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Differential Hydrocarbon Enrichment and its Main Controlling Factors in Depressions of the Bohai Bay Basin

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Abstract: Significant differential hydrocarbon enrichment occurs in depressions in a petroliferous basin. There are multiple depressions in the Bohai Bay Basin, and each depression as a relatively independent unit of hydrocarbon generation, migration and accumulation, contains significantly different hydrocarbon generation conditions and enrichment degree. On the basis of previous documents and a large number of statistical data, this work comparatively analyzed the differential hydrocarbon enrichment and its major controlling factors in depressions of the Bohai Bay Basin. The results show that depressions in the Bohai Bay Basin have various hydrocarbon enrichment degrees, and can be categorized into four types, namely enormously oil-rich, oil-rich, oily and oil-poor depressions. In general, the enormously oil-rich and oil-rich depressions are distributed in the eastern part of the basin along the Tan–Lu and Lan–Liao faults, whereas depressions in the western part of the basin are poor in hydrocarbons. Moreover, the vertical distribution of hydrocarbons is also highly heterogeneous, with Pre-Paleogene strata rich in hydrocarbons in the northern and western depressions, Paleogene strata rich in hydrocarbons in the entire basin, and Neogene strata rich in hydrocarbons in the off-shore areas of the Bohai Bay Basin. From early depressions in onshore areas to the late depressions in offshore areas of the Bohai Bay Basin, the source rocks and source-reservoir-cap rock assemblages gradually become younger and shallower, and the hydrocarbon resource abundance gradually increases. Hydrocarbon supplying condition is the key factor constraining the hydrocarbon enrichment for different depressions, while the main source-reservoir-cap rock assemblage, sufficient hydrocarbons and the transportation capacity of faults control the vertical distribution of hydrocarbons. The main factors controlling hydrocarbon enrichment are different for different layers. The hydrocarbon supplying condition of source rocks is the key controlling factor, whereas the source-reservoir configuration, the main source-reservoir-cap rock assemblages, and the fault transportation are the main factors of hydrocarbon enrichment in the Paleogene, Paleogene and Neogene, respectively.

Key words: differential hydrocarbon enrichment, hydrocarbon distribution, hydrocarbon-rich depression, fault transportation, main controlling factors, Bohai Bay Basin

1 Introduction

The Bohai Bay Basin is a typical Meso-Ceozoic petroliferous basin in eastern China, and contains dozens of depressions and uplifts (Li Desheng, 1980; Lu Kezheng, 1997; Liu et al., 2016). The basin is characterized by multi-episode basin formation, coexisting multi-depressions, multi-source rocks and multi-layer oiliness (Tian Keqin et al., 2000; Zhao Wenzhi and Chi Yingliu, 2000; Gao Ruiqi et al., 2004). Each depression is a relatively independent unit of hydrocarbon generation, migration and accumulation, but the hydrocarbon enrichment and distribution layers are significantly heterogeneous in different depressions in the Bohai Bay Basin (Hu Jianyi and Huang Difan, 1991; Qiao Hansheng, 2002; Hao et al., 2007; Jiang Youlu et al., 2014; Teng Changyu et al., 2014; Liu et al., 2014; Wang et al., 2014; Min et al., 2015). The Dongying, Western Liaohe, Qikou

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and Zhanhua depressions are enormously rich in hydrocarbons, whereas the Weibei, Jinxian and Shenxian depressions are poor, and there are still many depressions which have not yet received commercial hydrocarbon flow. Moreover, hydrocarbons are rich in different strata in different depressions. For instance, hydrocarbons are mainly enriched in Neogene strata in the Zhanhua and Bozhong depressions around the Bohai sea area, while hydrocarbons are mainly enriched in Paleogene strata in the Dongying and Dongpu depressions (Jiang Youlu et al., 2016) and in Pre-Paleogene strata in the Raoyang (Fei and Wang, 1984) and Damintun depressions in the onshore areas of the basin. Many studies have been carried out on the hydrocarbon enrichment laws and their major controlling factors (Tian Keqin et al., 2000; Zhao Wenzhi and Chi Yingliu, 2000; Qiao Hansheng, 2002; Isaksen et al., 2002; Gao Ruiqi et al., 2004; Dou et al., 2007; Hu Jianyi and Huang Difan, 1991; Brekhuntsov et al., 2011; Jiang Youlu et al., 2014; Teng Changyu et al., 2014; Jiang Youlu et al., 2015a). However, comparative studies on the differential hydrocarbon enrichment in different depressions and the major controlling factors are relatively insufficient. On the basis of the previous documents and a large number of statistical data, the distribution characteristics of hydrocarbons and their heterogeneities for different depressions in the Bohai Bay Basin were systematically analyzed, then the hydrocarbon migration laws at the basin scale were analyzed, and finally, the major controlling factors of differential hydrocarbon enrichment in different depressions were discussed.

2 Geological Setting

The Bohai Bay Basin includes the North China Plain, the Bohai Sea area and the lower Liaohe Plain, which covers a total area of about 20×10^4 km^2. It borders the Jiaoliao Massif in the east (Huang and Liu, 2014), the Taihang fault in the west, the Western Shandong uplift in the southeast and the Yanshan orogenic belt in the north. The basin consists of the Liaohe, Bozhong, Changwei, Huanghua, Jiyang, Jizhong and Linqing depressions and the Neihuang, Chengning, Cangxian and Xingheng uplifts (Fig. 1). This basin is a Meso-Cenozoic superimposed basin developed on the Paleozoic crystalline basement. The Bohai Bay Basin underwent two major tectonic cycles, i.e. the Mesozoic and Cenozoic rifting. The Cenozoic, as the dominant formation stage of the basin, can be further divided into three tectonic stages, including the Kongdian, Sha-4 member to Sha-3 member and the Sha-2 member to Dongying stages (Huang and Pearson, 1999; Qi and Yang, 2010; Huang et al., 2012). The basin has entered a stable settlement stage since the Cenozoic (Lu Kezheng, 1997; Hou Guiting et al., 1998).

Tectonic movement controls the development of sedimentary sequences and source-reservoir-cap rock assemblages (Zhai, 1986; Hao et al., 2011; Zhang et al., 2013; Wu, et al., 2013). There are multiple sets of source rocks, including the Kongdian Formation (E_1k), the fourth member (E_2s_4), the third member (E_2s_3) and the first member (E_2s_1) of the Shahejie Formation (the four members of the Shahejie Formation from bottom to top are E_2s_4, E_2s_3, E_2s_2 and E_2s_1) and the Dongying Formation (E_3d). From the onshore areas of the Bohai Bay Basin to the Bozhong area, the burial depth of the source rock gradually becomes shallower. Pre-Paleogene (buried hill), Paleogene and Neogene are hydrocarbon reservoirs, and Paleogene is the main reservoir. E_2s_3, E_2s_1, E_3d and the Minghuazhen Formation (Nm) are the major regional cap rocks. The three sets of reservoirs combined with the source rocks and cap rocks form three reservoir-forming assemblages of lower, middle and upper ones (Jiang Youlu et al., 2014).

The tectonic evolution history varies in different depressions in the Bohai Bay Basin, and each depression is a relatively independent unit of hydrocarbon generation, migration and accumulation. Based on the tectonic evolution histories and the basin-filling sediments, depressions in the Bohai Bay Basin can be divided into three types: early depressions, inherited depressions, and late depressions (Zhao Wenzhi and Chi Yingliu, 2000; Jiang Youlu et al., 2014). From the depressions in the margin area to the Bozhong area of the Cenozoic basin, the tectonic movement gradually becomes later and the depocenter gradually becomes thicker. Moreover, the tectonic-sedimentary center gradually migrates to the Bozhong area (Cai et al., 2007), leading to heterogeneities in the source-reservoir-cap rock assemblages for different depressions. From the early depressions to inherited depressions and then to late ones, the source-reservoir-cap rock assemblages change from the lower type to the middle type and then to the upper reservoir-forming assemblages.

3 Differential Hydrocarbon Enrichment

The Bohai Bay Basin is very rich in hydrocarbon resources. According to the Third National Resource Evaluation, the petroleum resources in the basin are 235×10^8 t, indicating the huge exploration potential of the basin (Zhai Zhongxi and Bai Zhenrui, 2008). Due to the evolution of tectonic and depositional system, there are some change rules in basin-filling sediments, hydrocarbon accumulation conditions and hydrocarbon distribution for different depressions in the Bohai Bay Basin.

3.1 Macroscopic heterogeneities in hydrocarbon enrichment

Horizontally, hydrocarbons are widely distributed in almost all sub-basins of the Bohai Bay Basin except the north part of the Linqing sub-basin and the large uplift belt (Fig. 1). However, the enrichment of hydrocarbons is significantly heterogeneous in different sub-basins. Overall, hydrocarbons are highly enriched and widely distributed in the Jiyang, Bozhong and Huanghua sub-basins that are located in the eastern and central areas of the basin, whereas hydrocarbons are relatively poor in the Jizhong and Linqing sub-basins in the western areas of the basin. Therefore, hydrocarbons are rich in the eastern part but poor in the western part, and they are generally distributed near the Tan–Lu (Gilder et al., 1999) and Lan–Liao faults.

There are multiples of hydrocarbon-bearing layers in the Bohai Bay Basin, and hydrocarbon reservoirs have been discovered in the Archean, Proterozoic, Paleozoic, Mesozoic and Cenozoic strata from bottom to top. According to the tectonic evolution history of the basin and the accumulation characteristics of different layers, the hydrocarbon-bearing strata can be categorized into three major formations of Neogene, Paleogene and Pre-Paleogene (buried hill). The horizontal distribution of hydrocarbons in different strata is regional. The Pre-Paleogene hydrocarbons are limitedly distributed in the sub-basins in the edge areas of the basin, such as the Liaohe and Jizhong sub-basins (Zha, 1984), whereas the Paleogene hydrocarbons are distributed across the entire basin and form multiple hydrocarbon accumulation zones, and the Neogene hydrocarbons are mainly distributed around the Bohai Sea area, including the northern part of the Bozhong (Hao et al., 2009) and Jiyang sub-basins and eastern part of the eastern Huanghua sub-basin, but barely distributed in the edge areas of the basin (Fig. 2). In

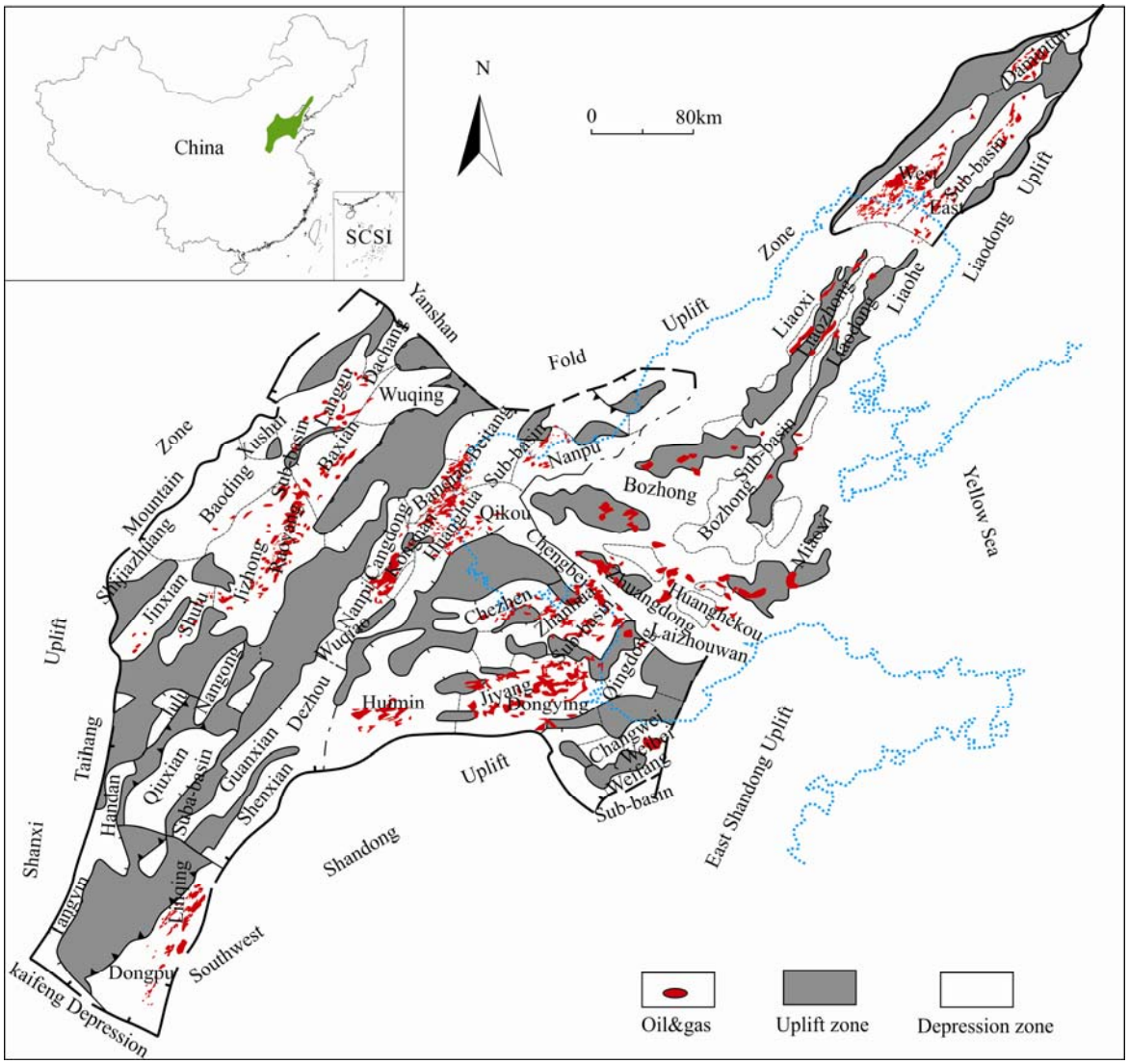

Fig. 1. Map showing tectonic unit division and distribution of hydrocarbons in the Bohai Bay Basin (modified from Hao et al., 2007).

summary, the Bohai Bay Basin is characterized by that Pre-Paleogene strata rich in hydrocarbons in the peripheral sub-basins, Paleogene strata rich in hydrocarbons across the entire basin, and Neogene strata rich in hydrocarbons in the central areas of the Bohai Bay Basin.

The distribution of hydrocarbons in the vertical strata is highly heterogeneous in different sub-basins. The hydrocarbons enriched in the Paleogene are distributed in each sub-basin heterogeneously. The Paleogene hydrocarbon resources in the western poart of Huanghua, central to southern part of Liaohe, eastern part of Linqing and southern part of Jiyang sub-basins account for more than 70% of the Paleogene hydrocarbon resources in the basin. The sub-basins such as northern part of Liaohe and Jizhong sub-basins in the edge areas of the basin has the higher rate of Pre-Paleogene resources, and the Bozhong sub-basin in the central areas of the basin has the highest rate of Neogene resources, reaching more than 70% (Fig. 3).

3.2 Heterogeneities in hydrocarbon enrichment for different depressions

The Bohai Bay Basin has abundant oil and gas resources. However, the hydrocarbon resources are significantly heterogeneous in different depressions. Hydrocarbon resources are abundant in the Bozhong, Dongying, Zhanhua, Western Liaohe and Dongpu depressions, whereas hydrocarbon resources are relatively poor in the Weibei, Jinxian, Beitang and Langgu depressions, and partial depressions have not yet received commercial hydrocarbons (Fig. 4).

In the vertical strata, the distribution of hydrocarbons in the three strata is highly heterogeneous. Paleogene is the main oil-bearing reservoir in majority depressions, and the hydrocarbon reservoirs that have been found in several depressions all occur in Paleogene, such as the Jinxian, Beitang and Eastern Liaohe depressions. Meanwhile, the reserves in the Baxian, Raoyang, Chezhen and Damintun depressions, account for a large proportion, and the rate of Pre-Paleogene reserves in the Raoyang depression accounts for more than 60%. The Neogene reserves of those depressions, such as the Nanpu, Qikou, Zhanhua and Bozhong depressions, are richest, and the rate of Neogene reserves in the Bozhong depression reaches 70% (Fig. 5).

For further investigation of the heterogeneities in hydrocarbon enrichment for different depressions, taking the total resources, resource abundance and proven reserves as the classification standard of hydrocarbon enrichment degree, this paper divided depressions in the Bohai Bay Basin into enormously oil-rich depressions, oil-rich depressions, oily depressions and oil-poor depressions (Table 1).

Horizontally, the extremely oil-rich depressions are mainly concentrated in the eastern part of the basin, Bohai Sea area and offshore areas, while oil-rich depressions, oily depressions and oil-poor depressions are distributed over the whole basin. The distribution of hydrocarbon-rich depressions is closely related to the large fault zones. Enormously oil-rich depressions and oil-rich depressions are concentrated on both sides of the Tanlu Fault Zone (such as the Bozhong, Liaohe and the Dongying depressions) and the Lanliao Fault Zone (such as the Qikong and Dongpu depressions), while oil-poor depressions are distributed in the edge areas of the basin and the areas near large uplifts. The enrichment degree of hydrocarbons in the eastern depressions is significantly higher than that of western ones. In eastern areas, enormously oil-rich depressions and oil-rich depressions with a higher hydrocarbon enrichment degree are the primary type, whereas oily depressions and oil-poor depressions with a lower hydrocarbon enrichment degree are the main type in western areas, although there are many depressions (Fig. 6).

4 Major Controlling Factors on Heterogeneities in Hydrocarbon Enrichment

4.1 Hydrocarbon generation condition controlling hydrocarbon enrichment degree

4.1.1 Tectonic evolution and hydrocarbon generation background

The tectonic evolution of a depression, controlling development of a depositional system (Tiercelin et al., 1992) and formation of source rock, reservoirs and caps, determine the hydrocarbon accumulation background (Foster and Beaumont, 1987; Chi Yingliu et al., 2000; Wang et al., 2015). So, different evolution types of depressions have different development degrees and distribution of source rocks. Meanwhile, the intensive rift during early Paleogene mainly developed in the

Table1 Classification standard of hydrocarbon enrichment degree, Bohai Bay Basin

Enrichment type	Total resources (10^8 t)	Resource abundance (10^4 t/km^2)	Proved reserves (10^8 t)	Typical depressions
enormously oil-rich depression	≥25	≥50	≥10	Dongying, Western Liaohe and Bozhong
oil-rich depression	5–25	20–50	1–10	Dongpu, Huimin, Nanpu and Raoyang
oily depression	1–5	10–20	0.1–1	Weibei, Jinxian, Shulu and Wuqing
oil-poor depression	<1	<10	<0.1	Baoding, Nangong, Shenxian and Shenxian

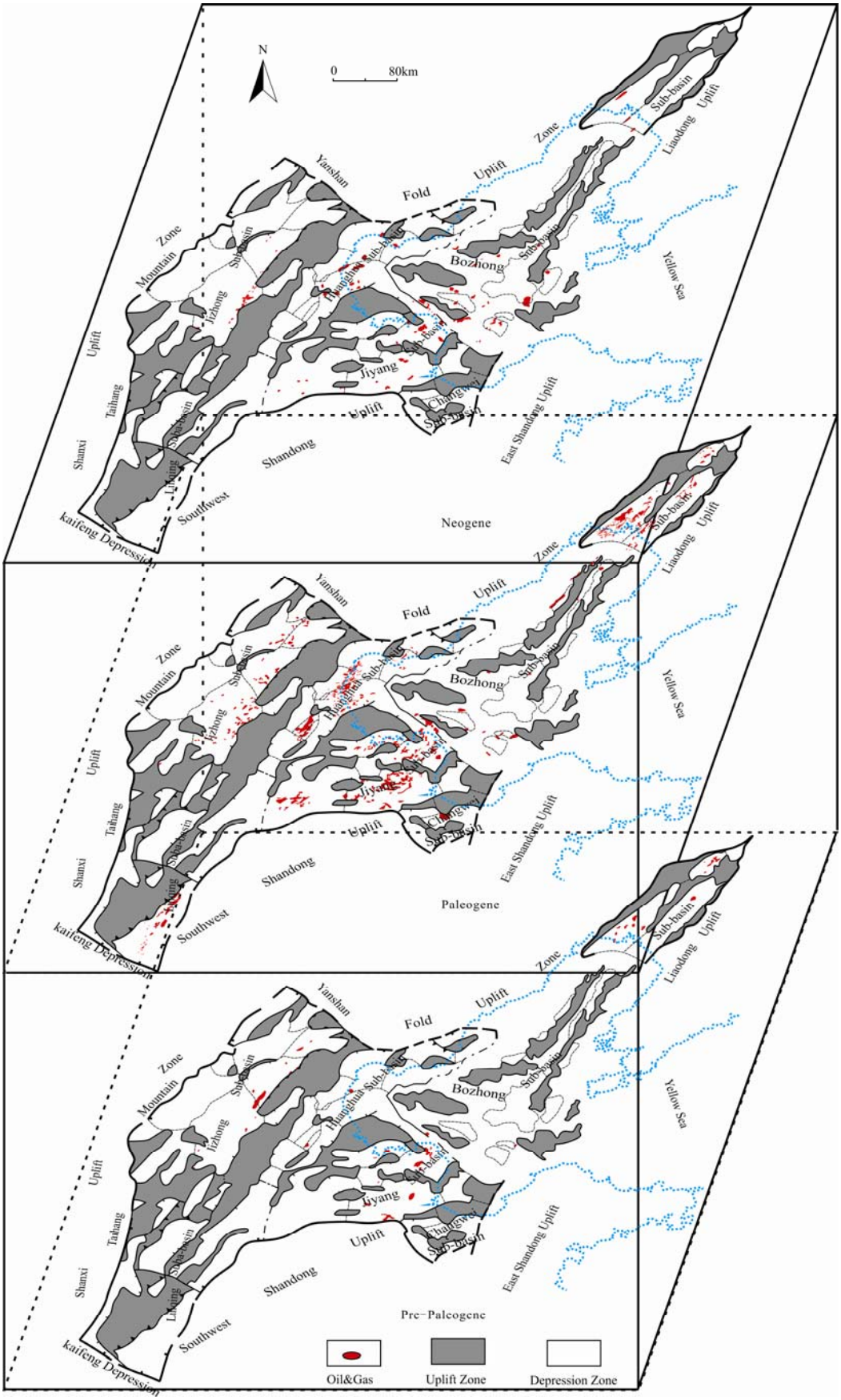

Fig. 2. Hydrocarbon distribution in different layers of the Bohai Bay Basin.

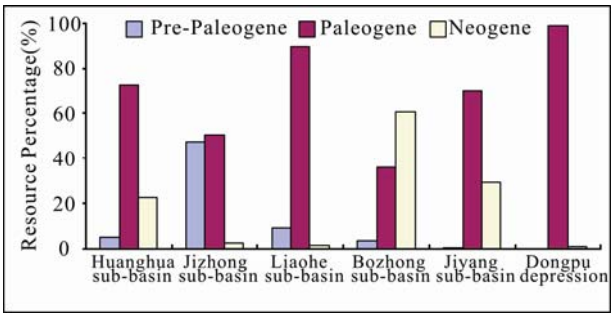

Fig. 3. Resource distribution in different sub-basins of the Bohai Bay Basin.

depressions located in the edge area of the basin. Based on the tectonic evolution and the basin-filling sediments, depressions of the Bohai Bay Basin are divided into three types: early depressions, inherited depressions, and late depressions (Zhao and Chi, 2000; Jiang Youlu et al., 2014). The intensive rifting during the early Paleogene mainly occurred in the depressions with E_1k or E_2s_4 source rocks in the onshore areas of the basin, such as the Weibei and Damintun depressions. Due to the strong uplifting during the late Paleogene, the compensation thickness of Neogene and Quaternary was less than the erosion thickness, therefore, the early depressions have relatively poor hydrocarbon supplying conditions, in which hydrocarbons were accumulated in the end of Paleogene. The inherited depressions are widely distributed in the whole basin, and thanks to the inheritably subsiding during the Neogene, developed many sets of high-quality source rocks (such as E_2s_4, E_2s_3 and E_2s_1) during the basin expansion period, thus have great hydrocarbon generating potential and better oiliness. The late depressions rapidly

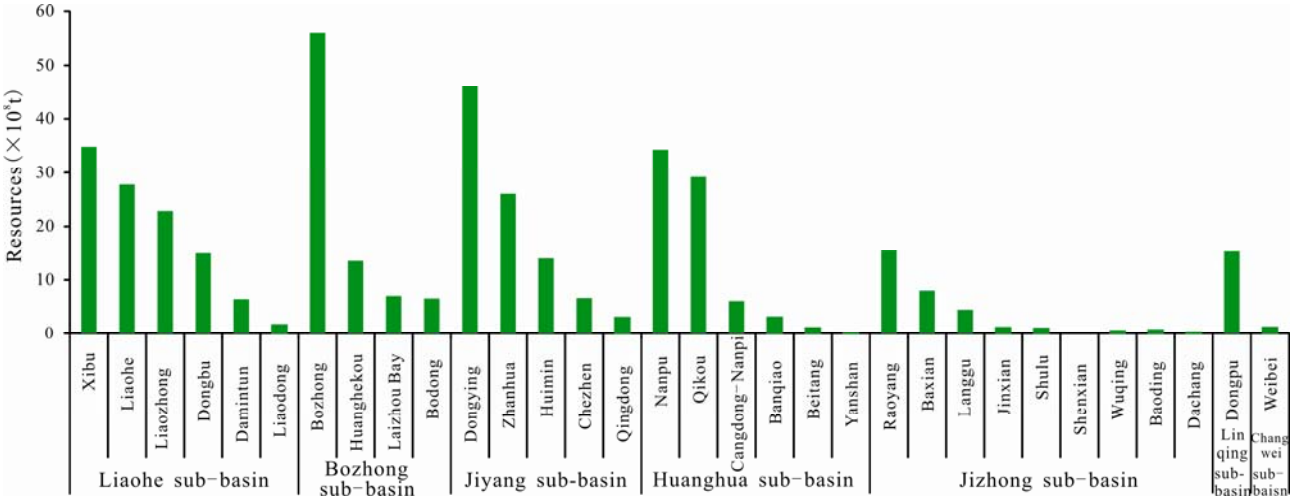

Fig. 4. Resources in different depressions of the Bohai Bay Basin.

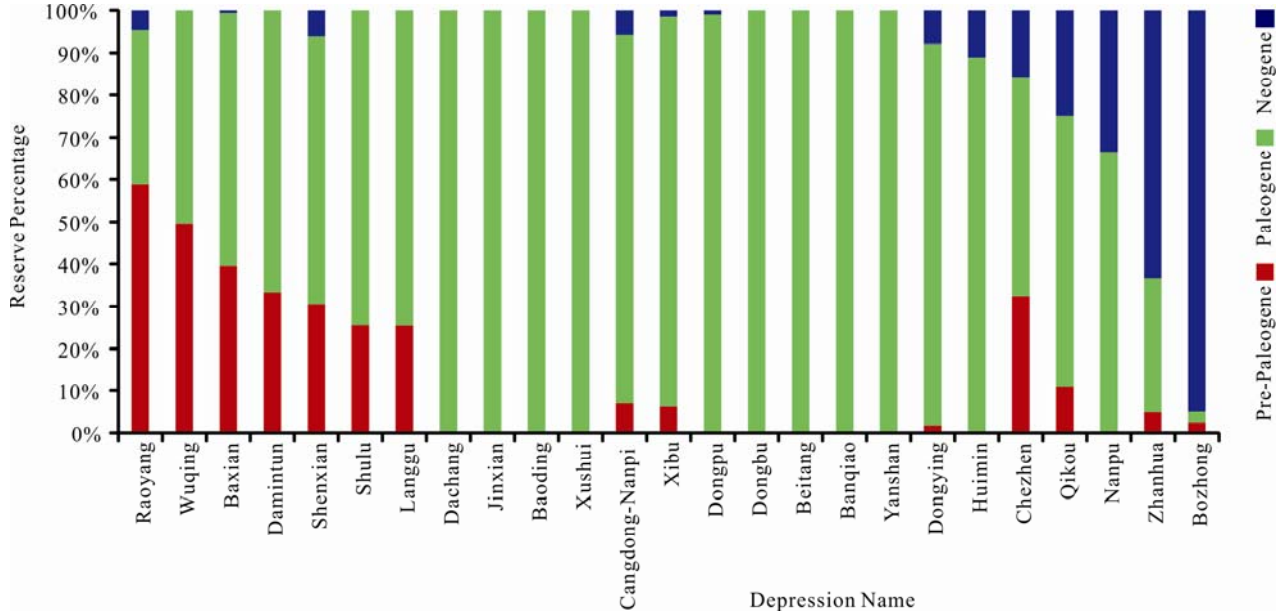

Fig. 5. Reserve percentage of the three strata in different depressions, Bohai Bay Basin.

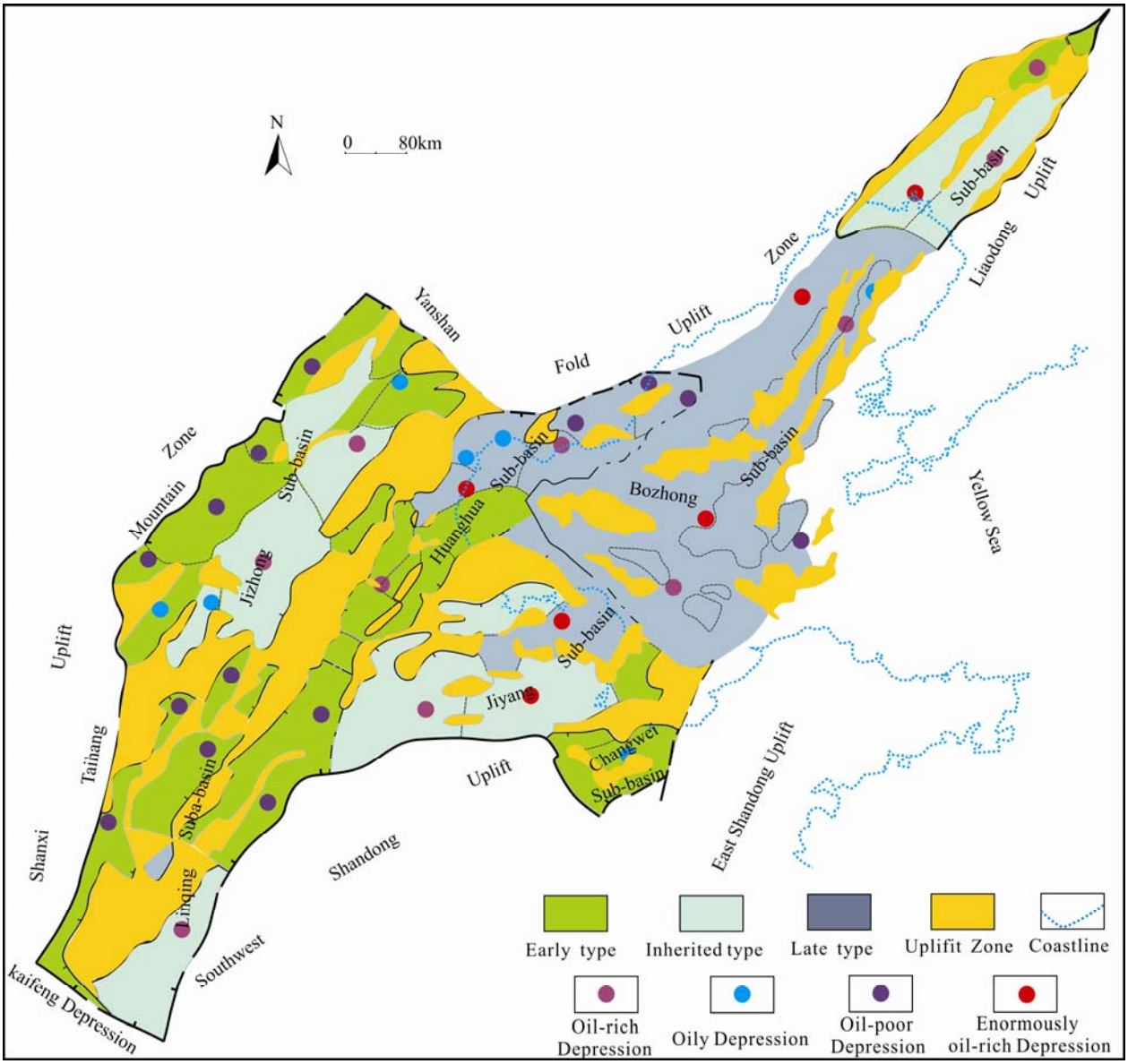

Fig. 6. Composition of enrichment type and evolution type, Bohai Bay Basin.

subsided during the E_3d-Neogene period, such as the Bozhong and Liaoxi depressions (Jia Nan et al., 2015; Guo et al., 2013). The late depressions developed E_2s_3, E_2s_1 and E_3d_1 high-quality source rocks, among which E_2s_1 and E_3d_1 have great contribution to the hydrocarbon generation, and thus have advantageous oiliness. On the whole, the inherited and late depressions, with many sets of source rocks and better hydrocarbon generation, conditions correspond to enormously oil-rich and oil-rich depressions, whereas the early depressions with relatively poor hydrocarbon generation conditions correspond to oily or oil-poor depressions(Qiao Hansheng et al., 2002; Fig. 6).

Different depressions have various tectonic evolution and thus have different main source rocks (Niu Jiayu and Li Feng, 2000; Fig. 7). E_1k source rocks are the main source rocks only in the Weibei, Cangdong-Nanpi and few of depressions, whereas E_2s_4 source rocks are the main source rocks in the Dongying and partial depressions of Jizhong Sub-basin. Meanwhile, E_2s_3 source rocks, which are most widely distributed and have the greatest hydrocarbon generating ability, are effective source rocks in most depressions. E_2s_1 source rocks are mainly concentrated in the Jizhong Sub-basin and areas around Bohai Sea and are good source rocks. And E_3d source rocks are only distributed in the Bohai Sea areas. Overall, most depressions take E_2s_3 as the main source rocks, while depressions around Bohai Sea develop E_2s_3, E_2s_1 and E_3d high-quality source rocks with great hydrocarbon generating capacity, thus have higher degree of hydrocarbon enrichment. Whereas depressions in the onshore areas of the basin only develop E_1k and E_2s_4

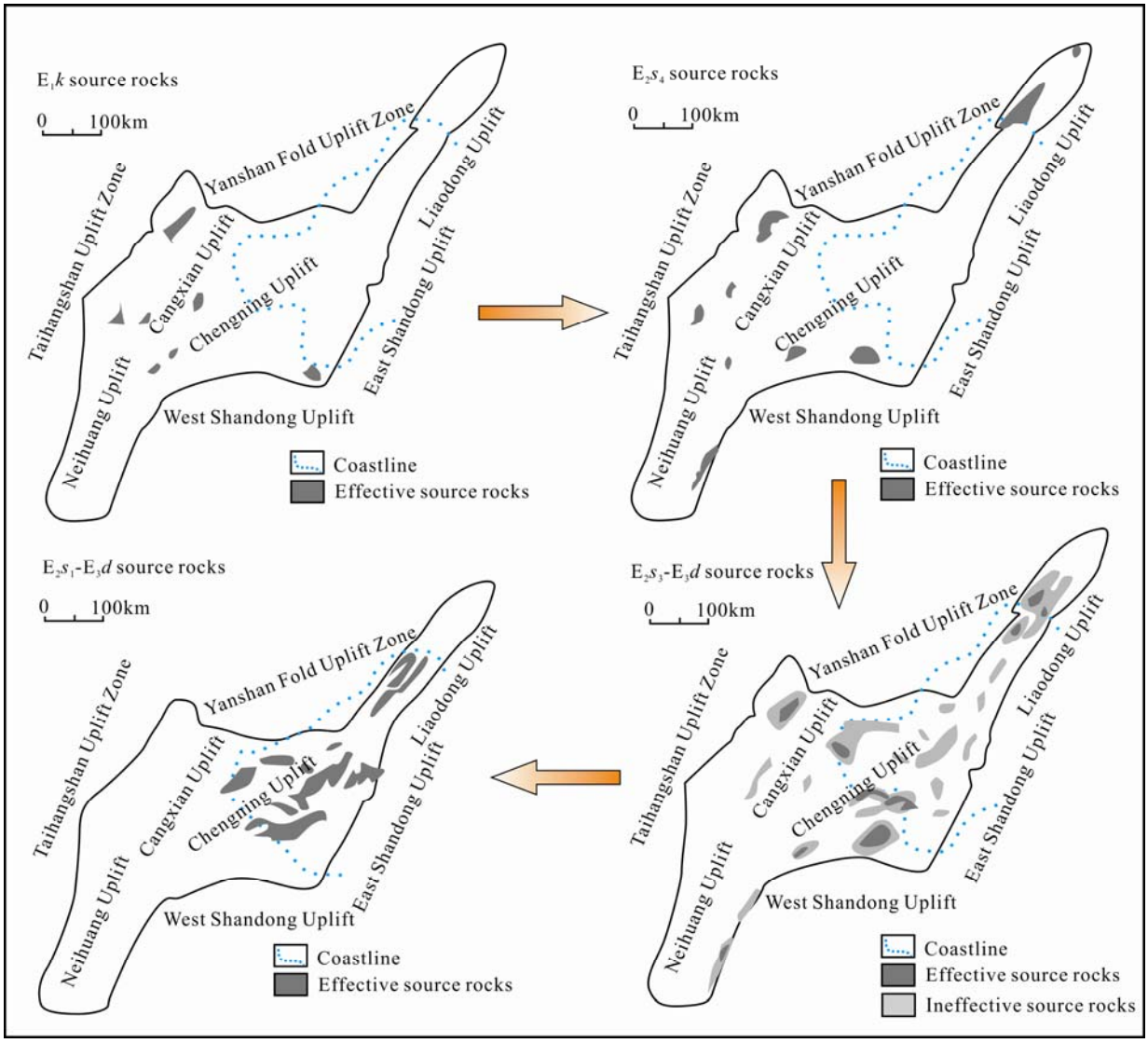

Fig.7. Plane evolution of source rocks in different layers of Cenozoic, Bohai Bay Basin (modified from Niu Jiayu and Li Feng, 2000).

source rocks, a majority of which have relatively hydrocarbon generating conditions and thus have relatively lower degree of hydrocarbon enrichment.

4.1.2 Source rock maturity and hydrocarbon supplying potential

The tectonic evolution provides macro background for hydrocarbon generation and accumulation, while the abundance, type and maturity of organic matters control the hydrocarbon supplying potential of source rocks, and then the two factors mutually determine the hydrocarbon enrichment degree of a depression (Kingston et al., 1983).

There are significant heterogeneities in organic matter abundance for different depressions and different layers in the Bohai Bay Basin (Chen Jianping et al., 2014). The organic matter abundance of the main source rocks, i.e. E_2s_3, is greater in each depression (Fig. 8). In most depressions except the Dongpu depression with salt sediments in the Bohai Bay Basin, E_2s_1, E_2s_3 and other main source rocks have relatively smaller heterogeneities in abundance and types of organic matters, with the abundance of organic matters generally greater than 1.0% (Fig. 8) and type Ⅱ$_1$ and Ⅱ$_2$ as the main kerogen types, and are prone to generate hydrocarbons. Compared with the heterogeneities in abundance and types of organic matters, the heterogeneities in the thermal degree of the main source rocks in different depressions are greater, and are the key factors resulting in the diverse hydrocarbon generating abilities.

Taken the E_2s_3 source rocks as an instance, the differences in burial depth and geothermal gradient of source rocks result in the different maturity between depressions in the west and the east of the basin. In the western part of the basin, due to the lower burial depth and geothermal gradient of E_2s_3 source rocks, the main source rocks are still in the low mature to mature stage of thermal

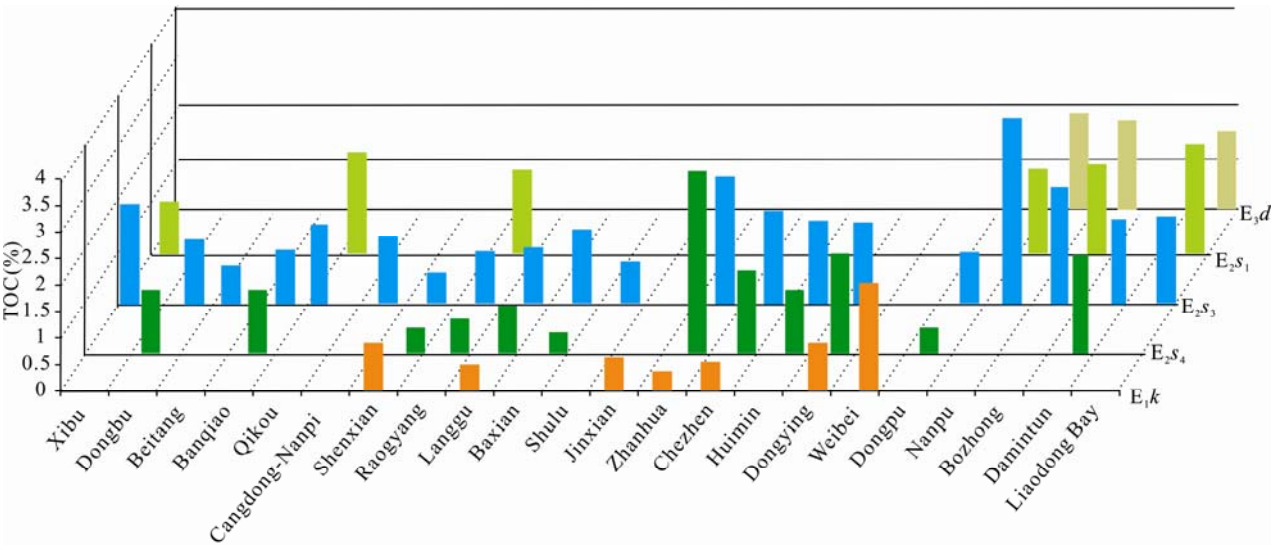

Fig. 8. TOC of the major source rocks in depressions of the Bohai Bay Basin.

evolution, and low mature oil was obtained during the exploration practice. Therefore, the thermal evolution leads to the lower enrichment degree of hydrocarbons, which is the key factor giving rise to the poor exploration effectiveness (Jiang Youlu and Xiong Jihui, 1997). Due to the deep burial of E_2s_3 source rocks, higher geothermal gradient, the Dongying, Bozhong, Western Liaohe and other oil-rich depressions near Tan–Lu fault in the eastern part of the basin, have higher thermal evolution of organic matters. Moreover, the Bozhong depression has higher thermal evolution of organic matters than Dongying and Western Liaohe depressions because of its deeper burial of E_2s_3 source rocks (Zuo Yinhui et al., 2009). Thus it can be seen that almost all enormous oil-rich depressions in the Bohai Bay Basin are distributed in the eastern part of the basin with deep burial of the main source rocks and higher geothermal gradient, whereas the organic matters have lower thermal evolution extent due to the shallower burial of source rocks and the lower geothermal gradient in the western part of the basin, thus could not form large-scale hydrocarbons and limited the hydrocarbon enrichment of a depression. Therefore, it can be seen that the heterogeneities in thermal evolution of the main source rocks is the basic factor causing the great heterogeneities in hydrocarbon enrichment for different depressions.

4.2 The main source rocks and source-reservoir-cap rock assemblages determining the distribution of hydrocarbons in strata

According to the thought of "Source Control Theory" (Hu Chaoyuan, 1982), the favorable zones of hydrocarbon generation not only control the distribution range of hydrocarbons horizontally, but have the function of source control vertically. In other words, the distribution of major hydrocarbon-bearing layers is closely related to source rocks. The tectonic evolution of a depression controls the distribution of source rocks in the vertical strata, and the reservoirs adjacent to the source rocks preferentially trap hydrocarbons; thus, the spatial distribution of source rocks controls the preferential enrichment strata of hydrocarbons (Zhao Wenzhi and Chi Yingliu, 2000).

From the depressions in the edge areas to the Bozhong depression, the intensive rift periods of Cenozoic depressions gradually become late, leading to the source rocks gradually becoming newer and shallower, as well as the source-reservoir-cap rock assemblages (Fig. 9). The early depressions are enriched in hydrocarbons in Pre-Paleogene, such as Damintun and Weibei depressions, whereas the inherited depressions are mainly enriched in hydrocarbons in Paleogene, such as Dongying and Dongpu depressions, while the late depressions are enriched in hydrocarbons in Neogene such as Bozhong and Zhanhua depressions.

It can be seen that the evolution types of depression in the Bohai Bay Basin are perfectly correlated with the distribution of the three oil-bearing strata, indicating that the tectonic evolution determines the spatial distribution of the main source rocks and source-reservoir-cap rock assemblages, so as to control the hydrocarbon enriched layers vertically.

4.3 Heterogeneities in the major controlling factors for hydrocarbon enrichment in different layers

The major factors constraining the hydrocarbon enrichment in the three hydrocarbon-bearing layers are heterogeneous in the Bohai Bay Basin, including the hydrocarbon supplying ability, fault transportation and

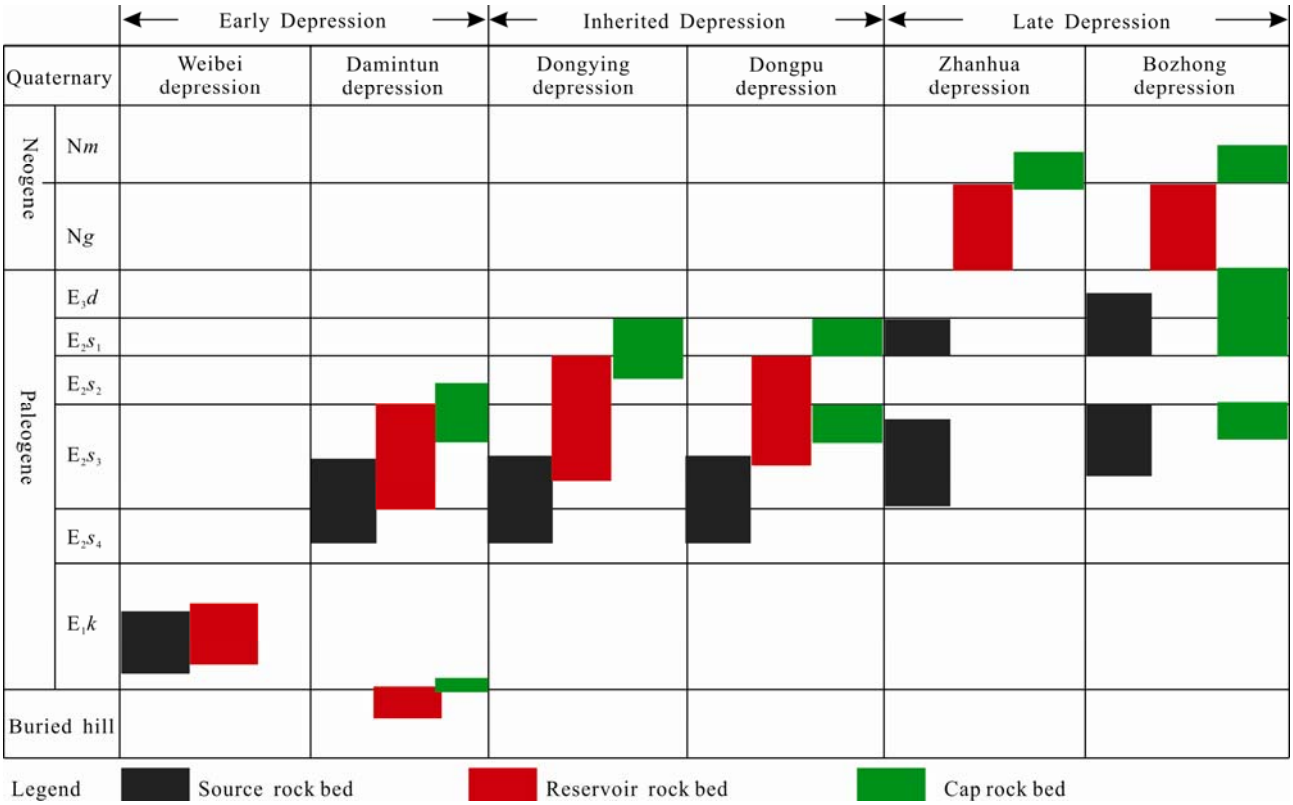

Fig. 9. Evolution of source-reservoir-cap rock assemblages in depressions, Bohai Bay Basin.

sealing and preservation conditions and source-reservoir assemblages. Hydrocarbons generated by Paleogene source rocks are prior to accumulating in Paleogene, and then transported and accumulated into Pre-Paleogene and Neogene through faults and other migration pathways. According to the complementarity principle of hydrocarbon distribution (Du Jinhu et al., 2004), the hydrocarbon adequacy and vertical transportation are the significant reasons causing the heterogeneities in hydrocarbon enrichment in different layers.

4.3.1 The relationship between fault transportation and hydrocarbon enrichment in Neogene

As the vertical transportation pathway of hydrocarbons, faults are of vital importance for Neogene hydrocarbon accumulation in the Bohai Bay Basin (Jiang Youlu et al., 2014). Neogene hydrocarbons come from underlying Paleogene, and are characterized by other source rocks supplying hydrocarbons and accumulating along the source faults. The vertical migration conditions are the key for hydrocarbon accumulation. Based on the study of the activity rate of source faults in the Neogene period, we find that the activity intensity of a fault in the late period influences the type of hydrocarbon enrichment of Neogene in the depression. With the increase of activity intensity of a fault, the enrichment types of depressions are changed from poor type to enriched type and then to highly-enriched type. Neogene hydrocarbons are concentrated in the areas where the fault activity rate is greater than 5 m/Ma from the late Neogene period to the Quaternary period and extremely enriched in the areas where the fault activity rate is greater than 10 m/Ma, whereas they appear less frequently in the areas where the faults are weak (Jiang Youlu et al., 2015b; Fig. 10). From an overall perspective, the larger the fault activity rate is, the more enriched the hydrocarbons of the Neogene strata are. Nevertheless, when the faults are too active (the fault activity rate is more than 25 m/Ma), it is difficult for hydrocarbons to accumulate due to the dispersion of hydrocarbons (Zou Huayao et al., 2010).

4.3.2 The relationship among hydrocarbon supplying ability of source rocks and sealing and preservation conditions with Paleogene hydrocarbon enrichment

As the main source rocks, the traps in Paleogene strata near source rock intervals preferentially accumulate hydrocarbons. Hydrocarbons from the depressions with poor hydrocarbon generation conditions and a small amount of resources are almost exclusively accumulated in Paleogene reservoirs (Fig. 4 and Fig. 5). Meanwhile, in hydrocarbon generating depressions, only when the traps in Paleogene strata are saturated with hydrocarbons**,** the extra hydrocarbons can migrate into the Neogene and Pre-Paleogene reservoirs far from source rocks. Thus, the

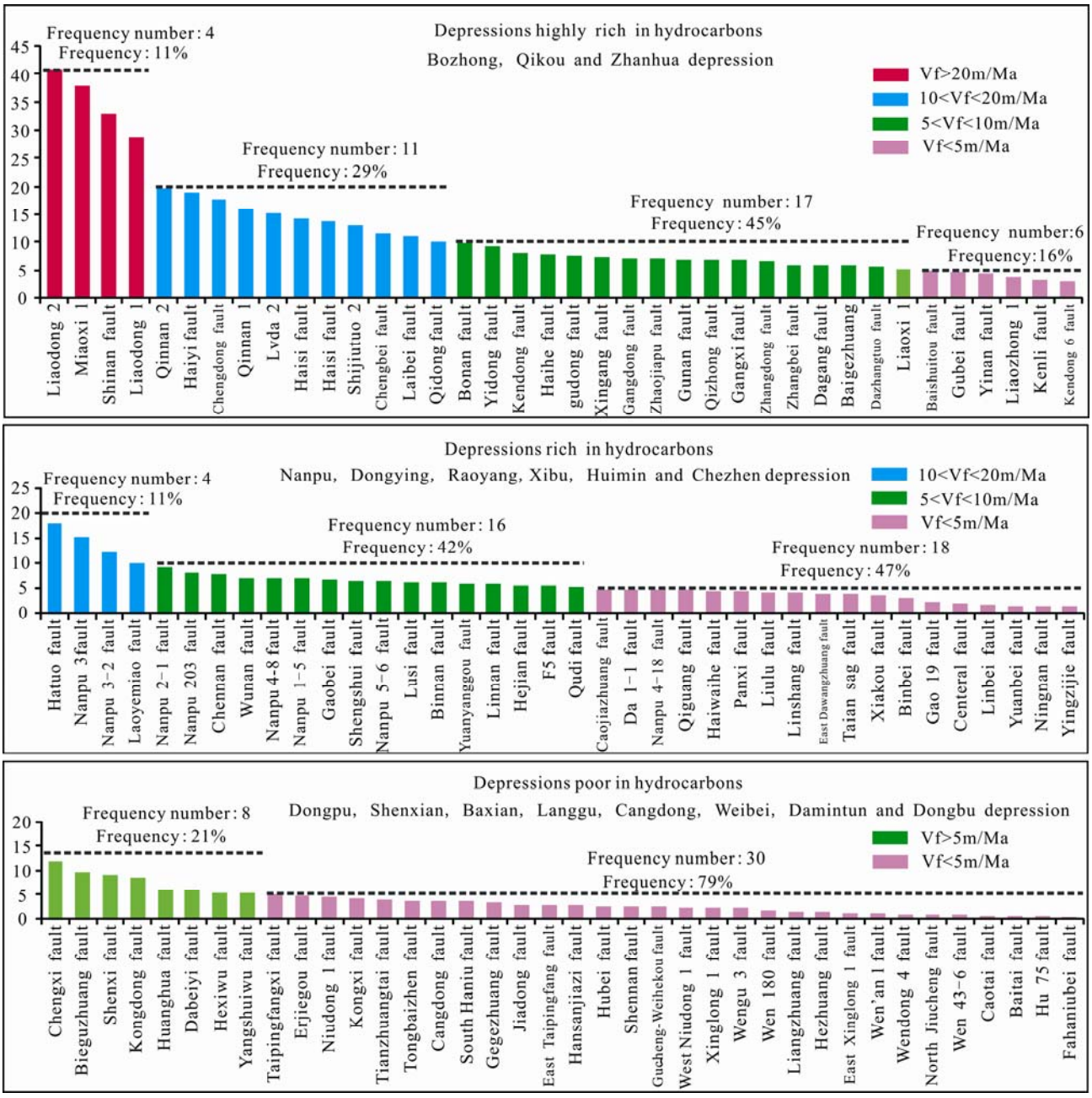

Fig. 10. Activity velocities of main source faults during Neogene period in different Neogene hydrocarbon enrichment depressions, Bohai Bay Basin.

depressions with low hydrocarbon enrichment are generally those with normal pressure or lower abnormal pressure, in which hydrocarbons are accumulated in Paleogene while Pre-Paleogene and Neogene have not been found massive resources. Moreover, depressions with hydrocarbons enriched in the three strata are the oil-rich and enormously oil-rich ones. The source rocks develop abnormal pressure and thus have higher charging dynamic.

The formation of overpressure in source rocks of depressions in the Bohai Bay Basin is closely related to the hydrocarbon generation, so the overpressure size of hydrocarbon generation layers can indirectly reflect their hydrocarbon generation capacity. The depressions with higher overpressure have relatively strong hydrocarbon generation ability, and thus can provide enough dynamic and hydrocarbons. The resource abundance correlates positively with pressure coefficient of hydrocarbon generation layers in different petroliferous depressions, indicating that the resource abundance increases with the increase of formation pressure. For example, the Dongying depression, which has pressure coefficient up to 1.8 (Zhang Shanwen et al., 2009), has higher resource abundance and is an enormously oil-rich depression.

Whereas the depressions with smaller pressure coefficient (such as the Huimin depression) have relatively smaller resource abundance, and the Weibei depression developing normal pressure has the smallest resource abundance (Table 2).

The pressure structure of a depression is closely related to the hydrocarbon enriched layers. According to the pressure field characteristics of the main hydrocarbon generation layers in depressions, depressions in the Bohai Bay Basin are divided into three types, namely normal pressure types, single overpressure types and dual overpressure types. Moreover, the hydrocarbon generation capacity varies among depressions of different pressure types, which is related to the hydrocarbon enriched layers. Hydrocarbons in depressions of normal pressure are mainly distributed in E_1k and Pre-Paleogene, while hydrocarbons in depressions of single overpressure are accumulated in Shahejie Formation of Paleogene, and hydrocarbons in depressions of dual overpressure are enriched in Neogene (Fig. 11).

Hydrocarbons generated from Paleogene source rocks were initially accumulated in Paleogene reservoirs, and when depressions have good hydrocarbon generation conditions and enough hydrocarbons, they can migrate and diffuse easily to shallow strata along the migration pathway under the action of buoyancy and overpressure of hydrocarbon generation layers. Therefore, the seal condition is crucial to hydrocarbon enrichment in

Table 2 Data of pressure coefficient and hydrocarbon abundance in depressions of different types in Bohai Bay Basin

Depressions	Resource abundance(10^4/km^2)	Pressure coefficient	Depressions	Resource abundance (10^4/km^2)	Pressure coefficient
Dezhou	2	1.01	Zhanhua	53	1.7
Weibei	8.8	1.2	Bozhong	64.67	1.75
Huimin	20.26	1.4	Nanpu	67.29	1.75
Raoyang	20.89	1.4	Qikou	69.75	1.7
Eastern Liaohe	21.77	1.4	Western Liaohe	78.47	1.7
Chezhen	23.33	1.45	Dongying	83.21	1.8

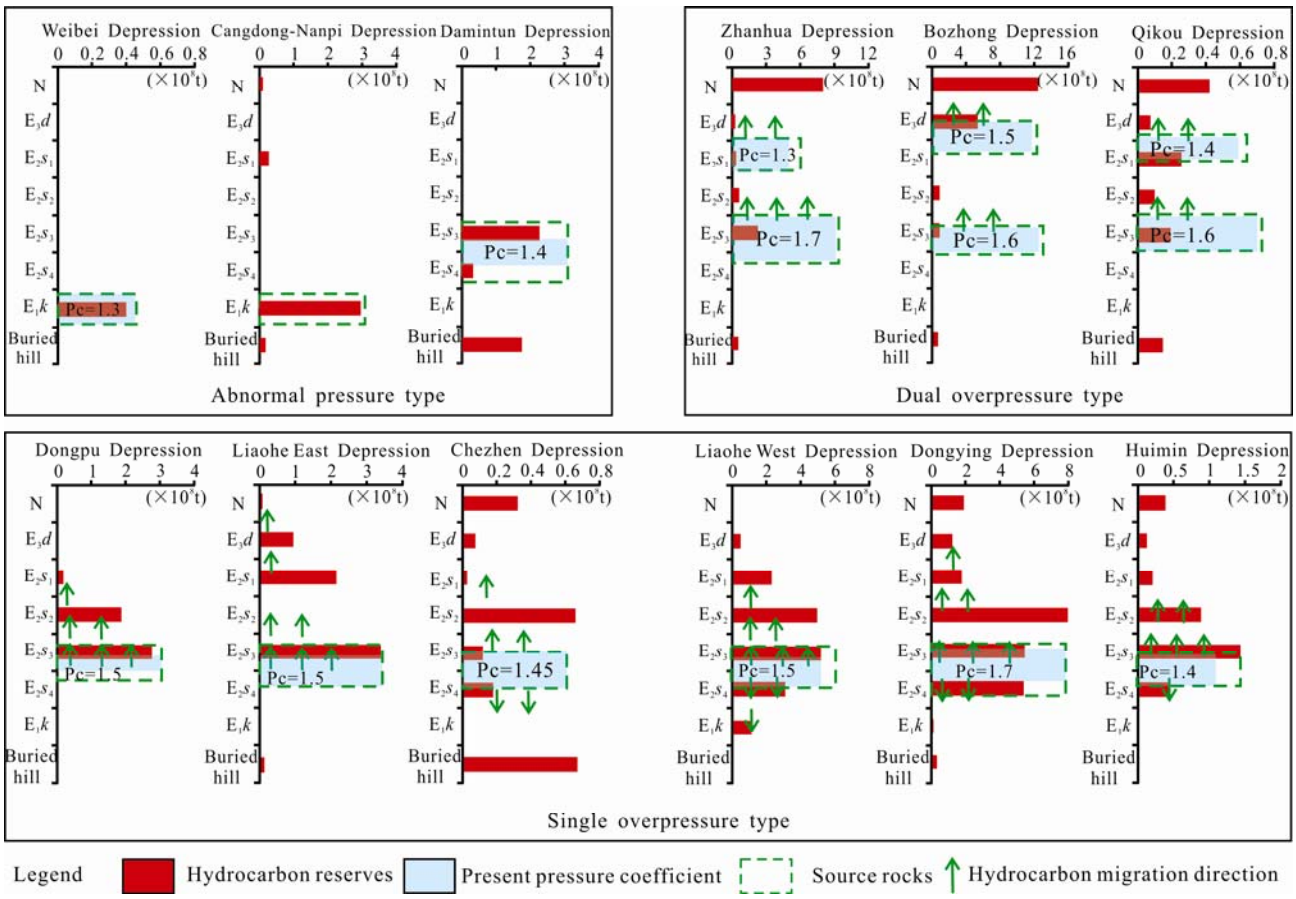

Fig. 11. Relationship between pressure characteristics of source rocks and vertical distribution of hydrocarbons in depressions of different pressure field types in the Bohai Bay Basin.

Paleogene strata. When a fault is active, fractures inside the fault are very developmental and thus the ability of vertical transportation for hydrocarbons is strong. Although the fault can significantly adjust the Paleogene pools, the thick mudstone cap from E_2s_1 to E_3d overlying the Paleogene strata weakens the vertical transportation of faults and thus can effectively seal Paleogene hydrocarbons vertically. Therefore, fault-cap assemblages are significant to the distribution of Neogene hydrocarbons in vertical strata.

Based on the thickness of the cap over the Paleogene area and the fault activity rate since the Neogene period, fault-cap assemblages are divided into three types: transportation type, preservation type and transportation-preservation type. The transportation fault-cap assemblages are those propitious to vertical migration of the hydrocarbons with larger fault activity rate and thinner mudstone caps. The preservation fault-cap assemblages are those with small-medium fault activity rate and thicker caps and thus unfavorable for upward migration of hydrocarbons. The transportation-preservation fault-cap assemblages are those with larger fault activity rate and a developed sealing cap and thus characterized by both transportation and preservation (Table 3).

Based on the percentage of proved reserves in three layers, the depressions in the Bohai Bay Basin can be categorized as four types, namely Neogene enrichment type, Paleogene enrichment type, Pre-Paleogene enrichment type and common enrichment type. The standard of Neogene enrichment type is that the proved reserves percent in Neogene should be more than 40%. The standard of Paleogene enrichment type is that the proved reserves percent in Paleogene should be more than 70%. The standard of Pre-Paleogene enrichment type is that the proved reserves percent in Pre-Paleogene should be more than 30%. The depressions without the above three types are classified as common enrichment type.

The transportation fault-cap assemblages are favorable for hydrocarbons to vertically migrate into the Neogene, breaking or bypassing the cap over the Paleogene, and

Table 3 Matching relationship between faults and cap rocks of Paleogene in depressions, Bohai Bay Basin

Depression	Neogene fault activity velocity (m/Ma)	Migration capacity	Thickness of cap rock (m)	Sealing assessment	Resources (10^8t)	Enrichment strata	Proved reserve	Result
Bozhong	40.88	strong	776	good	56	Neogene		poor
Dongying	5.8	poor	300~400	medium-good	46.9	Paleogene		good
Xibu	5.8	poor	400~600	good	34.81	Paleogene		good
Nanpu	25.1	strong	300~500	good	34.28	Pre-Paleogene, Paleogene and Neogene		good
Qikou	13.6	good	315	medium	29.16	Neogene		good
Liaoxi	8.43	poor	335	medium	27.77	Paleogene		good
Zhanhua	17.54	strong	250~400	medium	26	Neogene		good
Liaozhong	20.76	strong	484	medium	22.84	Paleogene		
Raoyang	5.6	poor	300~400	medium	15.4	Pre-Paleogene		good
Dongbu	5.12	poor	150~200	medium-good	14.93	Paleogene		good
Huimin	4.57	poor	150~200	poor	14	Paleogene		good
Huanghekou	13.88	good	326	medium	13.5	Pre-Paleogene, Paleogene and Neogene		good
Dongpu	0.92	poor	100	good	10.79	Paleogene		good
Baxian	2.4	poor	200~350	medium	8	Pre-Paleogene		good
Laizhou Bay	1.23	poor	200~350	medium	6.99	Pre-Paleogene, Paleogene and Neogene		poor
Chezhen	4.73	poor	350~500	medium-good	6.6	Pre-Paleogene		good
Bodong	5.21	poor	494	good	6.53			
Damintun	1.46	poor	150~350	poor-medium	6.41	Pre-Paleogene, Paleogene and Neogene		good
Cangnan	6.74	poor	150~200	poor	6.05	Paleogene		good
Langgu	3.68	poor	150~350	poor-medium	4.45	Pre-Paleogene, Paleogene and Neogene		good
Banqiao	3.0	poor	150~400	poor-medium	3.08	Paleogene		good
Liaodong	20.42	strong	317	medium	1.68	Paleogene		poor
Shenxian	3.18	poor	100~250	poor	1.62	Pre-Paleogene, Paleogene and Neogene		good
Weibei	2.3	poor	Erosion	poor	1.2	Paleogene		good

thus the hydrocarbons are mainly enriched in Neogene reservoirs. The preservation fault-cap assemblages have fine seal conditions and weak vertical transportation of the hydrocarbons, leading to a large amount of hydrocarbons accumulating under the cap over the Paleogene, corresponding to the accumulation of hydrocarbons in Paleogene and Pre-Paleogene reservoirs. The preservation and migration conditions are equivalent in the transportation-preservation fault-cap assemblages, and thus hydrocarbon reserves of the Neogene are roughly equivalent to those of the Paleogene. Therefore, the fault activities during charge timing constrain heterogeneities in hydrocarbon enrichment for Paleogene and Neogene strata. When faults are weak or inactive, the vertical transportation is weak and thus the hydrocarbons are mainly concentrated in Paleogene reservoirs. Conversely, when faults are active, the vertical transportation of hydrocarbons is strong and the hydrocarbons are mainly enriched in Neogene reservoirs.

4.3.3 Source-reservoir assemblages constraining the scale of hydrocarbon enrichment in Pre-Paleogene strata

The reservoir properties of Pre-Paleogene buried hills in the Bohai Bay Basin are influenced by the weathering degree and closely related to the tectonic evolution of the Pre-Paleogene period (Li Pilong et al., 2004; Zhang Shanwen et al). According to the characteristics of tectonic evolution in the Pre-Paleogene, the basements are divided into three types: type I basement of carbonate rocks in the Mesoproterozoic, Neoproterozoic and Early Paleozoic, type II basement of the Lower Paleozoic and type III basement of the Mesozoic. The distribution of reservoir and transport conditions becomes poor gradually from type II basement to type III basement. In the early and inherited depressions, the faults of the Neogene are weak during the late period, the thickness between the source and reservoirs is thin, and the source rocks are deep in vertical strata; thus, it is difficult for hydrocarbons to migrate into shallow reservoirs and they are mainly enriched in the middle to deep layers. The depressions with type I basement developed high-quality reservoirs with longtime erosion, and when there were sufficient hydrocarbons, they could highly accumulate hydrocarbons in buried hills. Meanwhile, the inherited depressions and the areas with type II basement had middle hydrocarbon enrichment in the buried hills. The late depressions, strongly rifting during the Neogene period and with larger thickness between the source and reservoirs and type II and type III basements, developed poor accumulation conditions; the faults were active during charge timing and thus the hydrocarbons can easily migrate into shallow strata, leading to the poor hydrocarbon enrichment in buried hills (Fig. 12).

The distribution of hydrocarbons in buried hill traps is constrained by the tectonic evolution. The Pre-Paleogene tectonic evolution influences the reservoir quality in the basin basement. The Cenozoic tectonic evolution controls the hydrocarbon generation ability of the depression. Both these tectonic evolutions determine the scale of hydrocarbon enrichment in buried hills (Zhang Shanwen et al., 2009; Zhao et al., 2015). From the edge areas to the center areas of the Bohai Bay Basin, the type of basement changes with the evolution of depressions from early type to late type, the quality of buried hill reservoirs and migration conditions become poor, and the hydrocarbon enrichment gradually becomes poor.

In summary, the evolution history of the basin controls the source-reservoir-cap rock assemblages and the migration conditions and then controls the layers of hydrocarbon enrichment. From the early depressions to the late depressions in the Bohai Bay Basin, the source-reservoir-cap rock assemblages gradually become shallower, the reservoir conditions of the buried hill gradually become poor, the thickness between the source and reservoirs is increased, the late-stage activity of faults continues strongly, and the generation ability of source rocks in shallow strata becomes strong. Overall, the accumulation predominance transfers from the Pre-Paleogene to Neogene, and so as the hydrocarbon enriched layers (Fig. 13).

5 Discussions

The characteristics of source rocks and migration conditions were controlled by depression structures, which further constrained the spatial hydrocarbon distribution features in the petroliferous basin. However, the heterogeneous features in hydrocarbon enrichment and their main controlling factors in different depressions are still unclear. Therefore, based on statistical analysis, the relationship between heterogeneities in hydrocarbon enrichment and their major controlling factors for different depressions was comparatively analyzed. Moreover, this paper primarily identified that it is the tectonic evolution and hydrocarbon generation conditions that resulted in the heterogeneities in hydrocarbon enrichment in diverse depressions. It is suggested that further study should pay attention to the quantitative relationships between different controlling factors and hydrocarbon enrichment, in order to provide theory reference for the further petroleum exploration in the petroliferous basin.

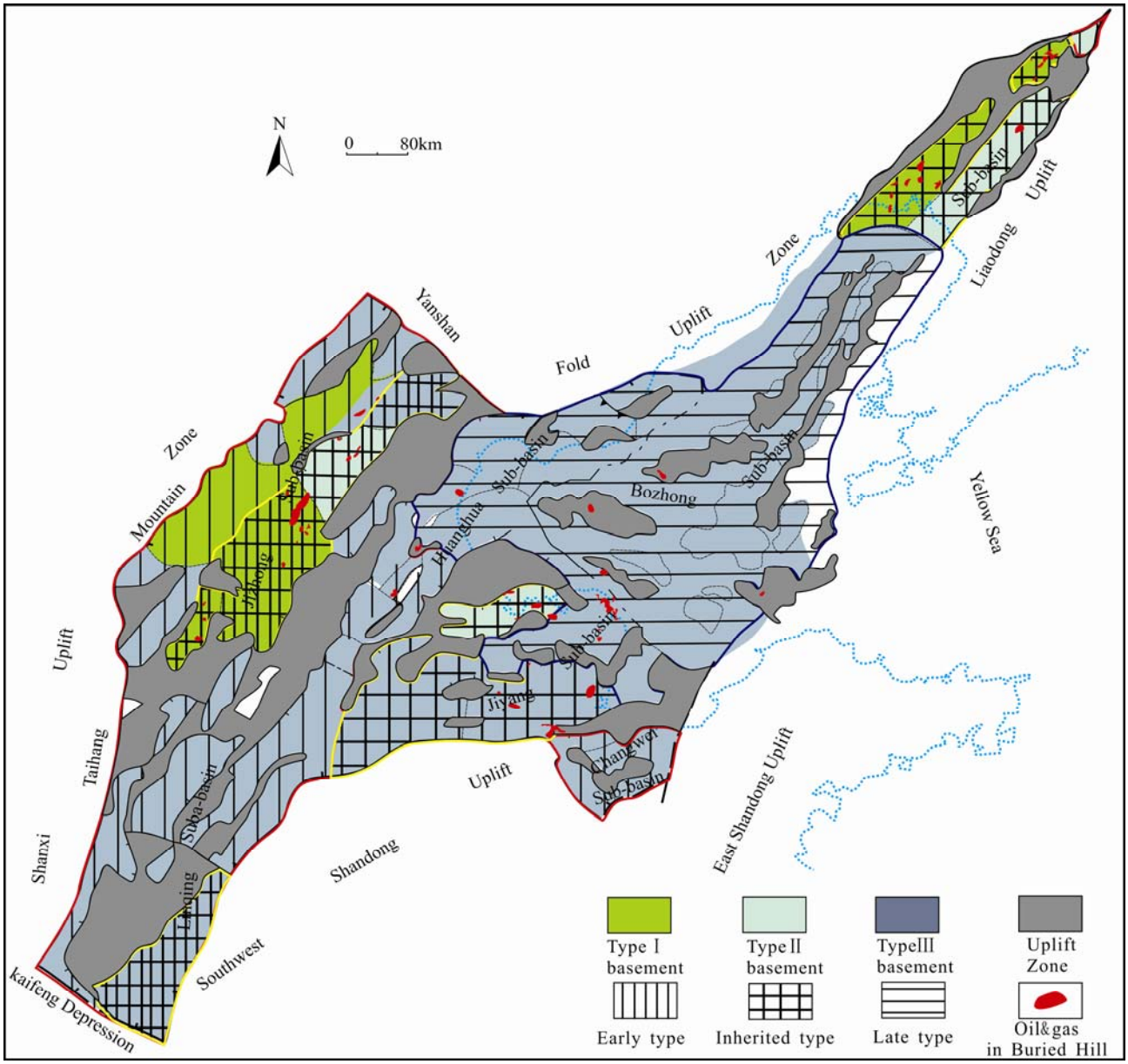

Fig. 12. The combination of basement type, depression evolution type and hydrocarbons in buried hills of the Bohai Bay Basin.

6 Conclusions

(1) The degree of hydrocarbon enrichment varies among different depressions in the Bohai Bay Basin, and the depressions can be divided into four types, namely enormously oil-rich, oil-rich, oily and oil-poor depressions. Moreover, the enormously oil-rich and oil-rich depressions are distributed in the eastern part of the basin with the most abundant hydrocarbons, and depressions around Bohai Sea are most enriched in hydrocarbons, whereas the depressions in the western part of the basin are poor in hydrocarbons. Overall, the basin can be characterized by "hydrocarbon rich in the east and poor in the west".

(2) The vertical distribution of hydrocarbons is highly heterogeneous and there is a regional migration rule: hydrocarbons are enriched in Pre-Paleogene strata and the lower parts of Paleogene strata in the depressions at the edge areas of the basin, enrichedin Paleogene strata in the entire basin, and to the Bohai Sea area in the center of the basin, hydrocarbons are enriched in Neogene strata. On the whole, the Bohai Bay Basin has characteristics of Pre-Paleogene strata rich in hydrocarbons in the marginal depressions, Paleogene strata rich in hydrocarbons in the entire basin, and Neogene strata rich in hydrocarbons in the center of the Basin.

(3) The tectonic evolution of the depressions controls the main hydrocarbon generation strata and source-reservoir-cap rock assemblages in a macroscopic view, and constrains the vertical distribution of hydrocarbon

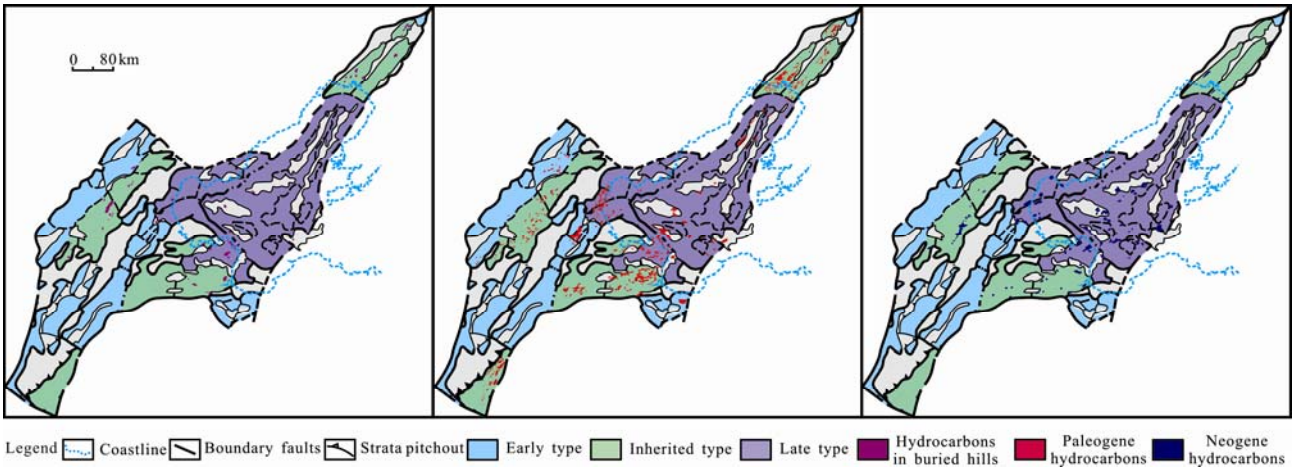

Fig. 13. The congruence of depression evolution type and hydrocarbon distribution, Bohai Bay Basin.

enriched layers. From the edge areas of the Bohai Bay Basin to the Bozhong depression, depressions transfer from the early type to late type, the source rocks and source-reservoir-cap rock assemblages gradually become shallow, the fault activity rate during the late period gradually increases, the hydrocarbon generation contribution of shallow source rocks increases and the hydrocarbon enriched layers gradually become newer.

(4) The hydrocarbon generation conditions basically control the hydrocarbon enrichment degree, and the thermal evolution level of source rocks is the major controlling factor. The early depressions have poor hydrocarbon generation conditions due to the small subsidence scope in the late period, while the inherited depressions have good hydrocarbon generation conditions because of the inherited subsidence and filling, and the late depressions have multiple sets of source rocks with higher maturity and relatively strong hydrocarbon generation capacity thanks to the intensive settlement and filling in the late period. A majority of enormously oil-rich and oil-rich depressions are late and inherited depressions with higher thermal evolution degree of the main source rocks, and thus the late and inherited depressions have better hydrocarbon generation capacity and hydrocarbon enrichment than the early depressions.

(5) The sufficient degree of hydrocarbons, main source-reservoir-cap rock assemblages and vertical transportation of faults control the vertical distribution proportions of hydrocarbons in Pre-Paleogene, Paleogene and Neogene strata in different depressions. However, the major factors controlling hydrocarbon enrichment in different strata are heterogeneous, with source-reservoir combinations for Pre-Paleogene hydrocarbons, source-reservoir-cap rock assemblages for Paleogene and migration conditions of faults for Neogene hydrocarbons when the hydrocarbon source is enough.

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