Characteristics of Paleogene source kitchen and its control on hydrocarbon accumulation in Qikou Sag, Bohai Bay Basin

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Abstract. Source kitchen is an important factor to control the distribution of oil and gas. In this paper, the characteristics of Paleogene source kitchen of Qikou Sag in Bohai Bay Basin and its relationship with hydrocarbon accumulation were analyzed using data from structure, geochemistry and thermal history. The results show that Qikou sag was a large continental fault-depression basin with long-term continuous subsidence, and multiple lacustrine source rocks were developed with the 1st and 3rd section in the Shahejie Formation of the Paleogene (hereafter referred to as Es\textsubscript{1} and Es\textsubscript{3}, respectively) as the main source rocks. The tectonic evolution of Qikou sag was controlled by basement subsidence and fault growth that leaded to the formation of multiple depressions in local subsidence centers. As a result, multiple source kitchens were developed in Es\textsubscript{1} and Es\textsubscript{3} with different oil and gas characteristics. Oil and gas fields were mainly distributed in the uplifts and slopes around the source kitchen which showed that source kitchen acted as an important factor in the process of oil and gas accumulation.

1. Introduction
Hydrocarbon source kitchen refers to the source rock which has been proved to generate and provide oil and gas for some petroleum accumulations [1-6]. Qikou sag is an important hydrocarbon-producing province in the Bohai Bay basin characterized by rich petroleum. As an area of mature exploration degree, a large amount of data has been acquired in drilling, logging and organic geochemistry, which provides the basis for the systematic study of source kitchen in this area. In this paper, the characteristics of Paleogene source kitchens and their relationship with oil and gas reservoirs were discussed based on the research on structure, thermal history and characteristics of source rocks.

2. Characteristics of source rocks
The formation of slopes in Qikou sag was controlled by basement subsidence and fault growth. Multiple depressions were formed in the local subsidence centers such as Qikou, Qibei and Banqiao. Under the control of tectonic activity, several sets of hydrocarbon source beds were developed in the Paleogene in Qikou Sag, such as Dongying Formation and Shahejie Formation, among which the main source rocks were the Es\textsubscript{1} and Es\textsubscript{3}.

2.1. Es\textsubscript{3} member
During the Es\textsubscript{3} deposition period, the lake was at its peak development stage, and the stratum thickness was relatively large, especially in Banbei and Changlu areas, with an average thickness of nearly 600m (Figure 1). The distribution range of the total organic carbon content (TOC) ranged from 0.52%
to 2.93%, with an average of 1.22%. The type of organic matter was mainly type II$_2$–III. The thermal evolution degree of source rock was relatively high, and the vitrinite reflectance (Ro) was distributed between 0.6% and 1.8%, meaning that it could be served both as oil and gas source.

2.2. $E_{S1}$ member

As a comparison, the lake was expanded again during $E_{S1}$ deposition period. However, due to the influence of trough migration, the sedimentary thickness of $E_{S1}$ was thinner than that of $E_{S3}$, and its distribution also changed greatly. The sedimentary center was located in the Shanggulin–Gaoshaling area (Figure 2). The distribution of TOC ranged from 0.52% to 3.07%, with an average of 1.65%. The type of organic matter was mainly type II$_2$–III. Its thermal evolution degree is moderate, the Ro was generally between 0.6% to 1.3%, meaning that it tended to generate oil.

3. Distribution and characteristics of source kitchen

3.1. $E_{S3}$ member

Multiple sedimentary centers were developed in the $E_{S3}$ member, which divided the source kitchen into five different parts (Figure 1). These were respectively located in Beitang–Tanggu, South of Lujue, Zengtai–Banqiao–Tangjiahe, Mapengkou–Qikou and Wangxuzhuang zhaojiapu. Most of the source rocks were buried at the depth of over 3000 m with the maximum depth was 4200 m. For example, the TOC of source rocks in Mapengkou–Qikou source kitchen and Zhaojiapu was greater than 1.6%. The thickness of the high-quality source rock (TOC > 2%) was more than 100 m with the thickest part was close to 700 m. These two kitchens, together with the one near Banqiao, constitute the main body of the $E_{S3}$ source kitchens and lay a solid foundation for oil and gas accumulation.

![Figure 1](image1.png)

**Figure 1.** The distribution of $E_{S3}$ source kitchens of Qikou sag.

![Figure 2](image2.png)

**Figure 2.** The distribution of $E_{S1}$ source kitchens of Qikou sag.

The climate of the $E_{S3}$ deposition period was warm and humid, and several kinds of algae were developed [7-9]. According to the characteristics of biomarkers, $C_{27}/C_{29}$ ratios of regular steranes in all source kitchens were small. In terms of Pr/Ph ratio, the largest located in Banqiao area that was 1.25-2.71, while that near Qikou and West zhaojiapu was 1.03-1.59 and 1.01-1.22 respectively. This difference might be related to the relatively deep-water body in Banqiao area. Due to the large buried depth and high thermal evolution degree of the source rocks in $E_{S3}$ member, its Ts/Tm ratio was relatively high, ranging from 0.72 to 4.29.
3.2. **Es$_1$ member**

The hydrocarbon source kitchen of Es$_1$ member was mainly developed in the north-central part of Qikou Sag, covering an area of about 1900km$^2$, including Mapengkou–Qikou–Zhangjuhe, east of Baishuitou, Gaoshaling–Xiaozhan and Lvjuhe–Tanggu (Figure 2). The thickness of source rock in the east of Baishuitou could reach 1200 m, while the thickness of other areas was within 200 m–600 m. As the TOC was concerned, the source rocks in Qikou–Zhangjuhe area were of the highest quality with TOC $> 1.0\%$. According to the current thermal evolution state of source rocks, the maturity in the east of Baishuitou was the highest with Ro around 2.0\%. The second highest area located in Lvjuhe, and the maturity near Zhangjuhe–Qikou and Banqiao–Xiaozhan was relatively low, but also above 1.0\%. Among them, the source kitchen in Mapengkou–Qikou–Zhangjuhe, Baishuitou and Banqiao–Xiaozhan were important for hydrocarbon accumulation in the slope zone.

When the Es$_1$ member was deposited, the fault block activity in Qikou sag was stable. The deepest water developed in the location of Banqiao and Qikou, which were shallow lake area, and most of the others were belonged to shore lake. According to the characteristics of biomarkers, the Pr/Ph ratio of the main depression was 1.34–3.59, while the ratio of Banqiao and Zhangjuhe were 1.15–2.02 and 0.90–1.67 respectively, which indicated that the whole distribution area of Es$_1$ member was deposited in the partial reducing water especially in the main depression zone because of its deep water. The ratio of Gammacerane/C$_{31}$H in Banqiao area was the highest, ranging from 0.80 to 0.38, indicating that the stratification of water body was better and the salinity of water body was relatively high. In terms of sterane composition, the ratios of C$_{27}$/C$_{29}$ of regular steranes in Banqiao, main sag and Zhangjuhe were 0.43–1.13, 0.93–1.47 and 0.67–1.58, respectively, indicating that the parent material of organic matter in Qikou sag was mainly low-grade floating algae. while most of the organic matter of Es$_1$ in Banqiao area were derived from high terrigenous sources as amount of humic amorphous and vitrinite components of plants were found in these kerogens.

4. **Relationship between source kitchen and hydrocarbon distribution**

4.1. **Oil and gas characteristics of source kitchen**

The geochemical characteristics of crude oils from different source kitchens had some differences (Figure 3). It could be found from the figure that the oil and gas supplied by the source kitchen of the Es$_3$ member in Mapengkou was significantly different from that of in Baishuitou. In terms of phase state, the wells of bin-22, Gangshen-50 and binshen-1601H near Qikou produced crude oil, and the carbon isotopes of oils in the same source kitchen area, Gangshen-33 and Gangshen-35, were also significantly lighter than that of Binhai-4 in the main depression, while the Pr/Ph ratio was also relatively low. As a contrast, the wells in the main depression such as Binhai-4 and Binhai-2 were characterized by simultaneous development of oil and gas and dominated by crude oil. Their isotopic and biomarkers compositions were also different from those supplied by Qikou source kitchen. For example, the terpane tricyclic/tetracyclic ratio and the Gammacerane/C$_{33}$H ratio of oil in Binhai-4 well were significantly higher than those in Gangshen-32, while the ratio of Ts/Tm was the opposite, which indicated that there were differences in the source of organic matter.
4.2. Oil and gas distribution

The source kitchen had obvious control effect on the oil and gas accumulation in the study area. The distribution of source kitchen in Es1 and Es3 just covered Banqiao, Tangjiahe, Mapengkou, Zhangjuhe and other major oilfields (Figure 4, Figure 5), indicating that most of the crude oil was formed by short distance migration. Among them, Yangerzhuang, Wangxuzhuang, Zhangjuhe, Zhouqingzhuang and other oilfields were distributed in a circular belt around the source kitchens of the Es3 in Qinan area and Es1 and Es3 in Qikou area. The oil and gas fields of Beidagang, Banqiao, Binhai were surrounded by Es1 and Es3 source kitchens of Banqiao, Qikou and Tangjiahe–Baishuitou. The Tanggu oil field was mainly located in the range of Beitang Es3 source kitchen.

5. Conclusions

Multiple sets of source rock series were developed in Qikou sag, such as Dongying Formation, Shahejie formation, during which the Es1 and Es3 members were the main source rocks. The formation of slope zones in Qikou sag was controlled by basement subsidience and fault growth. Multiple depressions were formed in the local subsidence centers, which controlled the development and evolution of high-quality hydrocarbon source rocks. The Es1 source kitchen was mainly developed in the middle and north part of Qikou sag with moderate maturity and mainly generated oil. The Es3 source kitchen was the most important one characterized by wide distribution, high maturity and complete hydrocarbon generation evolution. Oil and gas fields were mainly distributed close to or
around source kitchens in Qikou sag, indicating that hydrocarbon source kitchen played an important role in oil and gas enrichment.

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