in Jiyang depression.

2. Geochemical characteristics and source identification of oil in well Fengshenxie 101

The conventional GC-MS analysis shows that the content of sterane and terpane in well Fengshenxie 101 is scarcely, which can't be used anymore. Therefore, the light hydrocarbon fingerprint and adamantane parameters are selected for oil source correlation.

2.1 fingerprint characteristics of light hydrocarbon

The light hydrocarbons of condensate oil in well Fengshenxie 101 are dominated by n-alkanes, mainly with low carbon number, relatively few isomarkanes, and high contents of benzene and toluene. and its
relative content is significantly higher than that of MCC$_6$ and nC$_7$, which reflecting that the source rock is deposited in a strong reducing sedimentary environment$^{[2]}$. The higher content of nC$_7$ than that of MCC$_6$ means that the terrestrial plants contribute less to the source of sedimentary organic matter. The ratio of MCC$_6$/DMCC$_5$ is greater than 2.0, and the ratio of 2-MC$_6$/3-MC$_6$ is greater than 1, which indicates that the oil is generated mainly from type II organic matter.

The light hydrocarbon composition comparison results show that the condensate oil comes from the source rock of the lower Es$_4$ (Figure 1), which is consistent with the light oil with high oil gas ratio discovered in well Fengshen 1, Xinlishen 1 and other conglomerate in the northern Dongying belt$^{[3]}$.

### 2.2 maturity identification

There is a good linear relationship between MDI and $R_O$ of source rock$^{[4]}$. The MDI of light oil in well Fengshenxie 101 is 0.377, equivalent vitrinite reflectance value is 1.25% (Figure 2). Statistics show that the measured vitrinite reflectance of the lower Es$_4$ source rocks is close to the crude oil under the salt rock.

### 3. Resource evaluation of the lower Es$_4$ source rocks

#### 3.1 development characteristics of source rocks

Drilling data show that the stratum in the lower Es$_4$ in Dongying Sag is thin in the south and thick in the north. Dark mudstone is mainly distributed in the Lijin-Minfeng area where the gypsum-salt layer is relatively developed. Affected by basin-controlling faults in the steep slope zone and plastic puncture of the salt-gypsum layer, the Lijin and Minfeng sub-sags each developed a deposition center. The thickest dark mudstone in the Lijin sub-sag and Minfeng sub-sag is 200m and 300m, respectively.

![Figure 3. Sedimentary and lithologic association regularity of the lower Es$_4$ in Dongying Sag.](image)
In addition, due to the periodic changes of paleoclimate, water medium conditions, and the influence of tectonic activities, the lower Es₄ has obvious sedimentary characteristics of multi rhythm and complex rhythm. The gypsum-salt rock layers are concentrated on the top of lower Es₄ and the bottom of lower Es₄. During the deposition of the bottom gypsum-salt layer, the deposition centre is near well Fengshen 2. The water body is relatively small, with salt and dark mudstones limited distributed. While during the deposition of the top gypsum-salt layer, the range of water bodies was large, and the deposition range of salt and dark mudstone expanded and spread throughout the region. High-quality source rocks are also widely developed (Figure 3).

3.2 geochemical characteristics of source rocks

3.2.1 Abundance of organic matter.
In the study area, under the combined effect of high organic matter primary productivity and preservation conditions, high-quality source rocks often develop in gypsum-salt rock intervals [5]. The cyclic characteristics of Salt Lake facies lead to great differences in organic matter abundance vertically. The top layer is deposited in a permanent Salt Lake with anoxic organic phase. Its source rocks have high TOC range from 1.0% to 2.5%. While the bottom layer is deposited in oxidized shallow Salt Lake with oxygenated organic phase. Source rocks in this layer have relatively low TOC range from 0.4% to 1.0%, belonging to poor quality source rocks. The other geochemical indicators have the same variation characteristics in the vertical direction (Figure 4).

3.2.2 Types of organic matter.
The microscopic observation shows that the horizontal and residual lamina of the salt gypsum at the top of lower Es₄ are obvious, and the amorphous can also be seen, which indicates that the organic matter mainly comes from lake plankton, and the type is I-Ⅲ₂. As a comparison, there is no obvious laminar structure in the bottom, which is mainly composed of dispersed organic matter. Most are massive vitrinite, indicating that the parent is mainly from terrestrial plants, and the organic matter type is mainly Ⅲ₂ - Ⅲ (Figure 5).
3.2.3 Thermal evolution degree of organic matter.
The lower Es₄ in the northern belt of Dongying sag are mainly distributed below 3900m [6], with a high to over mature stage and dominated by generating condensate oil and gas (Figure 6). It should be noted that the Rₒ of source rocks near the gypsum salt bed is slightly lower than the normal value compared with the normal mature evolution of source rocks in Dongying sag.

4. Resource and favourable exploration direction of the lower Es₄ in Dongyang Sag
4.1 Restoration of organic matter abundance
In recent years, studies on some high maturity and high quality source rocks have found that the efficiency of oil and gas generation and expulsion is relatively high [7]. Therefore, for source rocks that have undergone hydrocarbon generation and expulsion, the residual organic carbon cannot accurately reflect the original abundance of organic matter. It is necessary to restore the original abundance and
original hydrocarbon generating capacity of organic matter, so as to make qualitative evaluation of source rocks and quantitative calculation of resource amount on a more credible basis.

Due to the high thermal evolution degree of the source rocks in the lower Es4 in the deep layer, there is a lack of low mature source rocks. Therefore, the low-mature source rock samples in Wendong Sag, which have a similar tectonic-sedimentary background to the Jiyang Depression, were selected as a substitute to simulate the thermal maturation evolution process of the source rock in the lower Es4. The vitrinite reflectance and organic carbon content of source rocks at different simulated temperatures are calculated and measured. Combined with the correlation between buried depth and vitrinite reflectance in Jiyang Depression, the relationship between organic carbon recovery coefficient and buried depth was then determined (Figure 7). At the same time, taking into account the differences between different kerogens, the better the kerogen type, the bigger the recovery coefficient. Therefore, the organic carbon recovery coefficient of the source rock at the top and the bottom of the lower Es4 should be 1.5-3.0 and 1.5-2.0 respectively.

4.2 Evaluation results of oil and gas resources

Through the restoration of the original organic carbon content, the distribution characteristics of the original organic carbon content were determined, and the organic carbon content contour maps of the two sets of source rocks in the lower Es4 are drawn. At the same time, combined with drilling data and logging interpretation data, the thickness maps of the two sets of source rocks are also drawn (Figure 8). Finally, the resource amount of source rocks at the top and bottom of the lower Es4 in Dongying sag are calculated by genetic method. The total resource is of $4.67 \times 10^8 \text{t}$, and the top and bottom of lower Es4 contribute 75% and 25% separately (Table 1).

| formation      | Effective source rock thickness (m) | Volume of source rock (km$^3$) | TOC (%) | expulsion coefficient of oil | expulsion coefficient of gas | Total resources ($10^8\text{t}$) |
|----------------|-------------------------------------|-------------------------------|---------|-----------------------------|-----------------------------|---------------------------------|
| The top of lower Es4 | 50-100                             | 106.33                        | 0-2.5   | 16%-28%                     | 3%-10%                      | 3.52                            |
| The bottom of lower Es4 | 100-200                           | 320.20                        | 0-0.8   |                             |                             | 1.15                            |

5. Prospect for exploration

Because the salt-gypsum layer is relatively developed in the lower Es4 in the northern Dongying belt, especially at the top, a relatively independent petroleum system is formed. According to previous studies on hydrocarbon generation and evolution of two sets of salt lake facies source rocks [8-9], there is big difference in the nature of hydrocarbon generation between the top and bottom of the lower Es4.
The top source rock can generate and discharge mainly liquid hydrocarbon in the low maturity stage, while kerogen cracking and soluble organic matter cracking in the high maturity stage can generate a large amount of natural gas. The cracking of deep reservoir crude oil can also generate a certain amount of natural gas. However, the bottom source rock is difficult to reach the oil discharge threshold in the low maturity stage due to the limited amount of hydrocarbon generation, so natural gas can only be generated in the high maturity stage.

Therefore, there is a certain difference between the accumulation mode of salt gypsum layer at the top and bottom. The upper reservoir is close to the high-quality source rock, and a certain amount of liquid hydrocarbon can be accumulated in the early stage. At later stage, with the increase of burial depth, a certain amount of crude oil that charged earlier will crack, and a large amount of natural gas will be injected, finally condensate gas reservoir is formed. However, the lower reservoir can only be charged by natural gas generated in later stage, so pure gas reservoir is generally formed. It was found that solid asphalt was observed in well Fengshen 1 that in the higher part of the structure, but there was no solid asphalt in well Fengshen 3 which in the lower part of the structure. This phenomenon indicates that the crude oil at the top of the lower Es4 has cracked and formed solid asphalt (Figure 9). According to this accumulation model, for the future exploration in the gypsum-salt layer of the lower Es4, as the increase of the burial depth of the target layer, the search object should be changed from condensate oil to natural gas. In addition, due to the poor sealing ability of cap rocks, the crude oil generated in the early stage and the natural gas generated in the later stage will accumulate in the shallower areas where there is no salt gypsum layer but more traps in the northern steep slope zone.

![Figure 9. Reservoir forming model of salt reservoirs in the lower Es4 in Minfeng sag.](image)

6. Conclusions

The newly discovered source rock in the lower Es4 has great hydrocarbon generation potential. At present, the source rock is in the stage of high to over maturity, and has the ability to generate condensate oil and wet gas. Different parts of source rocks have different accumulation patterns, so it is necessary to carry out targeted exploration.

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