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Mechanisms of Differential Enrichment of Oil and Gas in the Paleogene of the Bohai Exploration Area: Controlled by Sag Types and Source–Reservoir Coupling

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Abstract: As of 2019, 119 oil and gas fields were involved in the Paleogene of the Bohai exploration area, accounting for more than 85% of the total number of oil and gas fields in the Bohai Bay Basin. Previous studies have confirmed that there are significant differences in the degree of oil and gas enrichment in the Paleogene of the Bohai exploration area. However, how these differences affect the hydrocarbon generation potential, and oil and gas resource distribution in each region has not been thoroughly studied; the controlling factors contributing to these differences have also not been fully elucidated. In view of this, based on the research results of projects on oil and gas exploration in the Bohai Bay Basin over the past decade, this paper statistically analyzed a large amount of data on source rocks, sedimentation rates, etc., and explored the differential enrichment of oil and gas in the Bohai exploration area and its genetic mechanisms. The research shows that from the offshore to the center of the marine area, the Paleogene oil and gas enrichment horizons have the characteristics of changing from old to new; the Paleogene source rocks in the offshore and marine areas have significant differences in thickness, total organic carbon content, organic matter type and maturity, and these differences determine the hydrocarbon generation potential and oil and gas resource distribution in each area; the sedimentary filling process in the Bohai exploration area is mainly controlled by tectonic uplift and subsidence and changes in lake level, and it has experienced stages such as rifting and lake transgression, thus showing obvious differences in provenance and sedimentary reservoirs; three sets of source–reservoir–caprock combinations are developed in the Bohai exploration area, and oil and gas are mainly enriched in the source rock strata and adjacent reservoirs. The middle and upper source–reservoir–caprock combinations have the best configurations, and from the offshore to the marine area, oil and gas show a trend from enrichment in Es3 to enrichment in Es1–Ed. Due to the differences in sag types, there is differential enrichment of oil and gas in the Bohai exploration area. According to the sedimentation rate, the sag types in the study area can be divided into early-developed type, inherited-developed type and late-developed type. The sag types in the Bohai exploration area show the characteristics of gradually changing from the offshore to the late type in the marine area, and there is a good corresponding relationship between the sag types and the vertical enrichment strata of oil and gas. The research results can provide a reference for discussing the oil and gas accumulation laws and future exploration and development of the Bohai exploration area.

Keywords: Bohai exploration area; offshore; marine; Paleogene reservoirs; hydrocarbon differential enrichment; classification of sag types

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1. Introduction

The Bohai Bay Basin is located in the eastern part of China (Figure 1). It is a Mesozoic-Cenozoic rift basin developed on the basis of the North China Craton. The entire basin has multiple oil-bearing series and is rich in petroleum resources. It is one of the important petroleum-producing areas in China and holds a significant position in the field of petroleum exploration and development in China [1–3]. The Bohai Sea is situated in the eastern part of China, originating from the late Mesozoic to the early Cenozoic. It is the northernmost offshore sea area in China and is a semi-enclosed bay controlled by the evolution of various tectonic activities [4,5]. It is adjacent to the Liaodong Peninsula in the North, connected to the Shandong Peninsula in the South, and is linked to the Yellow Sea through the narrow Bohai Strait in the East [6]. Its coastline is approximately 4000 km long, with an area of about 80,000 square km and an average water depth of 18 m [7,8]. According to the topography and geomorphology, the Bohai Sea can be divided into four parts: Liaodong Bay, Bohai Bay, Laizhou Bay, and the Bozhong Shallow Sea Basin [7,8]. The Bohai exploration area is located in the eastern part of the Bohai Bay Basin (Figure 1) and often refers to the sea-covered area. In the field of petroleum geology, the Bohai exploration area is often divided into the offshore area and the marine area [6].

As of 2019, 139 oil and gas fields had been discovered in the Bohai Bay Basin, among which 119 were related to the Paleogene of the Bohai exploration area, accounting for more than 85% of the total in the whole basin. A total of 24 oil and gas fields are involved in the offshore area. Among them, in the Liaohe offshore area, there are Yuehai Oilfield, Kuihuadao Oilfield, Haiwaihe Oilfield, Bijialing Oilfield, Shuangnan Oilfield, Taiyangdao Oilfield, and Hainan Oilfield; in the Dagang offshore area, there are Zhaodong Oilfield, Banqiao Oilfield, Zhangjuhe Oilfield, Beidagang Oilfield, Changlu Oilfield, and Tangjiahe Oilfield; in the Shengli offshore area, there are Yingxiongtan Oilfield, Laohekou Oilfield, Dawangbei Oilfield, Zhuangxi Oilfield, Gudong Oilfield, and Changdi Oilfield; and in the Jidong offshore area, the Nanpu 1-5 structural belt is involved. In recent years, significant progress has been made in the exploration and development of oil and gas in the offshore area of the Bohai exploration area (Table 1). Well Yuetan 1 in the Liaohe offshore area is the first key risk exploration well completed by Liaohe Oilfield in 2020. It is located in the southern section of the Haiyue Slope Structural Belt in the eastern offshore area. Good oil and gas shows were observed in both the Dongying Formation and the Shahejie Formation. This well achieved a zero breakthrough in marine fracturing in Liaohe Oilfield and set the highest record for the scale of fracturing in China's offshore areas. The successful drilling of Well Yuetan 1 broke the situation of no exploration progress in the offshore exploration area for many years [9,10]. In the Nanpu 5 structural belt of the Jidong offshore area, various stratigraphic and lithologic traps related to volcanic rocks have developed in the Shahejie Formation. The volcanic rock reservoirs have undergone alteration to varying degrees, with great exploration potential and good development prospects, and have become the main exploration targets in recent years [11,12]. On 2 April 2018, the Tangjiahe Oilfield of the First Beach Oil Production Plant of Dagang Oilfield increased crude oil extraction by 105 tons per day, with a cumulative increase of 4350 tons in that year [13]. In 2020, the downhole oil–water separation and co-production injection technology was implemented in nine wells in the third fault block of the Tangjiahe Oilfield. Well Gang 521 had normal production and injection for 219 days. The water/oil ratio of the produced fluid was significantly lower than that of the formation fluid, and the effect of water control and oil stabilization was obvious. It successfully created the first block-level co-production and injection demonstration area of China National Petroleum Corporation. On 24 December 2020, after the perforation and production of Well Gang 539-3HK in the Tangjiahe Oilfield, which is under the control of the First Oil Production Plant of Dagang Oilfield, the daily increase in crude oil reached 15 tons for 20 consecutive days. In 2022, Well Zhuanghai 28

in the Shengli offshore area produced high-yield industrial oil and gas flow in the Paleogene strata. The daily oil production during the test was 102.5 m^3 and the daily gas production was more than 200 m^3, achieving a continuous breakthrough in the exploration of oil and gas in the Paleogene of the Zhuanghai area. A total of 95 oil and gas fields are involved in the marine area, including Bozhong 13-2, Bozhong 19-6, Bozhong 26-6, Penglai 19-3, Penglai 9-1, Jinzhou 25-1, Caofeidian 11-1, etc. Among them, there are 9 large oil fields, 1 large gas field, 38 medium-sized oil fields, with proved and controlled reserves of 5.763 billion tons of oil equivalent and tertiary reserves of 6.524 billion tons of oil equivalent. In 2022, a large amount of oil and gas was discovered for the first time in the deep Kongdian Formation fan delta glutenite reservoir above the bulge of Bozhong 19-6, with proved reserves of 253.4 billion m^3 of natural gas and 242 million m^3 of condensate oil [14] and tertiary reserves of 448.95 billion m^3 of natural gas and 420.044 million m^3 of condensate oil (800 million m^3 of oil equivalent).

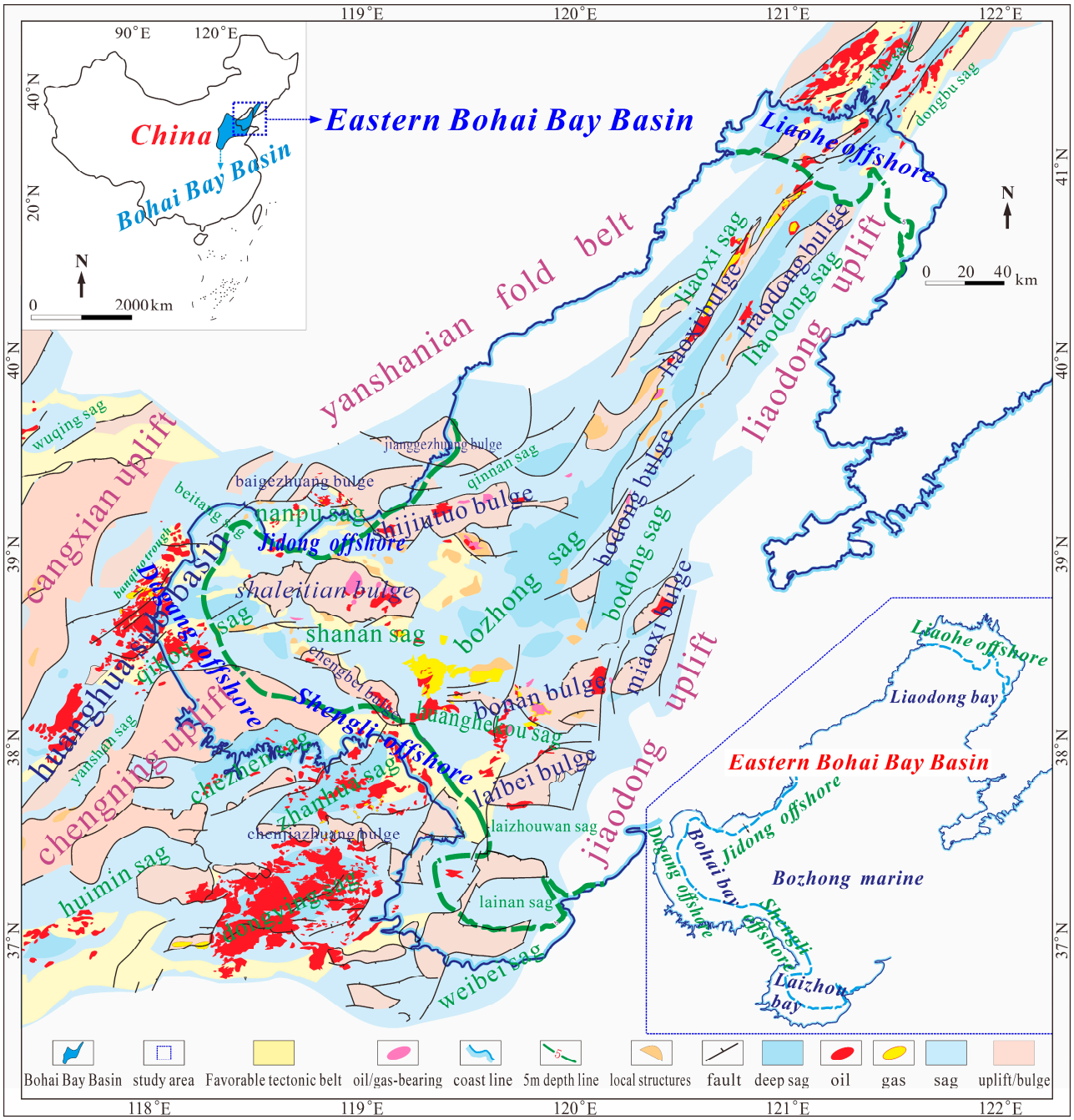

Figure 1. Geographical location and exploration status of the Bohai exploration area.

Table 1. Progress of oil and gas exploration in the Bohai exploration area.

Year	Region	New Wells/Reserve	Key Data/Achievements	Significance/Contribution
2018	Dagang Offshore (Tangjiahe Oilfield)	Production enhancement wells	Daily oil increase of 105 tons per well, cumulative annual increase of 4350 tons	First achievement in efficient extraction from mature oilfields in offshore areas, validating shallow reservoir potential.
2020	Liaohe Offshore (Haiyue Slope Belt)	Well Yuetan 1 (key risk exploration well)	Good oil and gas shows in Dongying and Shahejie Formations, setting a record for fracturing scale in China's offshore areas	First successful fracturing in Liaohe Offshore, breaking years of exploration stagnation
2020	Dagang Offshore (Tangjiahe Oilfield)	Downhole oil-water separation co-production/injection technology	Implemented in 9 wells; Well Gang 521 operated normally for 219 days with significantly reduced water-oil ratio	First block-level co-production/injection demonstration area in China, providing a new technical approach for high-water-cut oilfields
2022	Shengli offshore (Zhuanghai area)	Well Zhuanghai 28 exploration	Test production of 102.5 m^3/day oil and >200 m^3/day gas in Paleogene strata	Continuous breakthroughs in Paleogene exploration in the Zhuanghai area, revealing strong lithologic reservoir potential
2022	Bozhong Sag (BZ19-6)	Kongdian Formation fan-delta glutenite reservoirs	Proved reserves: 253.4 BCM natural gas, 2.42 MCM condensate; tertiary reserves: 448.95 BCM gas	Rare large-scale deep fan-delta gas reservoirs globally, expanding deep exploration in the Bohai Bay Basin
2022	Bozhong Sag	Billion-ton oilfield cluster	Kenli 6-1, Kenli 10-2, BZ13-2, BZ26-6, PL19-3, etc.	Cumulative proved + controlled reserves of >1 billion tons of oil equivalent, securing production replacement potential
2023	Jidong Offshore (Nanpu 5 Structural)	Volcanic reservoir exploration	Porosity increased by 5 - 8% in altered Shahejie volcanic reservoirs; test production >100 m^3/day	Breakthrough in volcanic reservoir evaluation, opening new exploration frontiers in Paleogene volcanic rocks

As of 2021, the proved reserves in the Bohai Sea were estimated to amount to 5.041 billion tons of oil equivalent, including 0.574 billion tons of oil equivalent in the offshore area and 4.467 billion tons of oil equivalent in the marine area. Taking the PetroChina exploration area in the Bohai Sea as an example, during the "13th Five-Year Plan" period, the proved geological reserves of conventional oil were 240 million tons in the Jidong offshore area, 149 million tons in the Liaohe offshore area, and 130 million tons in the Dagang offshore area. The total proved geological reserves of conventional oil in the PetroChina offshore area exceeded 500 million tons. During the "13th Five-Year Plan" period, the total proved geological reserves of conventional natural gas in the PetroChina exploration area in the Bohai Sea exceeded 5 million m^3. Among them, the proved geological reserves of conventional natural gas in the Dagang offshore area were 199,100 m^3, 1.6379 million m^3 in the Liaohe offshore area, and 3.9095 million m^3 in the Jidong offshore area. The proportion of proved reserves of conventional natural gas in the Jidong offshore area is relatively high, accounting for approximately 17% of the proved reserves of conventional natural gas in the Bohai Bay Basin block of PetroChina during the "13th Five-Year Plan". During the period from the "13th Five-Year Plan" to the "14th Five-Year Plan", there have been significant

breakthroughs in oil and gas exploration in the Bohai Sea area [15,16], and several-hundred-million-ton large oil and gas fields have been discovered: a hundred-million-ton integrated oilfield discovered at Kenli 6-1, a hundred-million-ton large integrated oilfield discovered at Kenli 10-2, proved reserves of the buried hill in Bozhong 13-2 exceeding a hundred million tons, a hundred-million-ton oil field in the Archean metamorphic rock buried hill at Bozhong 26-6, a thousand-billion-cubic-meter integrated condensate gas field at Bozhong 19-6, and a billion-ton extra-large integrated oil field at Penglai 19-3 [17–20].

The global petroleum industry is currently facing issues regarding the actual extraction process and extraction costs. The crude oil extraction cost of the Dagang Oilfield in the Bohai Bay Basin is approximately USD 50 per barrel [21]. Achieving the digital transformation of oil and gas extraction can facilitate the management and monitoring of production processes, optimize decision making and enhance efficiency [22]. The Dagang Oilfield has been exploring the path of digital transformation. By constructing an intelligent oilfield system, it has realized the comprehensive perception of production processes, real-time monitoring, and intelligent decision-making support [21]. It is necessary to conduct a detailed demonstration of the oil and gas enrichment in the study area before drilling operations.

For the Bohai Bay Basin in eastern China, the geological differences in oil and gas often refer to the differences in various geological elements related to oil and gas enrichment and reservoir characteristics (such as source rocks, sedimentary reservoirs, source–reservoir–caprock combinations, etc.) [23]. As the main source–reservoir series in the Bohai exploration area and even the Bohai Bay Basin [23,24], the Paleogene remains the main area for reserve increase in the future [23]. Predecessors have conducted in-depth research on the characteristics of oil and gas distribution and reservoir-forming conditions of the Neogene and pre-Paleogene in different regions of the Bohai Bay Basin [25–27], and have also identified significant differences in oil and gas enrichment in the Bohai Bay Basin [28]. However, research on the mechanisms of differential enrichment of oil and gas in the Paleogene of the Bohai exploration area and its main controlling factors has not yet been carried out. In view of this, this research work is based on four major projects or topics related to oil and gas exploration in the Bohai Bay Basin over the past decade: The special project of PetroChina Company Limited, “Deepening the Understanding of Oil and Gas Geology in Mature Exploration Areas and Analyzing Exploration Potential” (2014D—0710); The National Science and Technology Major Project, “Research on the Laws of Oil and Gas Enrichment and Oil and Gas Reserve Increase Areas in the Northern Bohai Bay Basin” (2016ZX05006); The forward-looking major project of PetroChina Company Limited during the “14th Five-Year Plan” period, “Research on Exploration and Evaluation Technologies for Buried-hill Inner-part and Complex Fault-block Oil and Gas Reservoirs” (2021DJ0701); and The National Key Research and Development Project, “Organic Carbon Transformation and Oil and Gas Enrichment and Distribution in Cenozoic Continental Lacustrine Basins in Eastern China” (2023YFF0804303). Through statistical analysis of a large amount of data on source rocks, source–reservoir–caprock combinations, sedimentation rates, and the mapping of large-scale sedimentary facies diagrams, this paper conducts a detailed exploration of the laws of differential enrichment of Paleogene oil and gas in the Bohai exploration area and its controlling factors, providing a reference for future geological scientific research in the Bohai exploration area and the division of key exploration blocks.

2. Geological Settings

In the field of petroleum geology, the marine area is often divided into the offshore part and the marine part. Among them, the offshore refers to the sea area where the tidal flat zone connects with the ocean. It is a transition zone between the land and the ocean,

and is jointly delineated by the coastline and the 5m water depth line [6]. Taking the Bohai exploration area in eastern China as an example, the Bohai exploration area is divided into two blocks: the Bohai offshore area and the Bohai marine area (Figure 1). The offshore part is the area composed of the 0–5 m water depth line, and the marine part is the area where the water depth exceeds 5 m. This division method is often applied to the coastal areas in eastern China [6].

The offshore operation and construction for oil and gas exploration in the Bohai exploration area carry a high risk, relying on advanced technologies and strong economic strength. It faces more challenges than onshore oil and gas exploration in aspects such as drilling and development technologies, oil platform construction, and prediction and avoidance of natural disasters [29]. The shape of the Bohai offshore area is controlled by the coastline and presents a "C" shape as a whole. According to the geographical location and mineral rights lines, it is divided into three major offshore areas: Nanpu offshore in the north, Dagang offshore in the west, and Shengli offshore in the south (Figure 1). The reason for separately dividing the 0–5 m water depth area as the offshore area is that the offshore area has rich potential for oil and gas resources. However, due to the particularity of its geographical location and complex geological conditions, its exploration degree is generally low, and the exploration potential is huge. It has the characteristics of "high investment, high risk, and high technology", and the difficulty of exploration and development is greater compared to onshore and marine areas. The offshore area is affected by factors such as river injection, wind and waves, and ocean currents. The surface sediments are loose and non-uniform, with thick layers of silt, low bearing capacity, and heavy siltation; the tidal range is large, and storm surges are frequent; the winter period is long, and the ice conditions are severe. It was once considered a forbidden area for exploration and development. In recent years, with the continuous innovation of ideas in the field of marine engineering construction, the application and practice of characteristic supporting technologies such as solid structure access roads, permeable flow structure access roads, and the construction of offshore drilling platforms, especially the construction of artificial islands in the offshore area, have provided important technical guarantees for the high-quality and efficient development of offshore oilfields, solving the technical problem that "onshore equipment cannot go down and offshore equipment cannot come up" in the offshore area [6]. This has gradually made the offshore blocks become exploration hotspots with frequent exploration breakthroughs. Exploration and development in recent years indicate that the southern part of the Dagang offshore area is a key exploration area for Dagang Oilfield to achieve a reserve increase and production increase [23].

The strata deposited in the Paleogene period of the Bohai exploration area are, from bottom to top, Kongdian Formation (Ek), Shahejie Formation (Es), and Dongying Formation (Ed), respectively. Among them, the Shahejie Formation can be further subdivided into the fourth member of the Shahejie Formation (Es4), the third member of the Shahejie Formation (Es3), the second member of the Shahejie Formation (Es2), and the first member of the Shahejie Formation (Es1). During the deposition periods of Ek and Es4, the Bohai exploration area had the characteristics of multiple sedimentation centers and significant variations in stratum thickness. The sags at the basin margin were the subsidence and sedimentation centers with large stratum thicknesses. The strata of Es3 and Es2 were widely developed throughout the basin. During the deposition periods of Es1 and Ed, the subsidence and sedimentation centers of the Bohai exploration area migrated to the central Bohai area [30]. At the end of the Paleogene, from the offshore to the center of the marine area, the uplift amplitude and erosion thickness gradually decreased. Since the Neogene, the central Bohai area in the marine area has always been the subsidence and sedimentation center of the Bohai exploration area. The stratum thickness of the Neogene and Quaternary

is extremely large, far exceeding that of other marine and offshore areas. The Bohai exploration area has experienced multiple tectonic movements and developed multiple sets of source rocks. Five sets of source rock strata were developed in the Paleogene, namely the second member of the Kongdian Formation (Ek2), the fourth member of the Shahejie Formation (Es4), the third member of the Shahejie Formation (Es3), the first member of the Shahejie Formation (Es1), and the Dongying Formation (Ed). In the sags of the offshore area, Es3 and Es1 source rocks were developed, and Ek and Es4 source rocks existed locally; towards the center of the Bohai marine area, the hydrocarbon generation strata gradually increased and became younger. The Ed source rock was added and the Ed source rock in the center of the marine area became the main source rock. The contribution of oil and gas from the younger source rock strata gradually increased [26,31].

There are a total of 26 sags involved in the Paleogene of the Bohai area. Among them, 14 sags are involved in the offshore part, namely the Western Sag and Eastern Sag in the Liaohe exploration area; Nanpu Sag, Changli Sag, Laoting Sag, Qinnan Sag and Jianhe Sag in the Jidong exploration area; and Beitang Sag and Qikou Sag in the Dagang exploration area; Chezhen Sag, Zhanhua Sag, Dongying Sag, Qingdong Sag and Huaibei Sag in the Shengli offshore area. Among them, the key hydrocarbon-generating sags are the Western Sag, Eastern Sag, Nanpu Sag, Beitang Sag and Qikou Sag. The marine part involves 14 sags, namely the Liaoxi Sag, Liaozhong Sag and Liaodong Sag in the Liaodong Bay exploration area; Bohai Central Sag, Bohai East Sag and Qinnan Sag in the Bohai Central exploration area; Nanpu Sag, Qikou Sag, Shinan Sag, Shan'an Sag, Chengbei Sag, Huanghekou Sag, Miaoxi Sag and Laizhouwan Sag in the peripheral area of Bohai Central. Among them, Bohai Central Sag, Chengbei Sag and Huanghekou Sag have been research hotspots in the past ten years. In Bohai Central Sag, several hundred-million-ton large oil and gas fields have been discovered one after another [32–36]. Conducting long-term and detailed exploration and development in the above key areas is of great significance for enhancing national energy security, promoting scientific and technological progress, promoting economic development, expanding exploration fields, and achieving environmental protection and sustainable development [37–40].

3. Geological Differences

3.1. Differences in Paleogene Source Rocks Between the Offshore and Marine Areas

The basic conditions of source rocks in the Bohai exploration area can be jointly characterized by using the contour maps of source rock thickness, the contour maps of organic carbon in source rocks, the contour maps of organic matter types in source rocks and the contour maps of source rock maturity, which is helpful for the comparative analysis of the differences in oil and gas enrichment in the Paleogene of the offshore–marine areas, and is of great significance for analyzing the conditions of large-scale oil and gas enrichment in the Bohai exploration area (Figure 2, Table 2).

The contour maps of maturity of source rocks of the Paleogene in the offshore–marine areas reflect the mature state of organic matter after thermal evolution (Figure 2a–d). Source rocks with high maturity usually have high hydrocarbon generation and expulsion intensity, but at the same time, they may also have decreased hydrocarbon generation and expulsion capacity due to excessive maturity. The difference in maturity is reflected in the following: a small amount of mature source rocks appear in the Liaodong Bay, Bohai Central area and Liaohe offshore area in the Ek and Es4 stages, while there are no mature source rocks in the Dagang offshore area and Nanpu offshore area in the Ek and Es4 stages; the four sets of source rock strata are generally mature but are affected by the migration of the subsidence center in the Bohai exploration area, and the evolution degree of source rocks of the same strata is relatively higher in the marine part.

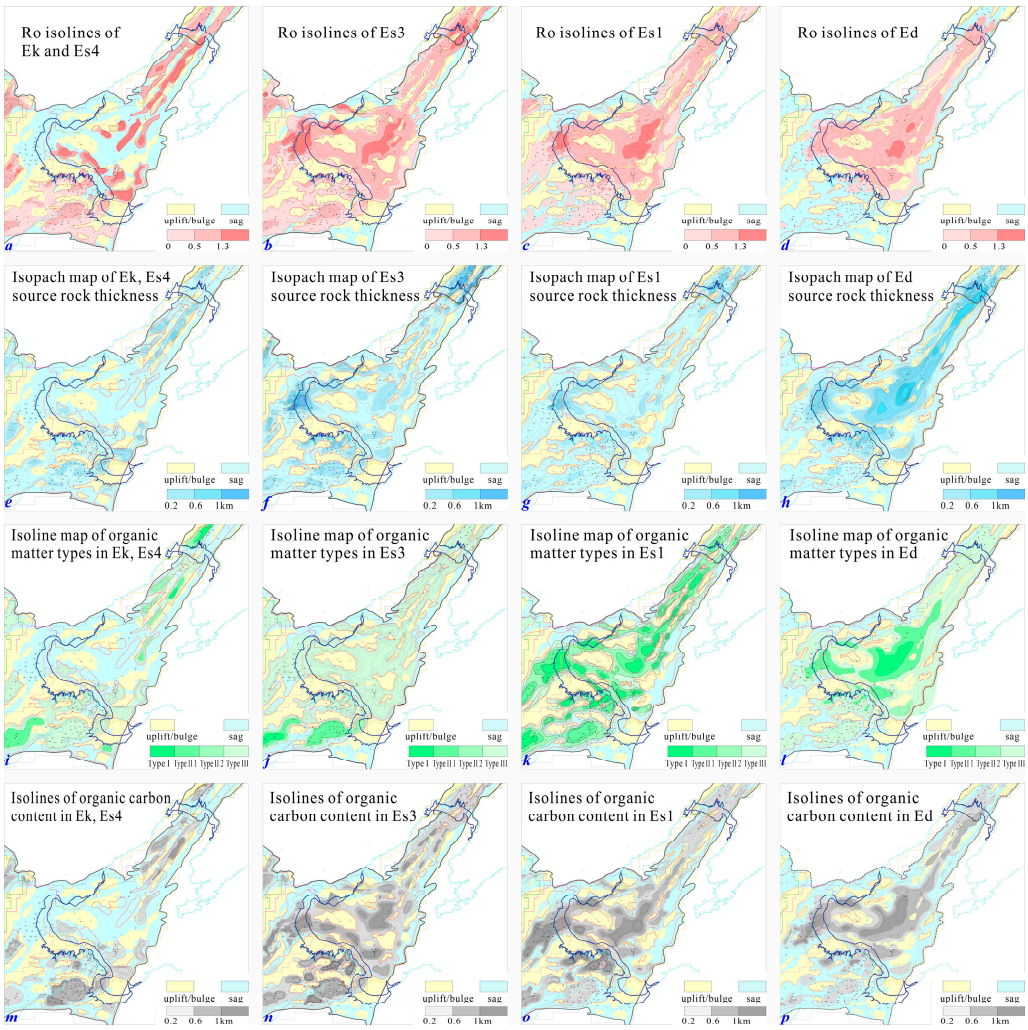

Figure 2. Evaluation contour map of Paleogene source rocks in Bohai exploration area ((**a**–**d**) isograms of the maturity of source rocks from the Kongdian Formation (Ek) to the Dongying Formation (Ed); (**e**–**h**) isopach maps of the thickness of source rocks from Ek to Ed; (**i**–**l**) isoline maps of the organic matter types of source rocks from Ek to Ed; (**m**–**p**) isoline maps of the organic carbon content of source rocks from Ek to Ed).

Table 2. Summary table of source rock characteristics in the Bohai exploration area (Paleogene).

Sag/Region	Source Rock Thickness (m)	TOC (%)	Organic Matter Type	Maturity (Ro, %)	Sag Type	Typical Structures/Wells
Western Sag, Liaohe Offshore	500–1000 (Es3)	1.0–2.5 (High)	Predominantly Type II, locally Type I	1.0–1.3 (Mature)	Inherited-type	Well Yuetan 1, Haiyue Slope Belt
Eastern Sag, Liaohe Offshore	300–600 (Es3)	0.5–1.5 (Medium)	Predominantly Type III	0.8–1.1 (Low-Maturity)	Early-type	Taiyangdao Oilfield
Bozhong Sag	>600 (Ed) (Dongying formation)	2.0–4.0 (Very High)	Type I–II	1.3–1.6 (High Maturity)	Late-type	PL19-3, Kenli 6-1
Huanghekou Sag	400–800 (Ed) (Dongying formation)	1.5–3.0 (High)	Predominantly Type II	1.2–1.5 (Mature–High Maturity)	Late-type	KL10-2, BZ19-6
Nanpu Sag	600–1000 (Es3)	1.2–2.8 (High)	Predominantly Type II, locally Type III	1.1–1.4 (Mature)	Inherited-type	Nanpu 5 Structural Belt, Well Zhuanghai 28

Table 2. *Cont.*

Sag/Region	Source Rock Thickness (m)	TOC (%)	Organic Matter Type	Maturity (Ro, %)	Sag Type	Typical Structures/Wells
Qikou Sag	800–1200 (Es3)	2.0–3.5 (Very High)	Type I–II	1.0–1.3 (Mature)	Inherited-type	Qikou Oilfield, Qikou Sag
Dagang Offshore (Tangjiahe)	200–400 (Es4)	0.8–1.2 (Medium)	Type III	0.7–1.0 (Low Maturity)	Early-type	Well Gang 521
Shengli Offshore (Zhuanghai)	300–500 (Es1)	1.0–2.0 (High)	Type II	1.0–1.2 (Mature)	Inherited-type	Well Zhuanghai 28, Zhuanghai Area

The contour maps of source rock thickness of the Paleogene in the offshore–marine areas reflect the distribution thickness of source rocks in the strata (Figure 2e–h), which are used to evaluate the scale of source rocks and the potential amounts of oil and gas resources. The thickness of source rocks directly affects their hydrocarbon generation potential. The greater the thickness, the more organic matter accumulates, and theoretically, the greater the hydrocarbon generation potential. The thickness of source rocks of Ek and Es4 is generally thin as a whole, with an overall thickness ranging from 200 to 300 m. The thickness of source rocks of Ek and Es4 in the Liaodong Bay of the marine area is the largest, among which the thickness of source rocks in the Liaoxi Sag and Liaozhong Sag exceeds 500 m. The source rocks of Es3 show obvious regional migratory changes. The thickness of Es3 in the Dagang offshore area and Liaohe offshore area is the highest, with both exceeding 1000 m. The thickness of source rocks in Jidong offshore exceeds 600 m, while the thickness of source rocks in marine areas such as Bozhong marine area and Liaodong Bay is relatively thin, with an overall thickness of about 200 m. The source rocks of Es3 are the main source rocks in the offshore area. The thickness of source rocks of Es1 shows an inherited trend, and the thickness is larger in the offshore part, locally exceeding 1000 m. The thickness of source rocks of Ed changes significantly in the Bohai exploration area. The thickness in Liaodong Bay and Bozhong marine of the marine area increases significantly. The thickest part is located in Bozhong marine area of the marine area. The thickness of source rocks in the offshore area is still large, exceeding 600 m as a whole. The thickness in Dagang and Liaohe offshore exceeds 1000 m, but the thickness center has migrated and gradually transitions to the central Bohai Sea.

The difference in the thickness of source rocks in the offshore–marine areas is mainly manifested as follows (Figure 2e–h): the scale of source rocks in the offshore part is thicker in the stages of Es3, Es1 and Ed, mainly Es3; the thickness of source rocks in the marine part is thinner in the early stage, and the scale of source rocks of the Dongying Formation is the largest. The thickness of source rocks shows a trend of gradual transition from the offshore to the center of the marine area.

The contour maps of organic matter types of source rocks of the Paleogene in the offshore–marine areas reveal the types of organic matter in source rocks and their distribution, which are used to evaluate the hydrocarbon generation potential and hydrocarbon expulsion efficiency of source rocks (Figure 2i–l). The organic matter types of source rocks can be divided into Type I, Type II and Type III. These classifications reflect the different sources and maturities of organic matter in source rocks, as well as their influences on the hydrocarbon generation potential and hydrocarbon expulsion efficiency. Type I is usually related to the mixed input of lower aquatic organisms and higher terrestrial plants, indicating that it has a high hydrocarbon generation potential and hydrocarbon expulsion efficiency; Type II is mainly composed of relatively high proportions of sapropelic organic

components; Type III is related to the generation of more gaseous hydrocarbons and a higher content of vitrinite in the microscopic components, indicating that its hydrocarbon generation and expulsion capacity are low. Different organic matter types have significant influences on the hydrocarbon generation capacity and oil and gas composition of source rocks. The organic carbon mass compensation coefficients of organic matter source rocks of Type I, Type II1, Type II2 and Type III are different, reflecting their differences in the hydrocarbon generation process. The source rocks of Ek, Es4 and Es3 in the offshore and marine areas are mainly Type III; a large amount of Type I and Type II organic matter appears in the source rocks of Es1 in the Dagang offshore area, Nanpu offshore area, Liaodong Bay and Bohai Central exploration area, indicating that this set of source rocks in this area is rich in organic matter, has a high degree of thermal evolution, is suitable for the generation of oil and natural gas, and has a high hydrocarbon generation potential; only Type I–Type II are developed in the source rocks of Ed in Bohai Central exploration area, and Type III is mainly in the offshore part.

The difference in the organic matter types of source rocks of the Paleogene in the offshore–marine areas is mainly manifested as follows (Figure 2i–l): both the offshore and marine areas are mainly Type III before Es2. From Es1, the organic matter types of the offshore–marine areas start to be better. In the Ed stage, only the organic matter types of source rocks in the marine area are better, and the organic matter types in the offshore area gradually decline.

The contour maps of total organic carbon (TOC) of source rocks of the Paleogene in the offshore–marine areas show the content of organic carbon in source rocks in different areas (Figure 2m–p), which can accurately and effectively evaluate the abundance of source rocks. Source rocks with high organic carbon content usually have better hydrocarbon generation potential. The TOC of Ed + Es4 source rocks in Liaodong Bay of the marine area is relatively high, and the TOC in the offshore part is approximately 0; the total organic carbon content of Es3 source rocks in Liaohe offshore is low, and the organic carbon of Es3 in Shengli offshore is 0. The TOC values in the trough areas such as Dagang offshore, Nanpu offshore, Liaodong Bay and Bohai Central exploration area are all very high, showing good hydrocarbon generation potential; the total organic carbon of Es1 source rocks in Liaodong Bay and Liaohe offshore shows a downward trend, while the total organic carbon in the Dagang, Nanpu offshore and Bozhong marine areas is still very high; the TOC of Ed source rocks in Liaohe offshore area and Liaodong Bay shows a recovery trend. The high TOC area appears in Liaodong Sag and Eastern Sag. The TOC in the Dagang offshore, Nanpu offshore and Bohai Central exploration area is still in the effective stage, greater than 1.0, among which the distribution range of TOC > 1.0 in Bohai Central exploration area is wider.

The main manifestations of the quality difference of source rocks of the Paleogene in the offshore–marine areas are as follows (Figure 2m–p): the range of high TOC in the offshore area is Es1 > Es3 > Ed > Ek + Es4, reflecting the trend that the range of high TOC first increases and then tends to be flat or gradually decreases from old to new; while the range of high TOC in the marine area is approximately Ed > Es1 > Es3 > Ek + Es4, reflecting the trend that the range of high TOC gradually expands from old to new.

3.2. Differences in Sedimentary Reservoirs of the Paleogene Between the Offshore and Marine Areas

The sedimentary filling process of the Paleogene in the Bohai exploration area was mainly controlled by tectonic uplift and subsidence and changes in lake level, experiencing stages such as rifting and lake transgression. During this process, various sedimentary systems such as fan deltas, sublacustrine fans, and large lacustrine delta deposits developed, and the zonal characteristics of the sedimentary system from the Shahejie Formation to the Dongying Formation were obvious (Figure 3).

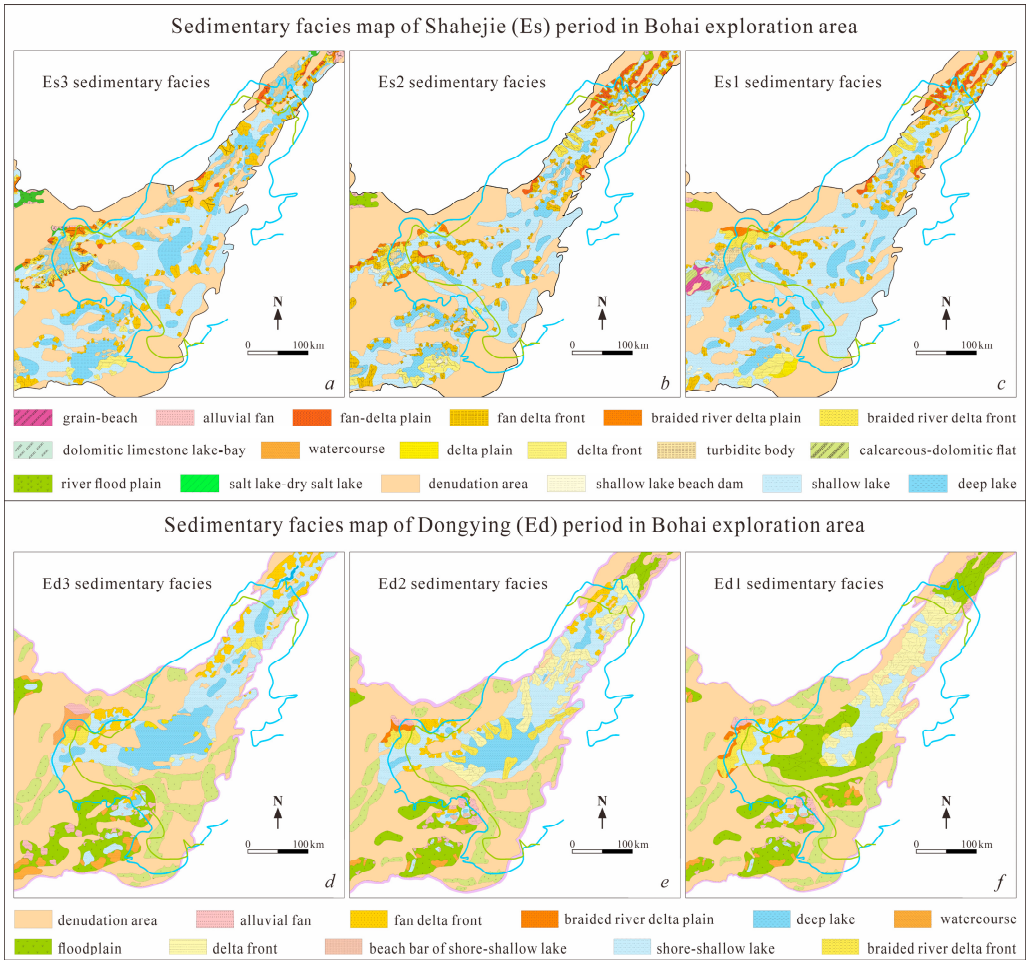

Figure 3. The migration diagram of Paleogene sedimentary filling in Bohai exploration area ((**a**–**c**) sedimentary facies map of Es in Bohai exploration area; (**d**–**f**) sedimentary facies map of Ed in Bohai exploration area).

The offshore area was controlled by two sets of deep and large faults, and there was a tectonic transfer zone along the coastline, indicating that the sedimentary characteristics of the offshore area were mainly controlled by the provenance of the Yanshan Fold Belt, Chengning Uplift and Cangxian Uplift. The sedimentary system of the Paleogene in the Bohai Central Sag of the marine area was mainly controlled by tectonic uplift and subsidence and changes in lake level. Tectonic activities dominated the sand control mechanism and sedimentary filling process of the multi-faulted lake basin through tectonic transfer zones, slope break zones, secondary faults and steep slope zones. The tectonic contraction of the Bohai exploration area, the fall in sea level and the cessation of basement subsidence were the key factors determining the evolution direction of the Bohai Sea. The Paleogene of the Bohai exploration area experienced three stages of rifting and lake transgression. The Es sedimentary period was a rifting stage, mainly dominated by fan delta and sublacustrine fan deposits (Figure 3a–c); the Ed sedimentary period was a lake transgression stage, mainly developing large lacustrine delta deposits (Figure 3d–f). These stages reflect the overall control of episodic faulting.

The sedimentary process during the Paleogene in the Bohai exploration area was extremely complex, significantly influenced by specific provenance areas, which in turn were closely related to the spatial distribution of sedimentary systems and oil and gas accumulation. The offshore area was mainly controlled by two sets of deep-seated faults, and there was a tectonic transfer zone along the coastline. Its sedimentary characteristics were

primarily dominated by the provenance provided by the Yanshan Fold Belt, Chengning Uplift, and Cangxian Uplift.

During the second rifting stage in the Bohai exploration area, namely the sedimentary period of Es3, it was a typical fault subsidence lacustrine basin, and fan deltas developed towards the lake basin (Figure 3a–c). The provenance was abundant, mainly sourced from the Shijiutuo Uplift, Bonan Uplift, and Miaoxi Uplift. As the lake level rose, these fan deltas showed retrogradational sedimentation. During the sedimentary periods of Es2 and Es1, the provenance relatively decreased. In the Ed sedimentary period, large-scale lacustrine delta sediments were mainly developed and gradually transitioned to braided river facies (Figure 3d–f). For instance, during the Ed3 sedimentary period, the provenance mainly came from the Shijiutuo and Shadongnan Uplifts. In the Ed2 sedimentary period, a large-scale transgression occurred, forming a shallow to semi-deep lake environment. A large number of paleo-water systems around the sag carried the provenance into the sag for sedimentation. These sedimentary systems were obviously controlled by the tectonic paleogeomorphology and provenance channels.

The sedimentary systems developed under the influence of the provenance areas provided favorable conditions for oil and gas accumulation. The fan deltas, sublacustrine fans, and large-scale lacustrine deltas developed during the Paleogene formed excellent reservoirs. In the Es3 period, with abundant provenance and well-developed fan delta sediments, the thick sandstone layers could serve as high-quality reservoirs. The source–reservoir–caprock combinations were also affected by the sedimentary systems. For example, in the lower source–reservoir–caprock combination, the alluvial fans, fan deltas, and beach–bar sand bodies of Ek and Es4 (related to the sedimentary systems controlled by the provenance) were the main reservoirs. In the middle source–reservoir–caprock combination, the upper parts of Es3 and Es2 (also part of the sedimentary systems influenced by the provenance) developed thick sandstones for oil and gas storage. In the upper source–reservoir–caprock combination, the fluvial deltas and fan delta sand bodies of Es1 and Ed (formed by the sedimentary processes related to the provenance) were the main reservoirs.

The Es3 sedimentary period was in the second rifting stage of the Bohai exploration area, being a typical faulted lake basin. The sequence was in the lake expansion system tract, close to the basin margin faults. Fan deltas developed towards the lake basin and showed retrogradational deposits with the rise in the lake level. During the Es3 sedimentary period, the provenance was abundant, mainly from the Shijiutuo Bulge and Bonan and Miaoxi Bulges; the provenance decreased relatively during the Es2 and Es1 sedimentary periods; during the Ed sedimentary period, large lacustrine delta deposits were mainly developed and gradually transitioned to braided river facies. The provenance during the Ed3 sedimentary period mainly came from the Shijiutuo and Shadongnan Bulges; during the Ed2 sedimentary period, the large-scale lake transgression made this area a shallow lake–semi-deep lake environment, and a large number of ancient water systems around the sag brought the provenance into the sag for deposition. The types and planar distribution of these sedimentary systems were obviously controlled by the tectonic-paleogeomorphology and provenance channels.

In conclusion, the sedimentary filling process of the Paleogene in the Bohai Sea area was complex and diverse, affected by tectonic uplift and subsidence, changes in lake level, rifting and lake transgression stages, and the development of various sedimentary systems, including fan deltas, sublacustrine fans, large lacustrine deltas, etc. The provenance analysis showed the differences in provenance and provenance direction in different sedimentary periods, thus causing differential changes in reservoir development characteristics (Figure 3).

3.3. Differences in Source–Reservoir–Caprock Combinations of the Paleogene Between the Offshore and Marine Areas

The tectonic and sedimentary history of the sags macroscopically determines the vertical distribution of the main hydrocarbon-generating strata, while the reservoirs adjacent to the source rock layers have the condition of preferentially capturing oil and gas, and oil and gas are preferentially enriched in the source rock strata and adjacent reservoirs. Three sets of source–reservoir–caprock combinations were developed in the Paleogene of the Bohai exploration area (Figure 4). The lower source–reservoir–caprock combination takes Ek and Es4 as the hydrocarbon-generating strata. The alluvial fan, fan delta and beach bar sand bodies of Ek and Es4 are the main reservoirs, and the gypsum layer at the top of Es4 and the mudstone of the middle and lower subsections of Es3 are the caprocks. The Ek source rock is a Type III–Type II, relatively good source rock with poor hydrocarbon generation conditions; the Es4 source rock is a Type II, good source rock with relatively good hydrocarbon generation conditions. However, the distribution range of Ek and Es4 source rocks is relatively limited, and only some source rock strata develop overpressure. The vertical migration distance of oil and gas is short, mainly characterized by self-generation and self-storage, and oil and gas are mostly enriched in Ek–Es4 with low reserves. The middle source–reservoir–caprock combination takes Es3 as the main hydrocarbon-generating strata, the upper part of Es3 and Es2 are the main reservoirs, and the dark mudstone of Es1 is the regional caprock. The Es3 source rock is a Type II1–Type I, good source rock, which is the most widely distributed and has the strongest hydrocarbon generation capacity in the Bohai exploration area. The source rock strata develop overpressure and the vertical migration distance of oil and gas is large. The upper part of Es3–Es2 develops thick sandstone layers such as rivers, alluvial fans, deltas and shore–shallow lakes, and Es1 develops a thick mudstone layer with stable distribution, which can effectively prevent the upward movement of oil and gas and form oil and gas accumulation in the lower part. This source–reservoir–caprock combination has the best configuration. The oil and gas generated by the middle and lower source rocks of Es3 enter the reservoir sand bodies of the upper section of Es2 and Es3, forming the best source–reservoir–caprock combination with the overlying regional caprock of Es1, and the degree of oil and gas enrichment is high.

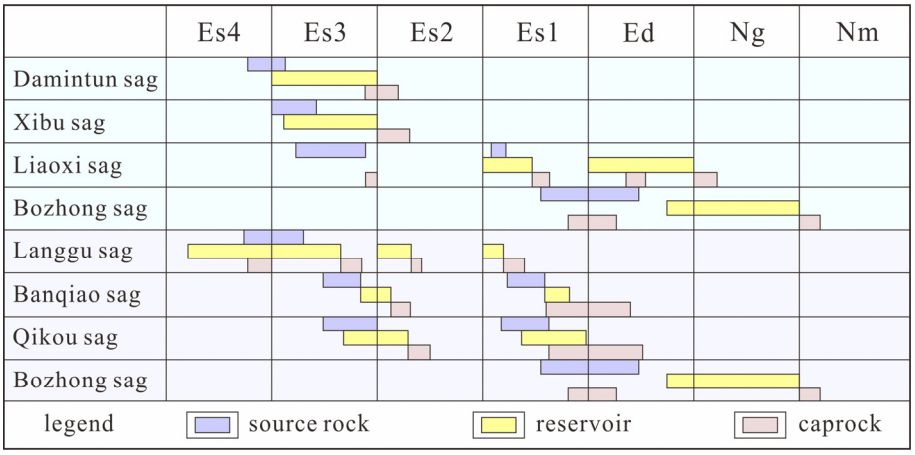

Figure 4. Distribution of Paleogene source–reservoir–caprock assemblage in Bohai exploration area.

The upper source–reservoir–caprock combination takes Es1 and Ed as the hydrocarbon-generating strata. The sand bodies such as river deltas and fan deltas of Es1 and Ed are the main reservoirs, and the Ed mudstone is the regional caprock. The Es1 and Ed source rocks are Type II, good source rocks with good hydrocarbon generation conditions. However, affected by the burial depth, except for the area around Bohai Central, the maturity of these

two sets of source rocks in most sags is low and the hydrocarbon generation amount is small. The source rock strata in areas with a higher degree of evolution develop overpressure, the vertical migration distance of oil and gas is large, and oil and gas are mainly enriched in the Es1 and Ed strata. The thickness of the Ed caprock determines the scale of its oil and gas enrichment. On the whole, the thickness of the Ed caprock gradually increases from the basin margin to the marine area, with the largest thickness in the Bohai Central area and strong sealing capacity. The proportion of Ed oil and gas reserves is the largest.

When observing the Bohai exploration area longitudinally, it can be noticed that from the land and offshore areas to the center of the marine area, that is, from the Damintun Sag (the Damintun Sag is located 20 km to the north of the Xibu Sag), the Xibu Sag and the Liaoxi Sag to the Bozhong Sag during the transition process, the main hydrocarbon-generating strata series gradually become younger and more abundant, which leads to the main source–reservoir–caprock assemblages also becoming younger and shallower accordingly (Figure 4). Similarly, it can be found that this rule also exists horizontally in the Bohai exploration area. Specifically, from the onshore and offshore areas towards the center of the marine area, there is a tendency for the source–reservoir–caprock assemblages to become younger.

4. Comparative Analysis of the Geologic Differences of Oil and Gas in the Paleogene of the Offshore—Marine Areas

4.1. Differences in Oil and Gas Distribution Between the Offshore and Marine Areas

During the development of the Paleogene in the Bohai exploration area, the tectonic framework of the Mesozoic basin was inherited, and the sedimentary center generally migrated to the central part of the Bohai exploration area [41]. The extensional tectonic movement of "three periods and two directions" gave rise to the development of multiple sets of source–reservoir–caprock [23,42]. The main source rocks of the Paleogene in the Bohai exploration area are divided into three strata: Es3, Es1 and Ed. The main hydrocarbon-generating intervals gradually become more numerous and newer from the offshore to the marine area, and the contribution of new source rock layers gradually increases [31]. The Paleogene reservoirs are well developed, mainly including sand bodies such as deltas, fan deltas, subaqueous fans and beach bars [43]. The Paleogene mainly developed two sets of regional caprocks of Es3 and Es1, which are stably distributed in the whole area and are mainly mudstone types [44]. The Paleogene in the Bohai exploration area can be divided into four oil-forming assemblages, namely the upper oil-forming assemblage (Ed reservoir), the middle oil-forming assemblage (Es1 reservoir) and the lower oil-forming assemblage (Es3 reservoir or Es3–Es4–Ek reservoir) [23,44].

The Bohai exploration area shows the characteristic of being oil-filled throughout the basin (Figure 5). According to the distribution and enrichment degree of oil and gas resources, predecessors classified the sags into four types: extremely rich in oil, rich in oil, containing oil and poor in oil [41,45]. Thus, it can be known that areas such as Bozhong marine, Shengli offshore and Dagang offshore are extremely rich and rich in oil regions, while areas such as Liaohe offshore have relatively less oil and gas resources and are classified as oil-containing regions.

Observing the vertical distribution of oil and gas in the Paleogene of the Bohai exploration area (Figure 5), the study area can be divided into six oil-bearing intervals: Kongdian Formation (Ek), the fourth member of Shahejie Formation (Ks4), the third member of Shahejie Formation (Es3), the second member of Shahejie Formation (Es2), the first member of Shahejie Formation (Es1) and Dongying Formation (Ed), among which Es3 has the highest proved reserves and the largest distribution range (Figure 5). Analyzing the distribution characteristics of oil and gas in the Bohai exploration area from a planar perspective, it

can be found that for Ek, only a small amount of oil and gas is shown on the west side of Dagang offshore and the edge of Shengli offshore; for Es4, only the sags in Shengli offshore and Liaohe offshore have oil and gas enrichment; the Es3–Es2 intervals are enriched with oil and gas in the entire offshore area, and the enrichment degree is relatively high, while for the marine part, only a small amount of oil and gas is shown in the Bohai Central and Penglai areas; for the Es1 interval, there are a large number of oil and gas enrichment areas in the Dagang offshore and Liaohe offshore areas, and oil and gas shows occur in the Nanpu offshore, Shengli offshore and Bohai Central areas; for the strata of Dongying Formation, oil and gas shows exist throughout the Bohai exploration area. The degree of oil and gas enrichment is relatively high in the Liaodong Bay area and Bohai Central area. Although there are also oil and gas shows in the offshore area, the overall enrichment degree is relatively low. The oil and gas of the first member of Shahejie Formation and Dongying Formation show the characteristics of being "distributed in the offshore in the lower section, distributed throughout the area in the middle section, and distributed in the center in the upper section".

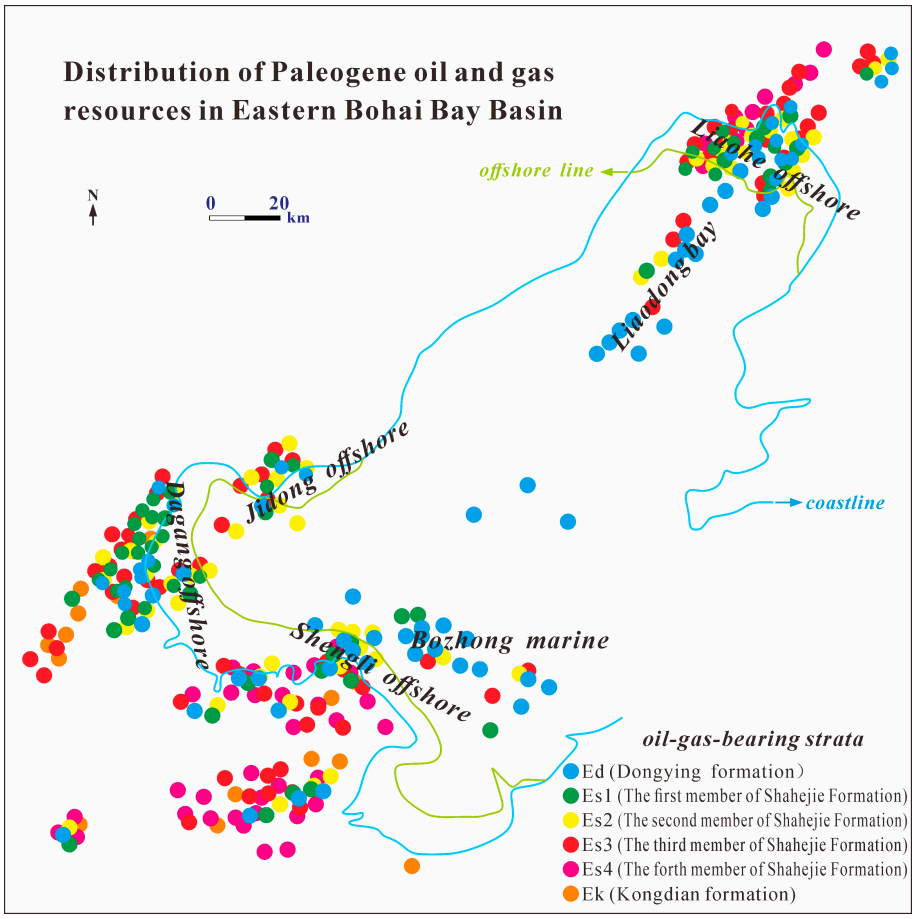

Figure 5. Distribution of oil and gas in the Paleogene of the Bohai exploration area.

Through the above statistical collation and analysis (Figure 5), the complexity and diversity of the distribution of oil and gas in the Paleogene of the Bohai exploration area can be observed. The onshore oil and gas-bearing intervals are mainly Es3, Es4 and Ek, the offshore part is mainly Es1 and Ed, and the marine part is mainly Ed. The overall trend shows that the oil- and gas-bearing intervals gradually become younger from the offshore to the center of the marine area.

4.2. Controlling Factors of the Differential Enrichment

The Paleogene in the Bohai exploration area includes sag areas such as Liaohe, Liaodong Bay, Bohai Central, Qikou and Nanpu, as well as uplift areas such as Chengning, Shaleitian, Shijiutuo and Bonan (Figure 1). According to the development scale of the sag areas from large to small, they can be divided into three grades: depression, sag and trough. For example, Huanghua Depression can be subdivided into Qikou Sag, Nanpu Sag, Beitang Sag, Chengbei Sag, etc. Qikou Sag can be further subdivided into Banqiao Trough, Qibei Trough and Qinan Trough, etc. It can be seen from Figures 1 and 5 that the distribution law of oil and gas coincides with the distribution law of sags, and the previous research results suggest that troughs will control the distribution of source rocks, affect the development of sand bodies and the scale of caprocks, and thereby control the differential enrichment of oil and gas. Therefore, the control effect of the development forms of different sags on the differential enrichment of oil and gas should be considered [23,46].

The tectonic evolution of the Paleogene in the Bohai exploration area has undergone three rifting and stretching periods [47,48]: from the middle of the Paleocene to the middle of the Eocene, the North China Plate began to rift, and the fault activities were weak; in the late Eocene, the rifting intensified and the fault activities strengthened; rifting and stretching occurred in the Oligocene, and the fault activities strengthened again in the late Oligocene. Since the Neogene, the Bohai exploration area has transformed from fault depression to overall depression and developed thick Neogene-Quaternary fluvial facies deposits. The rifting centers of the three secondary rifting episodes in the Paleogene of the Bohai exploration area migrated from the offshore to the center of the marine area, and from the outer zone of the basin to the center of the basin, forming different types of sags, respectively. By statistically calculating the subsidence rates of each sag, the sedimentary sags in the Bohai exploration area can be divided into three major types: early type, inherited type and late type (Figure 6, Table 3). The sedimentation rate of the early-developed sags was the highest during the Es3–Ek period, with an average of more than 100 m/Ma and a maximum of more than 150 m/Ma. After the Es3 period, the sedimentation rate decreased significantly, and there was almost no obvious subsidence in the Nm period. The deep lake facies range was mainly the bottom layer of the Paleogene. The sedimentation rate of the inherited-developed sags showed obvious inherited characteristics. The sedimentation rate reached the maximum in the Es3 period and gradually decreased after Es3. The sedimentary thickness still increased in the Nm period, and the deep lake facies range was mainly the middle layer of the Paleogene. The maximum sedimentation rate of the late-developed sags occurred during the Es1–Ed period, and the sedimentation rate in the Neogene was significantly higher than that of the early type and inherited type sags.

Table 3. Comparison of oil and gas geological differences among different sag types.

Sag Type	Early Developmental Sags	Inherited Developmental Sags	Late Developmental Sags
Sedimentation rate (m/Ma)	Es3–Ed period: >100 (max >150) Es1–Ed period: <50	Es3 period: 80–100 Ed period: 50–70	Es1–Ed period: >120 Neogene: >200
Source rock thickness (m)	Ek + Es4: 200–300 (locally >500)	Es3: 600–1000 (offshore)	Ed: >600
Maturity (Ro, %)	0.7–1.0	1.0–1.3	1.3–1.6
Main reservoir burial depth (m)	Ek (>3500)	Es3–Es2 (2000–3500)	Ed–Neogene (<2000)
Vertical migration distance (m)	<500	500–1500	>2000
Reserve proportion (%)	<10	40–50	40–50
Typical sag cases	Huimin Sag, Wuqing Sag	Qikou Sag, Nanpu Sag	Bozhong Sag, Huanghekou Sag

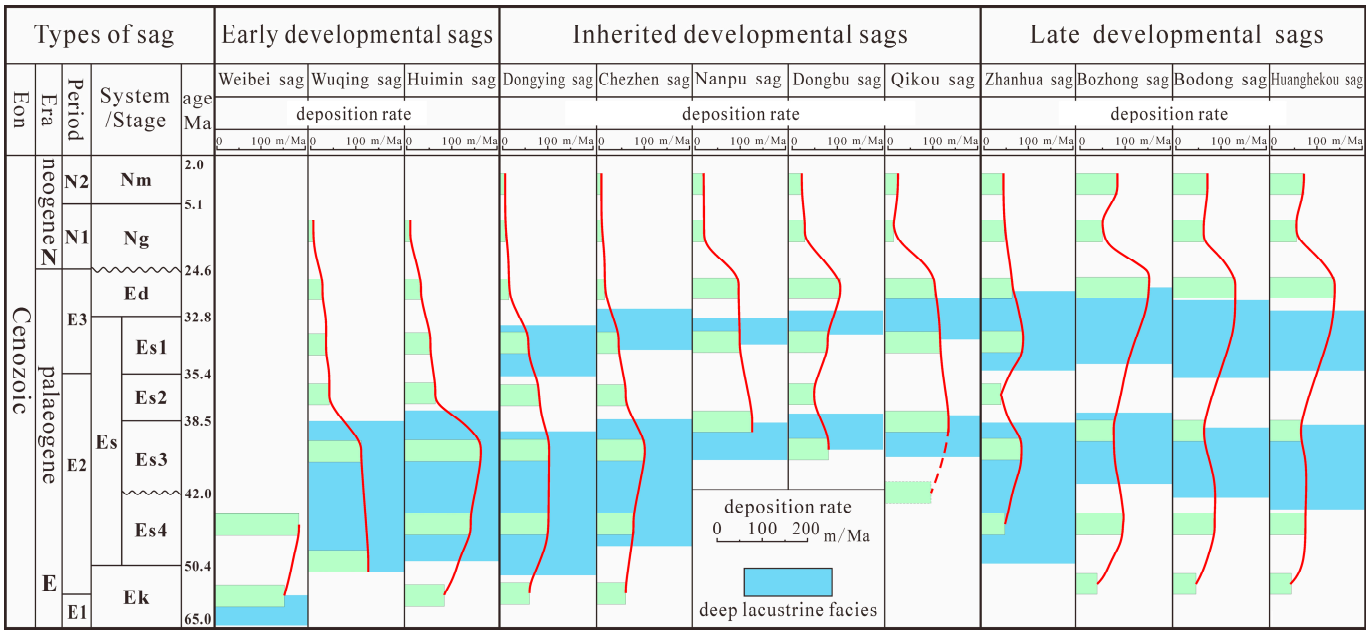

Figure 6. Classification of sedimentary sags in the Cenozoic based on the sedimentation rate.

Late-stage tectonic subsidence has a significant impact on the vertical migration and accumulation patterns of oil and gas. Late-stage tectonic subsidence leads to an increase in the burial depth of source rocks, which in turn causes an increase in temperature and pressure, accelerating the thermal evolution process of source rocks. This promotes the conversion of organic matter in source rocks into oil and gas, enhancing the hydrocarbon generation potential. In the late-developed sags such as the Bozhong Sag and the Huanghekou Sag in the Bohai exploration area, late-stage tectonic subsidence is very prominent. Due to the deep burial caused by late-stage subsidence, the source rocks of the Dongying Formation (Ed) in these sags have reached a high-maturity stage (vitrinite reflectance Ro: 1.3–1.6%), generating a large amount of oil and gas and providing an abundant material basis for oil and gas accumulation in the Dongying Formation and Neogene strata. Tectonic subsidence can also trigger the formation and activation of faults and fractures, especially the development of complex fault zones and deep-seated faults. It has been proven that the fault zones in the Bohai exploration area are important channels for the vertical migration of oil and gas [47,49]. The oil and gas generated from deep-seated source rocks can migrate upward along these channels into shallower reservoir rocks. In late-stage sags, late-stage tectonic activities are intense, resulting in the development of a large number of faults. For example, in the Bozhong Sag, the vertical movement of the basement during the late-stage subsidence process formed a complex fault system [50]. The oil and gas generated from the deep-seated source rocks of the third member of the Shahejie Formation (Es3) and the first member of the Shahejie Formation (Es1) can migrate along these faults into the reservoir rocks of the Dongying Formation and Neogene, forming large-scale oil and gas reservoirs [50]. Late-stage tectonic subsidence also affects the source–reservoir–caprock combinations. It can cause rock compaction, changing the physical properties of reservoirs and caprocks. At the same time, the relative positions between reservoirs and caprocks may also change, which has an impact on oil and gas accumulation. In the Huanghekou Sag, late-stage tectonic subsidence led to compaction of the overlying caprock, improving its sealing performance [51,52]. Meanwhile, subsidence also made the reservoir rocks of the Dongying Formation and Neogene combine more closely with the overlying caprock, creating favorable conditions for the preservation of oil and gas reservoirs. Therefore, a

large amount of oil and gas has accumulated in the Dongying Formation and Neogene strata of this sag.

In the Paleogene of the Bohai exploration area, from the offshore to the center of the marine area, tectonic activities gradually occurred later, the sedimentary center gradually migrated to the center of the marine area, and the evolution type of sag gradually transitioned from the early type to the late type (Figure 6, Table 3). During the sedimentary periods of Ek and Es4 of the Paleogene, the Bohai exploration area had the characteristics of multiple sedimentary centers and significant variations in stratum thickness. The offshore area was the sedimentation–subsidence center with a large stratum thickness; the strata of Es3 and Es2 were widely developed throughout the basin; during the sedimentary periods of Es1 and Ed, the sedimentation–subsidence center of the Bohai exploration area migrated to the central part of the marine area (i.e., the Bohai Central area) [53,54]. At the end of the Paleogene, from the offshore to the center of the marine area, the uplift amplitude and erosion thickness gradually decreased. Since the Neogene, the Bohai Central area has always been the subsidence and sedimentation center of the Bohai exploration area, and the sedimentary thickness of the Neogene and Quaternary far exceeds that of other areas [53,55]. The Bohai exploration area has experienced multiple tectonic movements and developed multiple sets of source rocks. A total of five sets of source rock strata including Ek, Es4, Es3, Es1 and Ed were developed in the Paleogene. From the offshore to the center of the marine area, the hydrocarbon-generating strata gradually became more numerous and newer, and the contribution of oil and gas from the newer source rock strata gradually increased. Each sag is the subsidence and sedimentation center of the Bohai exploration area and has relatively independent tectonic evolution and sedimentary burial history. Previous studies have proved that the degree of oil and gas enrichment is closely related to the type of sag. The sags composed of inherited and late-developed sags have great hydrocarbon generation potential and a high degree of oil and gas enrichment, and most of them are rich and extremely rich oil sags, while the sags mainly composed of early-developed sags are mostly oil-containing and poor oil sags [55].

The sedimentation–subsidence history of the sags in the Bohai exploration area macroscopically determines the vertical distribution of the main hydrocarbon-generation strata, while the reservoirs adjacent to the source rock layers have the condition of preferentially capturing oil and gas, and the oil and gas are preferentially enriched in the source rock strata and the adjacent reservoirs. The three types of sedimentary sags have different source–reservoir–caprock assemblages, thereby controlling the differential enrichment characteristics of oil and gas (Figure 7). Most of the sags located on land and near the offshore are early-type sags, such as the Huimin sag on land, the Wuqing sag, and the Weibei sag that occupies both land and offshore areas. The early-type sags mainly use Ek and Es4 as the main hydrocarbon-generation strata, with an earlier main hydrocarbon-generation period, and the oil and gas are mainly hosted in Ek and Es4. For example, the oil and gas discovered in the Weibei sag are all hosted in Ek. The inherited-type sags are mostly located on the offshore area and on land near the offshore area, and all the parts of the offshore are inherited-type sags. For example, the Qikou sag is located in the Dagang offshore area, the Nanpu sag is located in the Jidong offshore area, the Eastern sag and the Western sag are located in the Liaodong offshore area, and the Chezhen sag is located in the Shengli offshore area. The hydrocarbon-generation strata of the inherited-developed sags cover the entire Shahejie Formation (Es), with Es3 as the main hydrocarbon-generation strata. The main hydrocarbon-generation period of most sags is relatively late, and the vertical enrichment strata of oil and gas are relatively concentrated, mainly enriched in the Shahejie Formation (Es). Except for the Zhanhua sag located on land, all the late-developed sags are located in the sea area, such as the Bozhong sag, the Bodong sag, and the Huanghekou sag,

which are located in the central part of the sea area, and the Liaodong sag and the Liaoxi sag are located in the Liaodong Bay. The late-type sags use Es3, Es1, and Ed as the main hydrocarbon-generation strata, with a late main hydrocarbon-generation period, and the oil and gas are mainly enriched in Ed and the Neogene. For example, the billion-ton large oil and gas fields such as PL19-3, KL10-2, KL6-1, BZ29-6, BZ36-1, and QHD27-3 discovered in the sea area in recent years are all enriched in the Neogene.

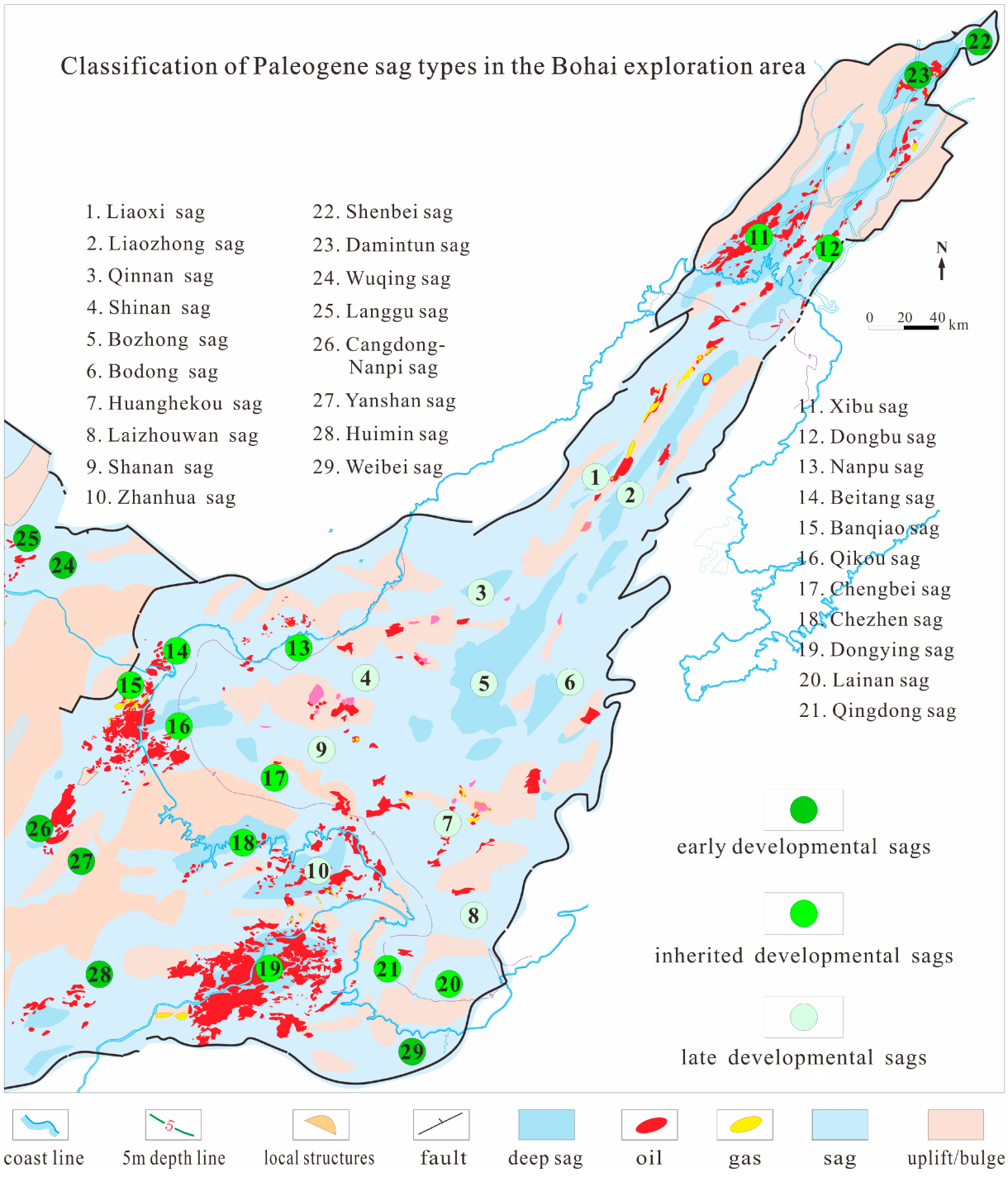

Figure 7. Classification of Paleogene sag types in the Bohai exploration area.

In the Paleogene of the Bohai exploration area, different sag types play different roles in controlling the vertical distribution of oil and gas enrichment layers and are closely related to sedimentation rates (Figures 6 and 7, Table 3). In the early developmental sags,

the average sedimentation rate exceeded 100 m/Ma during the Es3–Ek period, with a maximum exceeding 150 m/Ma, and then decreased significantly. There was almost no obvious subsidence during the Nm period. Oil and gas in these sags are mainly enriched in the Ek and Es4 strata. For example, all the oil and gas in the Weibei Sag are in the Ek layer. This indicates that due to the high sedimentation rate in the early stage of early developmental sags, thick-layer sediments were rapidly accumulated, providing a material basis for the development of source rocks in Ek and Es4. However, the sharp decline in the sedimentation rate in the later stage is unfavorable for the formation of new source rocks and the migration of oil and gas, confining the oil and gas to the lower strata. Thus, the vertical enrichment layers are relatively deep and single. In the inherited developmental sags, the sedimentation rate reached its maximum during the Es3 period and then gradually decreased. Nevertheless, the sediment thickness still increased during the Nm period. Oil and gas are mainly enriched in the Shahejie Formation (Es), predominantly in Es3. The inheritance of the sedimentation rate in this sag type allows it to continuously receive sediment during the continuous subsidence process, creating conditions for the development of source rocks in Es. The high sedimentation rate during the Es3 period brought abundant materials, resulting in thick and high-quality source rocks that generated a large amount of oil and gas. Although the sedimentation rate subsequently decreased, sedimentation still occurred, promoting the migration and accumulation of oil and gas within the Es layer. Therefore, the vertical enrichment layers are mainly concentrated in the middle strata. In the late developmental sags, the sedimentation rate was the highest during the Es1–Ed period, and it was significantly higher than that of the other two types of sags in the Neogene. Oil and gas are mainly enriched in the Ed and Neogene. For instance, many large-scale oil and gas fields discovered in recent years are in these layers. The high sedimentation rate in the late stage of late developmental sags led to the rapid accumulation of Ed and Neogene strata, and a large number of Ed source rocks developed. Meanwhile, the continuous subsidence of the sag increased the maturity of the source rocks, generating a large amount of oil and gas. The rapid sedimentation also formed a good source–reservoir–caprock combination, which is conducive to the enrichment of oil and gas in the shallow strata. Thus, the vertical enrichment layers are shallow and relatively new.

The tectonic evolution in the Paleogene of the Bohai exploration area controlled the sedimentation rate. During the Paleogene, the Bohai exploration area experienced intense extensional tectonic activity, leading to the formation and development of multiple depressions and uplifts. These tectonic movements caused rapid subsidence in local areas, providing sufficient space for sediments and thus increasing the sedimentation rate. In the Es3 period, intense extensional and fault activity accelerated both the subsidence rate and the sedimentation rate. The water depth and extent of the lake basin gradually expanded, creating a favorable sedimentary environment for dark mudstones and shales in the semi-deep to deep lake facies within the sag. Furthermore, tectonic activities could also cause changes in hydrodynamic conditions, such as seawater intrusion or river diversion, which would further affect the distribution of sediments and the sedimentation rate. Tectonic activities can regulate the sedimentary environment within the basin, thereby influencing the development of source rocks. The tectonic activities in the Paleogene led to the expansion and contraction of lakes, directly affecting the preservation conditions and types of organic matter, as well as its subsequent thermal evolution process. The faults formed by the tectonic movements in the Paleogene of the Bohai exploration area provided channels for the migration of oil and gas from the source rock to the reservoir rock, and formed a series of fault-type traps, which were conducive to the migration and accumulation of oil and gas [23,47,56]. The tectonic changes in the Paleogene of the Bohai exploration area not only directly influenced the sedimentation rate, promoting sediment accumulation

by altering the sedimentary environment and hydrodynamic conditions, but also had a profound impact on hydrocarbon reservoir formation. This included aspects such as the development of source rocks, the formation of traps, the establishment of oil–gas migration paths, and the integrity of caprocks.

Overall, the types of sags in the Bohai exploration area show the characteristics of gradually changing to the late type from the offshore to the sea area, and there is a good corresponding relationship between the types of sags and the vertical enrichment strata of oil and gas (Figures 5 and 7). The hydrocarbon supply power of the early-developed sags is relatively weak, the distance of oil and gas migration is relatively short, and the oil and gas are mainly hosted in the lower strata; in the inherited-developed sags, most of the oil and gas are enriched in the middle strata; in the late-developed sags, the oil and gas are relatively enriched in the shallow strata; from the early-developed type to the inherited-developed type and then to the late-developed type, the oil and gas enrichment strata in the sags gradually become more and newer.

5. Conclusions

The Bohai exploration area is located in eastern China, and its Paleogene remains the core stratum for future oil and gas reserve growth in China. Based on the statistics gleaned from a large amount of basic data, this paper systematically compares the differences in oil and gas distribution in the Paleogene between the coastal–shallow sea and the offshore areas. It explores the differentiation laws of source rock characteristics, sedimentary reservoirs, and source–reservoir–caprock combinations and classifies the sag types and their controlling effects on oil and gas enrichment. The research shows the following:

1. In the Paleogene of the Bohai exploration area, the oil and gas enrichment horizons tend to gradually become younger from the coastal–shallow sea to the offshore area.

2. In regions where the source rocks are thick, with high organic matter abundance (TOC > 2%), excellent types (Type I–II), and moderate maturity (Ro = 1.0–1.5%), the degree of oil and gas enrichment is remarkable. In the coastal–shallow sea, the source rocks of the third member of the Shahejie Formation (Es3) dominate the middle-layer enrichment, while in the offshore area, the highly mature source rocks of the Dongying Formation (Ed) drive large-scale reservoir formation in the shallow layers.

3. The Paleogene sedimentary filling process in the Bohai exploration area is synergistically restricted by multiple factors such as tectonic activities and lake-level fluctuations. It has gone through key stages such as rifting and lake transgression, giving rise to various types of sedimentary systems. There are significant differences in sedimentary patterns and provenance supplies between the on-shore and off-shore areas, which, in turn, lead to different reservoir development characteristics, ultimately affecting the distribution and enrichment of oil and gas.

4. In the early-developed sags, the hydrocarbon supply driving force is weak, the oil and gas migration distance is short, and the oil and gas are mainly hosted in the lower strata. In the continuously developed sags, the oil and gas are mostly enriched in the middle strata. In the late-developed sags, the oil and gas are relatively enriched in the shallow strata. From the early-developed sags to the continuously developed sags and then to the late-developed sags, the oil and gas enrichment strata in the sags gradually increase and become younger.

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Data Availability Statement: The processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

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