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Formation conditions of natural gas fields in the lacustrine basin in eastern China: Insights into the first discovery within the Bohai Bay Basin

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The hydrocarbon source of Bohai Bay Basin is dominated by oil-prone kerogens of type II_2-II_1 within semi-deep and deep lacustrine facies. In the Neogene period, faults were well-developed via significant structural activity. The Bohai Sea is generally considered to have no geological basis for the formation of large natural gas fields. Through analogous analysis of domestic and international gas fields, the key geological factors that restrict formation in continental rift lacustrine basins were studied, including gas source, preservation conditions, and reservoirs. A natural gas enrichment and accumulation model within a petroliferous basin is presented. The model indicates that rapid subsidence and high-intensity gas generation within petroliferous sags during the late stages were main contributors to natural gas field formation. Archean metamorphic buried hill reservoirs and thick, overpressure mudstone with strong vertical sealing ability provided favorable storage space and preservation, respectively. Using the model, an integrated Archaean metamorphic buried hill condensate gas reservoir, Bozhong 19–6, was discovered in the Bohai Bay Basin. The natural gas reserves are about $450\times10^9\ m^3$, equivalent to oil production of 800 $\times10^6\ m^3$, and signify a breakthrough in natural gas exploration of continental rift lacustrine basins in China.

KEYWORDS

continental rift lacustrine basin, large natural gas field, high intensity generation of natural gas, metamorphic rock buried hill, Bozhong 19–6

Introduction

The Bohai Bay Basin includes the Bohai Sea and coastal areas in eastern China. The Cenozoic continental lacustrine basin was developed on the North China Craton, which is one of the two super-basins in China. Through more than 60 years of exploration and development, a series of oil fields have been discovered using "Continental Oil Generation Theory" (Shi, 1981). Seven major oil regions, namely Shengli, Liaohe, Dagang, North China, Jidong, Zhongyuan, and Bohai have been built in the Bohai Bay Basin. These oil fields account for more than one-third of China's reserves and production (Hu and Zhou, 2006; Wang and Xi, 2009). So far, no large natural gas field has been discovered within this basin. Only the Banqiao and Qianmiqiao gas fields have reserves exceeding 200×10^8 m^3. In addition, the distribution of natural gas is limited and found only in a few depressions (Wang, 1997; Wang, 2005).

Xue (2002) and Xue et al. (2007) proposed the theory of "gas formation in lacustrine basins" and believed that natural gas enrichment areas exist in the Bohai Bay Basin. Based on the gas potential of more than 60 sags and sub-sags in the Bohai Bay Basin, combined with the dynamics of natural gas accumulation, gas field potential was hypothesized. The geological factors, such as structure and deposition, suggested that the Bohai Bay Basin can form natural gas fields under conditions that include the presence of a regional overpressure mudstone "quilt", strong sealing, and high-intensity gas generation in the late stage of source rock maturation (Xue, 2018; Xue and Li, 2018; Xu et al., 2019; Xue, 2019). By integrating enrichment geological theory with natural gas reservoir technologies and practices, the condensate gas field Bozhong 19–6 was discovered in the southwest of Bozhong sag. The field has gas reserves of about 450×10^9 m^3, which equals the oil production of 800×10^6 m^3, representing a breakthrough in natural gas exploration within continental lacustrine basins in eastern China.

Geological setting of the Bohai Bay Basin

The Bohai Bay Basin is bordered by the Jiaodong uplift and the Liaodong uplift to the east, the Taihang Mountain uplift to the west, the Luxi uplift to the south, and the Yanshan fold belt to the north (Figure 1) (Li, 1980; Qi et al., 1995). The Cenozoic basin developed as a result of Indosinian and Yanshanian movements in the China-Korea paraplatform after Paleozoic deposition (Jiang, 1999). Since the Cenozoic period, multiple episodes of rifting have occurred in the Bohai Bay Basin, and the filling structure shows the characteristics of two sets of structural units, the rifting unit in the Paleogene and the depression unit in the Neogene (Hou et al., 2001; Li et al., 2010). The Cenozoic strata, revealed by drilling wells from bottom to top, consist of the Kongdian and Shahejie Formations in the Paleogene and the Guantao and Minghuazhen Formations in the Neogene (Figure 1). The Paleogene basin shows obvious "basin-ridge" structure during the rifting stage, and primarily developed half-graben and graben internal depressions with pervasive vulcanism (Wang, 1998). In the Neogene, the basin mainly experienced post-rifting thermal subsidence (Gong, 2004; Wang et al., 2012). From the perspective of the whole basin, the strata distribution in sags were stable during the depositional periods of the Kongdian and Shahejie Formations. Nevertheless, the basin showed characteristics of differential subsidence in various sags. From the deposition period of the Dongying Formation, the subsidence

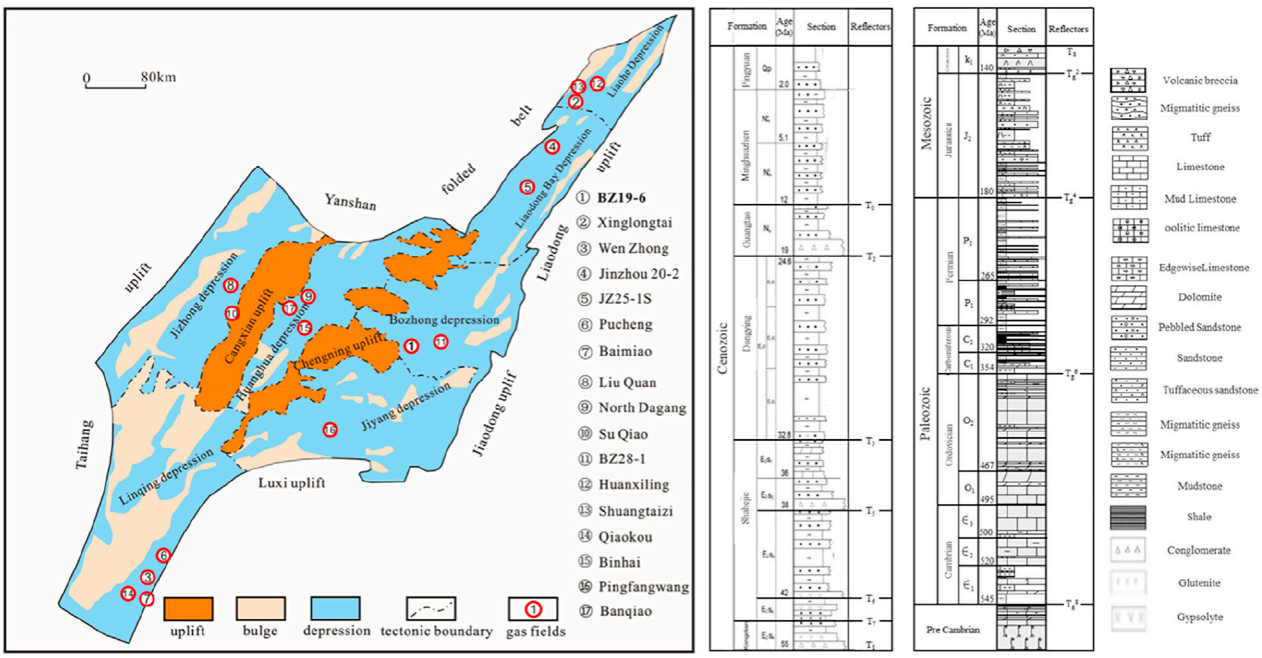

FIGURE 1
Schematic diagram of structural units in the Bohai Bay Basin and comprehensive stratigraphic column.

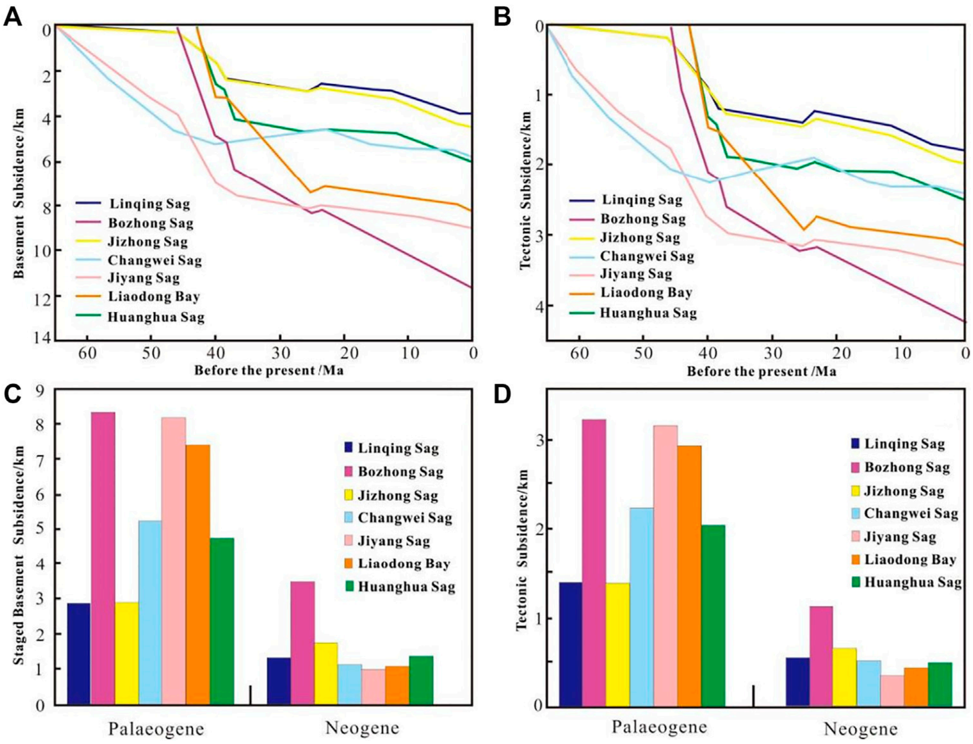

FIGURE 2
Basement/tectonic subsidence history and subsidence comparison of each depression in the Bohai Bay Basin. **(A)** Basement subsidence of various sags in the Bohai Bay Basin; **(B)** tectonic subsidence of various sags in the Bohai Bay Basin; **(C)** staged basement subsidence of various sags in the Bohai Bay Basin; **(D)** tectonic subsidence of various sags in the Bohai Bay Basin.

center of the basin gradually moved toward the sea. The Bozhong Depression became the depocenter of this basin in the Quaternary. During the Paleogene, several sets of hydrocarbon source rock were developed, including the Kongdian, Shahejie, and Dongying Formations. The Shahejie and Dongying Formations were major hydrocarbon-supplying strata, which commonly comprise organic matter of Type I, Type II_1, and Type II_2 kerogen, with total organic carbon (TOC) ranging from 2% to 4%.

Most of the depressions in the Bohai Bay Basin are located on land, except the Bozhong, Liaodong Bay, Huanghua, and Jiyang Depressions, which are fully or partially located in the sea. The Bozhong Depression exhibits the largest Cenozoic subsidence, reaching 11,000–12,000 m. However, the Jizhong, Linqing, Changwei, and Huanghua Depressions show the smallest subsidence, ranging from 4,000 to 6,000 m. In between are the Liaodong Bay and Jiyang Depressions, with about 9,000–10,000 m of subsidence (Figure 2A). The structural subsidence of each depression has similar characteristics to the base subsidence (Figures 2A,B). During the Paleogene rifting period, the Bozhong, Jiyang, and Liaodongwan Depressions had the largest total and structural subsidence, followed by the Changwei and Huanghua Depressions. The total and structural subsidence of the Linqing and Jizhong Depressions were the smallest (Figure 2C). In the Neogene post-rifting stage, the total and tectonic subsidence of the Bozhong Depression were the largest, while other depressions were smaller (Figure 2D). In general, the subsidence center of this basin migrated along the Tan-Lu fault zone during the Paleogene rifting period, showing a tendency to migrate from south to north and from west to east (Figure 2C). From the Guantao to the lower member of the Minghuazhen Formation, the subsidence centers were in the Bozhong and Huanghua Depressions in the middle of the Bohai Bay Basin, migrating from the land toward the sea. The subsidence center from the deposition period of the upper member of the Minghuazhen Formation to present has been completely immobilized within the sea, especially in the Bozhong sag near the Tan-Lu fault zone (Figure 2D). There have been many hydrocarbon discoveries within the Paleogene lacustrine deltaic sand bodies and Neogene fluvial sand bodies in the Bohai Bay Basin. In the onshore oilfields, the Paleogene Shahejie and Dongying Formations are the main oil-bearing formations, accounting for more than 60% of the discovered oil and gas reserves, followed by the Neogene strata, accounting for about 30%. In the offshore oilfields, the hydrocarbon reserves are predominately in the Neogene strata, accounting for about 60% (Jiang et al., 2021).

The pre-Cenozoic basement revealed by drilled wells in the Bohai Bay Basin is composed of five structural layers from bottom to top: the Precambrian metamorphic rocks; the Lower Paleozoic Cambrian-Middle Ordovician (Ꞓ-O) neritic platform carbonate interbedded with shale and clastic deposits; the Upper Paleozoic Carboniferous-Permian (C-P) carbonate, coal-bearing, and red clastic deposits developed in marine-terrestrial interaction areas; the Mesozoic Middle Jurassic (J_2) grey tuffaceous clastic, coal beds, and volcanic breccia deposits; and the Mesozoic Lower Cretaceous (K_1) volcanic rocks and variegated clastic deposits. Nevertheless, the Middle and Upper Proterozoic, the Upper Ordovician-Lower Carboniferous in the Paleozoic, and the Triassic, Lower Jurassic, Upper Jurassic, and Upper Cretaceous in the Mesozoic were generally absent in this area (Hou et al., 2001; Li et al., 2010). The discovery of buried hill oil and gas reservoirs in the Renqiu Oilfield in 1975 set off a flurry of buried hill exploration (Zhao and Zhang, 1991; Jiang and Cha, 2010). However, since 1995, the discovery of buried hill oil and gas in the Bohai Bay Basin has gradually decreased. In recent years, the pre-Cenozoic buried hill exploration has led to discovery of oil and gas (Kang, 2000; Dai et al., 2002; Jia et al., 2002). In 2005, hydrocarbon reservoirs of the Archean metamorphic rocks in the buried hill below the sedimentary rocks were discovered at a depth of 2500 m in the Xinglongtai area of the western Liaohe sag (Xue, 2010). In 2010, the ultra-deep carbonate buried hill at a depth of more than 6000 m in the Baxian sag was found to harbor hydrocarbon reservoirs. In 2012, the Mesozoic granite buried hill hydrocarbon reservoir, with reserves of 100×10^6 tons, was discovered in the central Bohai Sea. The above discoveries were primarily oil, like the Cenozoic hydrocarbon discoveries. No large natural gas fields were discovered. Thus far, the buried hill reservoirs have been the source of minor discoveries in this basin, with uneven distribution. The Jizhong Depression is the site of the most abundant hydrocarbon source yet discovered, with proven oil of about 540×10^6 tons in place and accounting for about 60% of the oil in the Bohai Bay Basin. The next largest source is the Xialiaohe Depression, with proven oil of about 400×10^6 tons in place and accounting for about 20% of oil in the basin. There were fewer hydrocarbon discoveries in buried hills in the Bohai Sea, accounting for only about 5% of the oil in the region.

Conditions for the formation of natural gas fields

The distribution of natural gas fields throughout the world is characterized by marine sedimentary basins with humic source kerogen (Jiang et al., 2017; Lan et al., 2017). These natural gas fields are mainly located in structurally stable areas with regional gypsum formations (Gong and Wang, 2001). The discoveries in lacustrine sedimentary basins are dominated by crude oil, with minor amounts of natural gas (Dang et al., 2001). The Bohai Bay Basin is a rifted lacustrine formation developed in the Cenozoic period and characterized by initial sedimentation, subsequent well-developed faults, lack of regional gypsum strata, and lacustrine sapropelic kerogen as source rock. Based on these geological conditions, the differences between the Bohai Bay Basin and other domestic or foreign gas-prone basins were compared. The formation conditions of gas reservoirs in more than 60 sags/sub-sags within the Bohai Bay Basin were also studied. Requirement of "one core and two key elements" for the formation of natural gas fields in the continental lacustrine basin of the Bohai Bay is proposed and the core element is interpreted as strong sealing by the overpressure mudstone cap rock. The two key elements are high-intensity gas generation of source rocks in the late stage and the storage space of buried hills.

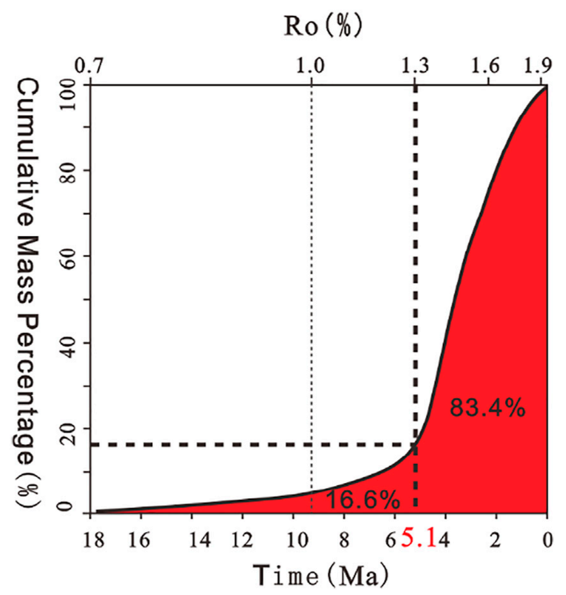

FIGURE 3
Subsidence rate, maturation rate, and gas generation pattern of source rocks in the Bozhong sag.

Production of natural gas from source rocks

Natural gas molecules are small and diffuse easily (Hao, 1994). The formation of natural gas reservoirs demands a continuous and sufficient supply of gas sources (Dai et al., 1997; Dai et al., 2003), requiring source rocks with gas generation intensity exceeding 20×10^8 m^3/km^2. The later the peak, the greater the intensity of gas generation, and the more favorable for the formation of gas fields.

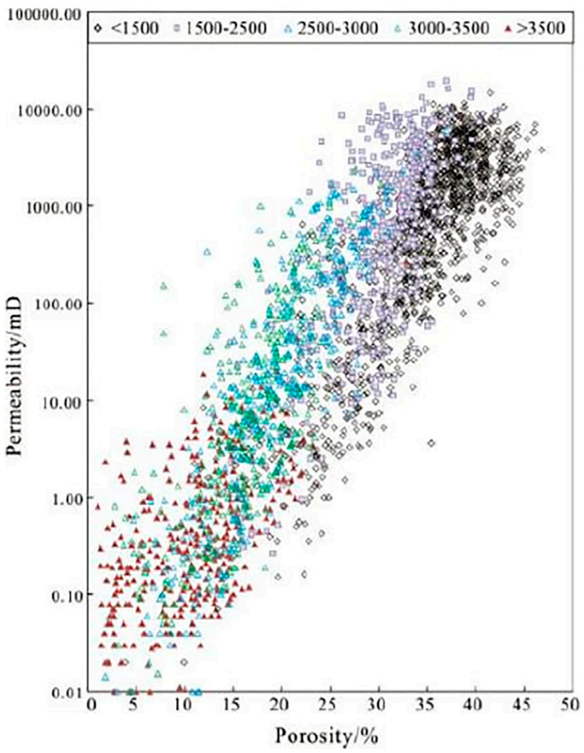

FIGURE 4
Physical characteristics of clastic rock reservoirs at different depths in the Bohai Sea.

The main hydrocarbon source rock in the Bohai Sea is type II_2-II_1 kerogen in the Shahejie Formation (Zhu, 2009). Over time, multi-stage structural movements and thermal evolution through numerous sags lowers the generation of gas. However, in the Late Neogene, subsidence rates of the Bozhong, Qinnan, and Qikou sags increased significantly, generally exceeding 200 m/Ma (Gong and Wang, 2001). Especially in the Bozhong sag, the subsidence rate was up to 320 m/Ma from 5.1 Ma to present (Xue and Li, 2018). The rapid subsidence of the sags increased the burial depth of the source rock and accelerated thermal evolution. The change rate of the main source rocks in the Shahejie Formation in the Bozhong, Qikou, and Qinnan sags exceeded 0.25% per million years. Among these formations, the change rate of source rock maturity in the Bozhong sag reached 0.41% per million years. The results of a new source rock evaluation in the Bohai Sea showed that the gas generation intensity of the Bozhong, Liaozhong, Qikou, and Huanghekou sags were greater than 20×10^8 m^3 in the Late Neogene (Gong et al., 2000). Among them, the natural gas resources in the Bozhong sag were the largest, with gas generation intensity up to $(50–200)\times10^8$ m^3/km^2 (Cai et al., 2001). The natural gas resource in this sag has changed from 0.3×10^{12} m^3 to 1.9×10^{12} m^3 from 5.1 Ma to present, which is

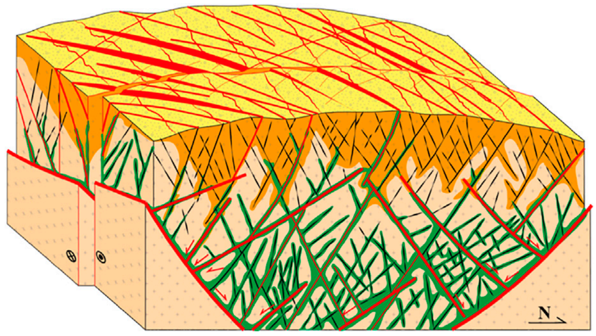

FIGURE 5
Genetic model of large metamorphic buried hill reservoir in the Bozhong sag.

a more than 5 times increase in this natural gas resource (Figure 3). These data indicate that the continental lacustrine basin in the Bohai Sea had favorable conditions for late-stage, large-scale gas generation.

Storage volume of buried hill reservoirs

A number of clastic rock reservoirs were developed in the Bohai Sea during the Cenozoic, consisting mainly of conglomerate, sandy conglomerate, gravelly coarse sandstone, and tuffaceous glutenite, with a small amount of coarse sandstone and fine sandstone. Mudstone was less developed in the glutenite, which was primarily distributed from 1,500 to 3,500 m in depth. The sand bodies below the mudstone of the Dongying Formation were generally more than 3,500 m deep. Based on the sedimentary characteristics of continental lacustrine basins, fan delta facies were dominant reservoirs, commonly with area of less than 50 km^2. The statistics of the physical properties of nearly 383 core and wall core samples of the glutenite reservoirs drop sharply when the reservoir depth exceeds 3,500 m. Reservoir porosity was generally less than 10%, and the permeability was less than 1 mD, indicating ultra-low porosity and permeability (Figure 4). Therefore, the clastic sedimentary rocks cannot provide enough storage space for large natural gas reservoirs.

Buried hills tended to develop reservoirs of more than 1,000 km^2 with various lithologies, including metamorphic rocks, granites, igneous rocks, carbonate, and clastic rocks. The Archean buried hills mostly comprised felsic-rich brittle minerals, such as plagioclase gneiss, mixed granite, mixed gneiss, and granulite. The Bohai Bay Basin has experienced multi-stage tectonic movements since the Indosinian period, resulting in many multi-stage structural fractures. The fractures developed at distinct stages were superimposed to form complex and intersecting fractures. Early fractures often experienced multi-stage uplifting and denudation, atmospheric

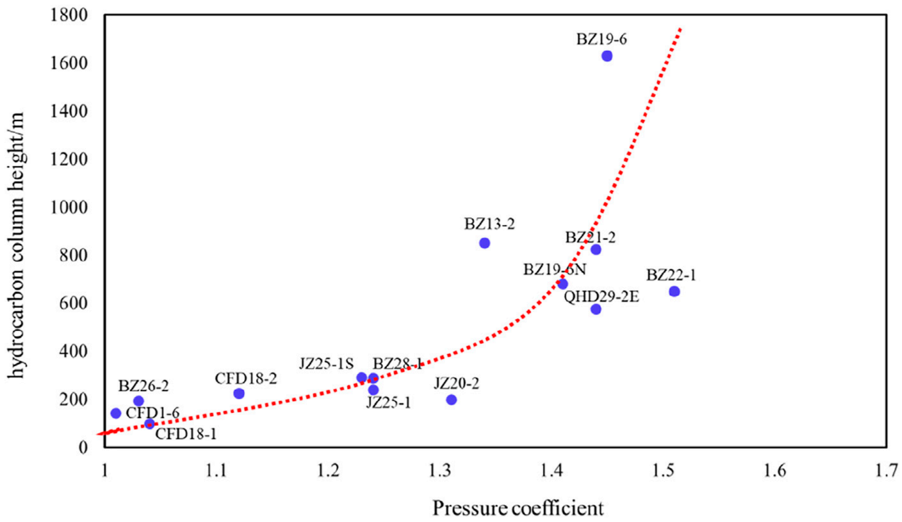

FIGURE 6
Relationship between hydrocarbon column height and cap rock pressure coefficient of the large and medium-sized oil and gas reservoirs in the Bohai Sea.

freshwater leaching, and dissolution of mantle-derived CO_2, hydrocarbon, and magmatic hydrothermal fluids (Xue and Wang, 2020). The storage space was modified by dissolution expansion pores along the fractures. The physical properties of the inner reservoir 1,000 m below the weathering crust were improved, forming three sets of structural fracture zones from bottom to top: the lower dissolution fracture zone, the middle fracture zone, and the upper weathering crust fracture zone (Figure 5). Many fractures developed in the weathering crust, and the inner part of the buried hill strengthened the storage capacity of the buried hill for natural gas. The discovery of the Bozhong 19–6 gas field has confirmed the development of large-scale reservoirs in buried hills. The thickness of drilled buried hill reservoirs exceeds 1,600 m, with average net-to-gross ratio of 42%, which is much higher than that of glutenite.

Preservation conditions of large gas fields

Later-stage preservation conditions were important for gas field formation (Bradley and Powley, 1994; Otroleva, 1994). Large natural gas fields are mainly formed under thick gypsum caps or in structurally stable areas (Lv et al., 2002; Liu et al., 2005). As a Cenozoic continental basin, Bohai Bay has undergone multiple intense tectonic activities. The Tan-Lu fault developed through the basin, and is made up of large, deep faults.

Exploration suggested that the pressure coefficient of the overlying cap of the gas reservoirs in the Bohai oilfield was significantly correlated with the height of the hydrocarbon column. The height of the hydrocarbon columns shows positive correlation with the pressure coefficients (Figure 6). The Paleogene Dongying Formation was developed in the Bohai Bay Basin during the periods of transition from rifting to depression. The depositional environment was deep lake in the early stage and semi-deep lake in the late stage, forming thick mudstone with an average thickness of more than 500 m. Due to late rapid subsidence, the mudstone generally shows under-compaction. Meanwhile, the hydrocarbon source rock in the Dongying Formation was accompanied by strong late hydrocarbon generation in the subsidence process and abnormal overpressure. The average displacement pressure was up to 10.24 MPa, and the pressure coefficient of mudstone cap was up to 1.2–2.0, which provided superior conditions for preservation of natural gas.

Although the Bohai Bay Basin experienced multi-stage tectonic movements in the Cenozoic, two sets of independent fault systems were formed in the Bozhong sag and other regions. Both the upper and lower fault systems disappeared in the thick mudstone of the Dongying Formation, which enabled the formation of regional overpressure mudstone caprocks in the Paleogene. However, there were differences in the fault systems of different sags, resulting in huge variations in the preservation conditions of different sags. Faults were well-developed in the Qikou and Huanghekou sags in the late stage, with most cutting through the Paleogene mudstone and destroying the regional mudstone cap rock conditions. The natural gas was often lost along the faults as the Cenozoic subsidence center of the Bohai Bay Basin, the Bozhong sag, developed the major source rocks in the Shahejie Formation, consisting of partially sapropelic kerogen dominated by oil generation, with less natural gas than crude oil generated in the early stage. Since 5.1 Ma, the large-area rapid subsidence in the sag

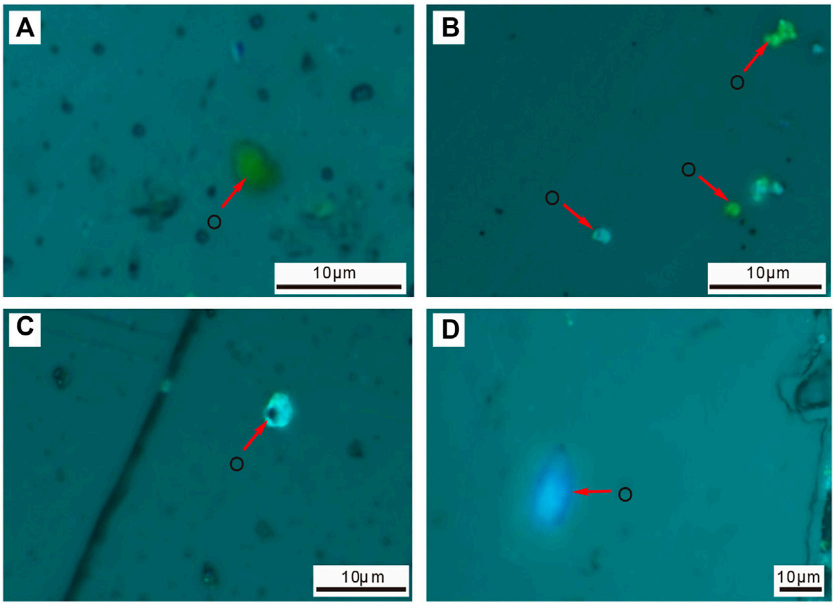

FIGURE 7
Microscopic characteristics of different fluorescent crude oil inclusions and gas inclusions. **(A)** BZ19-6-8, 4498.5 m, yellow-brown fluorescence of crude oil inclusions; **(B)** BZ19-6-1, 4428.5 m, yellow-green fluorescence of crude oil inclusions; **(C)** BZ19-6-10, 4435.16 m, light blue fluorescence of crude oil inclusions; **(D)** BZ19-6-7, 4600.2 m, bright blue fluorescence of crude oil inclusions.

area resulted in under-compaction, and the overpressure of the mudstone in the lower Dongying Formation was rapidly established and increased, providing the overpressure dynamic sealing conditions for the preservation of buried hill natural gas (Xue and Wang, 2020). At that time, the overpressure mudstone of the Dongying Formation began to form, which ensured that the natural gas generated was strongly downward charged and forced into reservoirs in the short term under control by the overpressure mudstone (similar to the action of gypsum rock in a gas-type basin), effectively reducing the loss of natural gas. Although faults were developed in the late stage, they did not penetrate the thick mudstone of the Dongying and Shahejie Formations. The sealing capacity of the regional overpressure mudstone adjacent to the natural gas was not compromised, which provided the necessary conditions for the formation of large gas fields.

Accumulation and depletion-enrichment model of natural gas in the Bohai Bay Basin

Accumulation model of natural gas reservoirs in buried hills of the Bohai Bay Basin

The main cause of the development of large gas fields in buried hills in the Bohai Bay basin was the thick overpressure mudstone overlying the Dongying Formation, with a thickness of more than 300 m and pressure coefficient of more than 1.4. The natural gas that was generated along with the crude oil migrated laterally under the set of overpressure capping layers and accumulated in the buried hill, forming a natural gas reservoir (Ma and Cheng, 2000). The condensate gas reservoir of Bozhong 19–6 in the Bozhong sag of the Bohai Sea followed the typical enrichment model, with overpressure mudstone undergoing the continuous gas-invasion accumulation process after the oil accumulated in the trap. The gas originated from kerogen cracking in the mudstone of the Paleogene Shahejie Formation in the Bozhong sag. Yellow-green and blue-white fluorescent oil inclusions were observed under the microscope (Figures 7A–D), and the homogenization temperatures of the associated saline inclusions were 90–160°C (Figure 8A). According to the burial history, the recovered crude oil charging period is generally 12.0–5.1 Ma (Figure 8B), reflecting the long-term continuous charging of crude oil with low maturity (yellow-green fluorescence) (Figures 7A,B) and high maturity (blue-white fluorescence) (Figures 7C,D). Many gas inclusions were also observed, with the homogenization temperature ranging from 140°C to 180°C. The natural gas filling occurred predominately from 5.1 Ma to the present (Figure 8B).

Oily asphalt, with vitrinite reflectance ranging from 1.3% to 1.6%, was found on the top of the buried hill, suggesting the cause of gas invasion. These observations indicate that the Bozhong

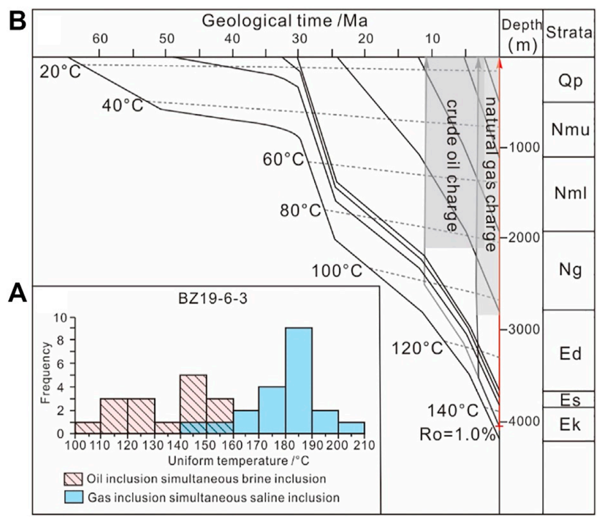

FIGURE 8
Homogeneous Temperature Histogram **(A)** and Thermal History of Oil and Gas **(B)** Inclusion in Well BZ19-6-3.

19–6 condensate gas reservoir experienced gas accumulation after oil accumulation. In the Middle Miocene to Early Pleistocene (12.0–5.1 Ma), the source rocks in the Shahejie Formation generated oil extensively, thereby generating overpressure. The pressure coefficient was routinely over 1.6, which was the main cause of hydrocarbon migration. The large amount of discharged crude oil filled the Archaeozoic buried hills and sand-conglomerate reservoirs in the Kongdian Formation, forming oil fields. Due to the neotectonics (5.1 Ma), some of the deep-buried crude oil migrated along the faults to the shallow Neogene reservoirs and formed the medium-sized BZ19-4 oilfield. The early filled oil was deeply buried with cracking (i.e., regular cracking to light oil). Based on the evolution of the Dongying Formation, the overpressure increased after the period of neotectonics, providing dynamic sealing conditions for the hydrocarbon in deeply buried hills. Since the Pleistocene (5.1 Ma), natural gas has been produced from highly to overmature source rocks. Fault activities brought more CO_2, which has caused gas invasion in the previously deep oil reservoirs. In addition, light oil was easily soluble in natural gas and converted into condensate gas. Under the cover of the "quilt-like" overpressure mudstone cap, the invasion process has continued to the present. The oil reservoirs gradually transformed into large-scale condensate gas reservoirs. According to data from simulation of temperature and pressure conditions, the fluid phase state of the Bozhong 19–6 condensate gas field has changed gradually, from 12 Ma to the present, from pure liquid to the critical state and the pure condensate gas phase. Based on the above discussion, the Bozhong 19–6 condensate gas field experienced a natural gas reservoir forming mode characterized by oil before gas, shallow formation and deep burial, and local adjustment and transformation. The preservation of the Paleogene "quilt-like" overpressure mudstone was the controlling factor in the enrichment and preservation of the deep atmospheric field in buried hills of the Bohai Bay Basin.

The gas field was well-developed and sheltered from dissipation by the mudstone cap. However, in different parts of the depression, limited by the overpressure mudstone in the Dongying Formation, the cap was poorly developed in the sand-rich area or the overpressure was destroyed by fractures or faults, leading to the development of oil or heavy oil fields, or even small-scale gas fields (Luo, 2003; Ma et al., 2019). Generally, the natural gas accumulated within the low buried hills; the small gas and the oil and gas fields within the buried hills are of medium depth, whereas the large-scale oilfields are structurally high (Figure 9). These features caused the circular distribution of the natural gas, middle-light oil, and heavy oil fields surrounding the source rocks.

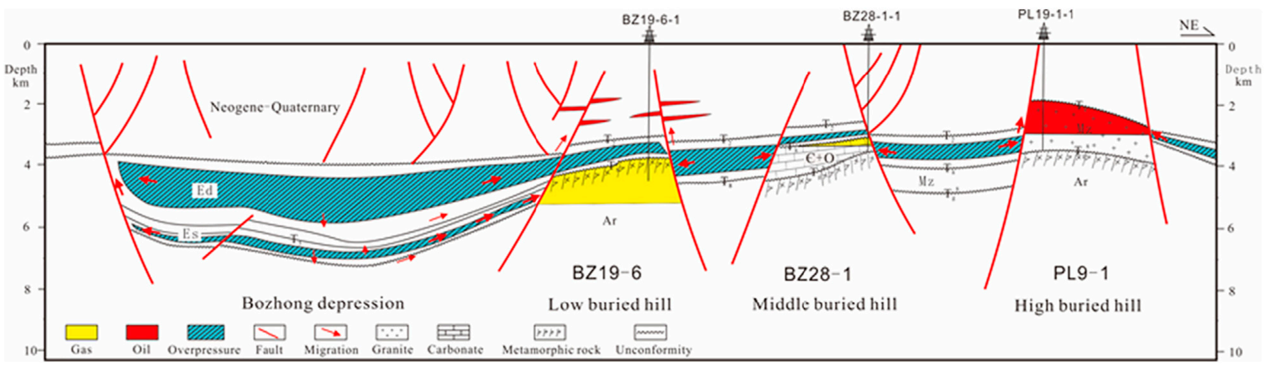

FIGURE 9
Schematic section of oil and gas accumulation in buried hills in the Bohai Bay Basin.

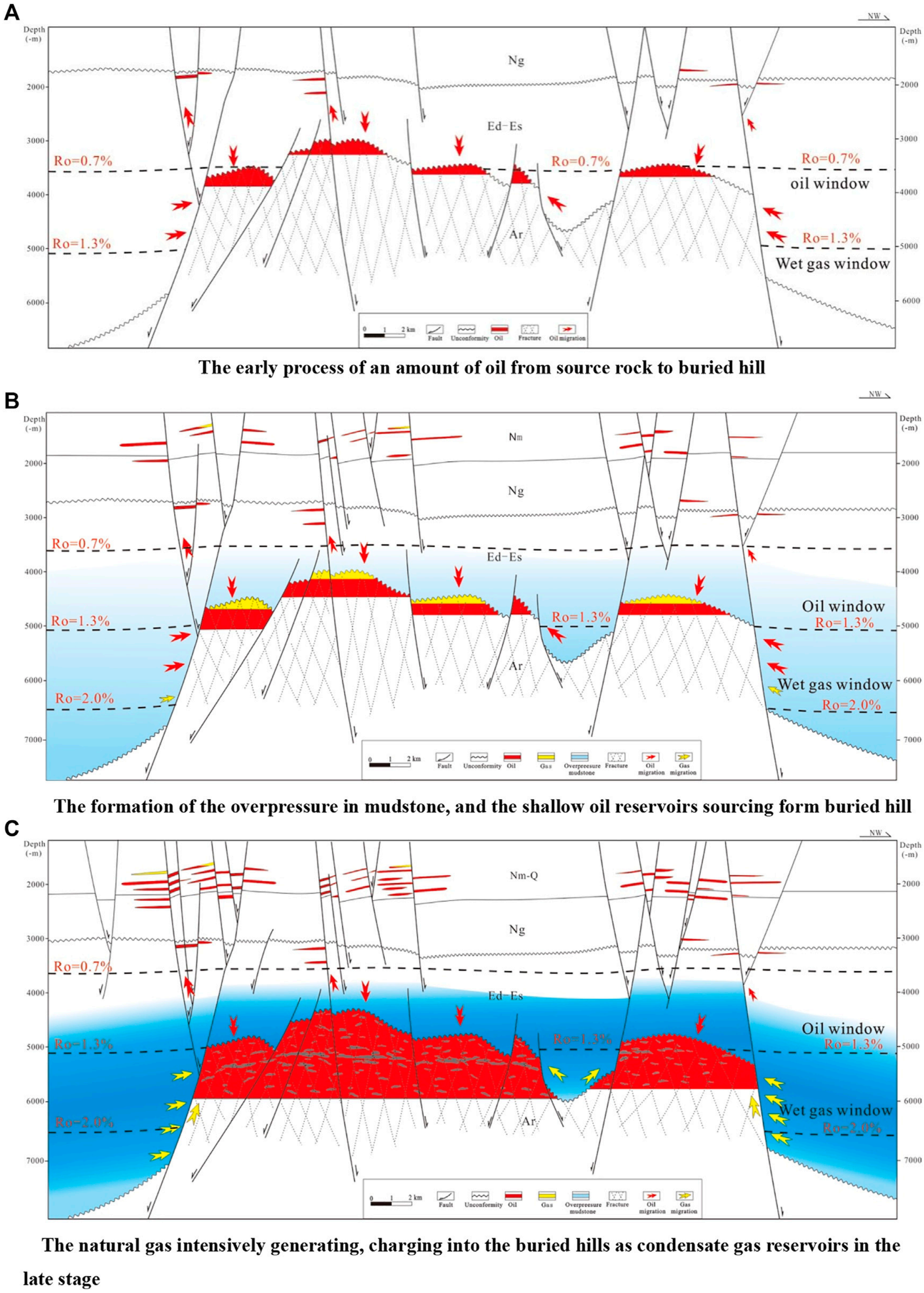

FIGURE 10
Enrichment and accumulation models of the Bozhong 19–6 large-scale natural gas field. **(A)** The early process of transition of an amount of oil from source rock to buried hill. **(B)** The formation of overpressure in mudstone and the shallow oil reservoirs sourced from buried hills. **(C)** Intensively generated natural gas charging into buried hills to form condensate gas reservoirs in the late stage.

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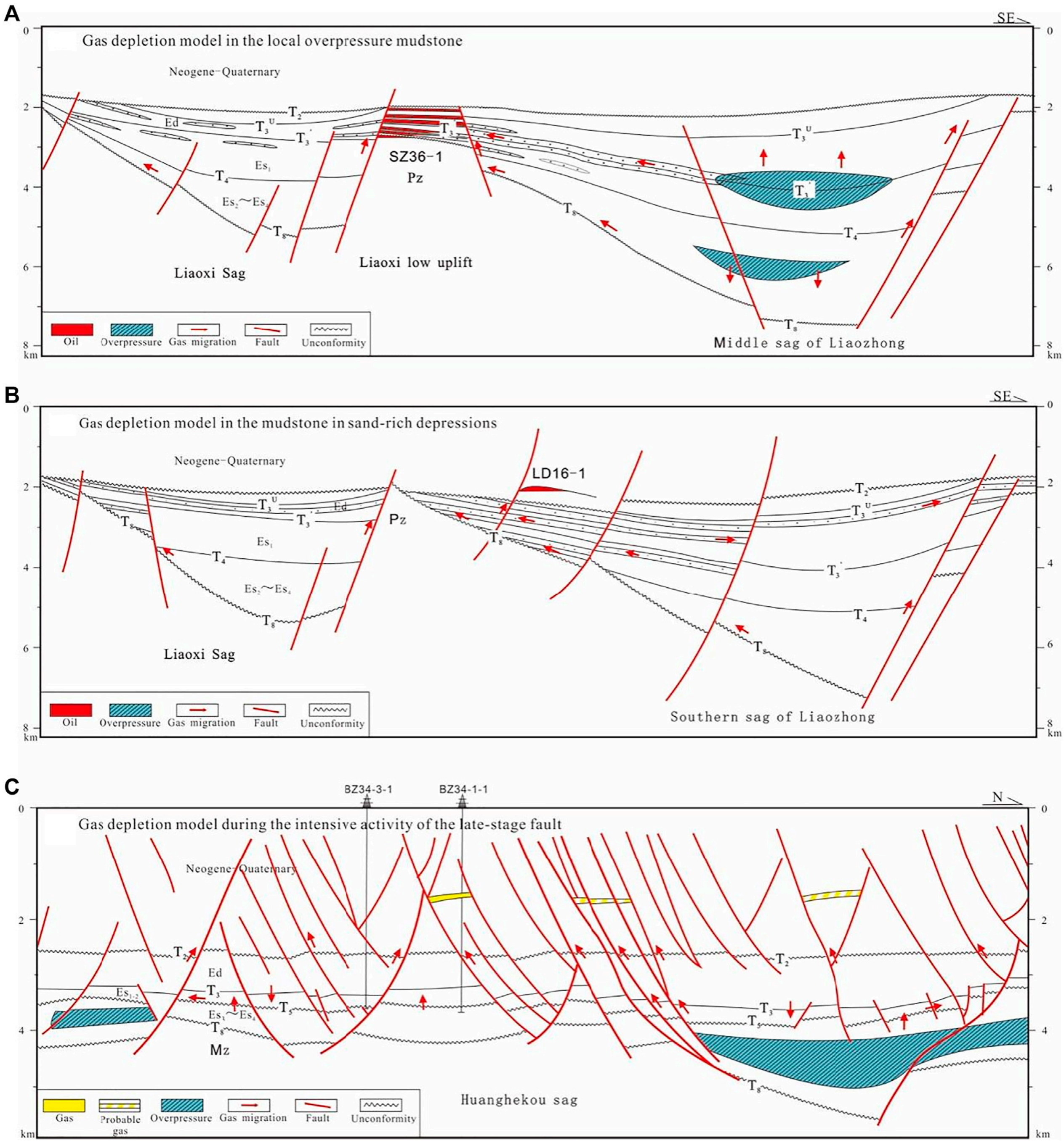

FIGURE 11
Large-scale natural gas depletion model in the Bohai Bay Basin.**(A)** Gas depletion model inthe local overpressure mudstone; **(B)** Gas depletion model inthe mudstone in sand-rich depressions; **(C)** Gas depletion model during the intensive activity of the late-stage fault.

Natural gas depletion-enrichment models

There are more than 60 sags distributed in the Bohai Bay Basin. According to the formation conditions mentioned above, combined with exploration practice, depletion-enrichment models for natural gas can be divided into four models.

Gas enrichment under regional overpressure mudstone

In gas-producing depressions and surrounding areas with humus-type or high-mature saprolite-type kerogen, the huge and "quilt-like" overpressure mudstone cap was deposited in the Dongying Formation (Shahejie Formation) above the source

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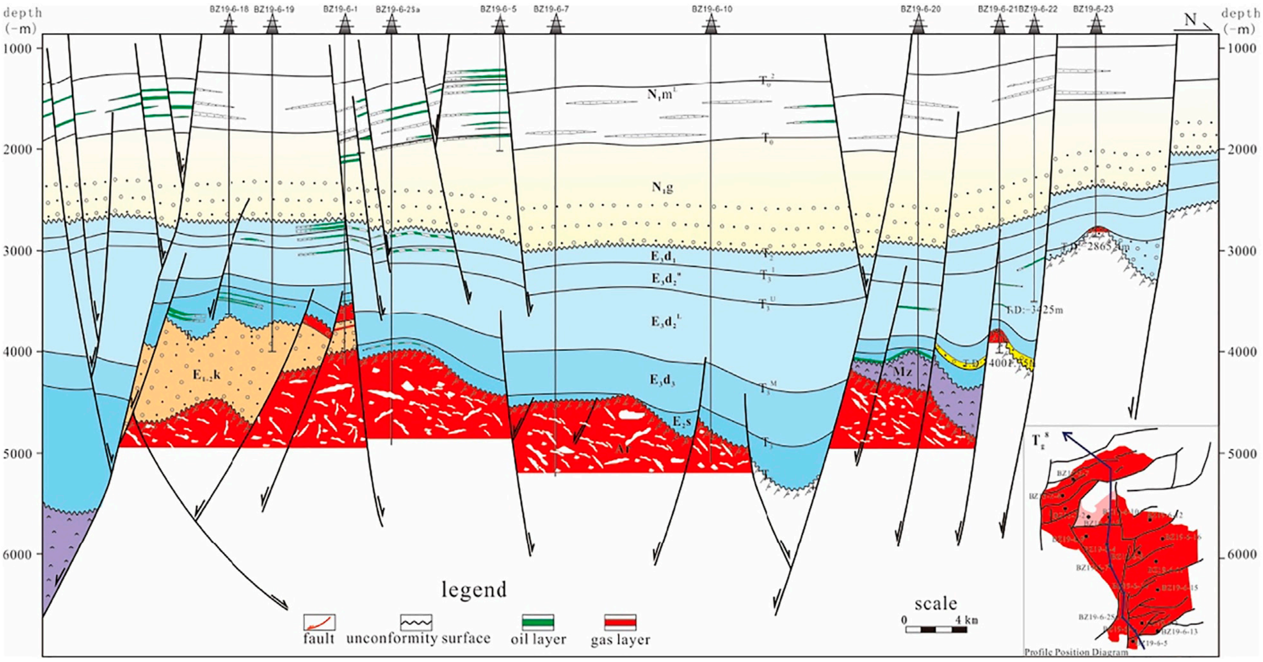

FIGURE 12
Oil and gas accumulation model of the Bozhong 19–6 condensate gas field.

rock. The cap was not damaged by the late-stage faults and contributed to the progressive development of the overpressure (Hao et al., 2004). Prevented from dissipating by the mudstone cap, the natural gas from the Paleogene migrated laterally and was trapped in the Dongying Formation. Particularly within the low buried hill of the sag, the gas field formed when the overpressure mudstone expelled the natural gas to form a strongly filled reservoir (Figure 10). This field is at the northern area of Liaodong Bay and the Bozhong sag.

Gas depletion in local overpressure mudstone

Although mudstone was widely deposited in the Dongying Formation of the Bohai Bay Basin, the sandstone-mudstone interlayers developed by river systems were dominant on the slopes of the sag. The fluids were discharged in a timely manner during sedimentation and compaction due to the conduction of sandstone on slopes. The mud-rich formation that generated the overpressure only formed in the central sag. As a result, the sealed cap was absent and the natural gas dissipated vertically through the cap. This type of mudstone in the Dongying Formation did not provide a seal for natural gas but did seal in crude oil, thereby forming the large and medium-sized oil fields in the central part of Liaodong Bay (Figure 11A).

Gas depletion in sand-rich sags

During the sedimentary period of the Dongying Formation, the depression entered the deposition stage. Due to the sufficient supply of external sources, sandstone and glutenite were widely deposited in the depression. The distribution range and thickness of mudstone decreased and its sealing capacity was significantly weakened. Most of the natural gas was lost and it was difficult to form a large-scale gas reservoir (Lv et al., 2005). Exploration and discovery are often dominated by reservoirs, as demonstrated in the southern area of Liaodong Bay (Figure 11B).

Gas depletion via intensive activity of the late-stage fault

Thick mudstone in the Dongying Formation (Shahejie Formation) was developed, yet late-stage faults penetrated the mudstone cap in the center and surrounding areas of the gas-producing sag. Under this condition, the natural gas dissipated instead of migrating along the pathways and being preserved by the cap. Some of the dissipated gas accumulated in the shallow-buried Neogene reservoirs. Due to gas dissipation, a large natural gas field was not formed, as observed in the Yellow River Mouth Sag (Figure 11C).

Exploration cases

Exploration cases

Exploration guided by an understanding of natural gas formation conditions allowed Bozhong 19–6 to be discovered as the first large gas field in the old oil region in eastern China. The open-hole test of the Archaean buried hill obtained high yield, with a daily gas production of 11.35×10^4 m^3~33.18×10^4 m^3 and a daily oil production of 111.06 m^3~338.76 m^3. The third-order natural gas reserves are about 450×10^9 m^3, and the oil equivalent reaches 800×10^6 m^3.

The Bozhong 19–6 gas field is in the southwest of the Bozhong sag, on a near-SN-trending structural ridge between the Bozhong Southwest Sub-sag and the Bozhong Main Sub-sag. The field was an anticline structural area cut by near-SW-NE-trending and near-EW-trending faults. This area has experienced multiple episodes of rifting and superimposed composite structural evolution of neotectonic movements, resulting in the superimposed structural characteristics of faulting and depressing. The Bozhong 19–6 structure was surrounded by the Bozhong, Shanan, and Huanghekou sags. The basement, with burial depth of 4,000–5,500 m, comprises mainly Archaean metamorphic rocks with regional distribution characteristics and is the metamorphic buried hill reservoir with the largest burial depth in the Bohai Bay Basin (Figure 12). The discovery of the Bozhong 19–6 large condensate gas field confirmed that the Archean metamorphic rocks had great exploration potential. Different from other metamorphic rock reservoirs, the Archean metamorphic rock reservoir in the Bozhong 19–6 structure showed the characteristics of large burial depth and high diagenetic strength. The development of high-quality reservoirs is closely related to the development of internal fractures in buried hills. The regional Tan-Lu fault activity and the coupling of high-quality lithology in buried hills have formed large-scale high-quality natural gas reservoirs. The deep-buried Archean metamorphic rocks in the Bozhong sag have a huge distribution area. The high-quality hydrocarbon source rocks in the center of the sag provided a sufficient resource base for the formation of natural gas. Coupled with multi-stage tectonic movements, the natural gas accumulation conditions were favorable, and the deep-buried hills in the Bozhong sag had great potential for natural gas exploration.

The Bozhong sag and the northern part of the Liaozhong sag are favorable for natural gas exploration

The Bozhong sag has the largest Cenozoic sedimentary thickness in the Bozhong Depression. Mudstone in the Shahejie and Dongying Formations were widely distributed, with thickness of more than 200 m. Since 5.1 Ma, the rapid subsidence of a large area in the Bozhong sag has led to under-compaction and rapid formation of mudstone overpressure (Ge and Zhu, 2001). Today, the pressure coefficient generally exceeds 1.6, which can seal most of the natural gas in deep layers and provide good sealing conditions for natural gas preservation. Three sets of high-quality source rock series were developed in the third member of the Shahejie Formation, the first and second members of Shahejie Formation, and the third member of the Dongying Formation in the Bozhong sag. The type of organic matter was mainly type II_1-II_2 kerogen. The hydrocarbon source rock of the third member of the Shahejie Formation had the largest burial depth and the highest thermal evolution degree of organic matter, with R_o exceeding 2.0%, indicating the dry gas stage. The thermal evolution degree of organic matter in the first and second members of the Shahejie Formation was up to 2.0%. The maturity of hydrocarbon source rocks in the third member of the Dongying Formation ranged from 0.7% to 0.9% in most areas. Only near the center of the Bozhong sag did the maturity reach 1.0%. Therefore, the large-scale development of high-quality, matured source rocks in the Shahejie Formation in the hydrocarbon generation center provided the foundation for the mass production of natural gas. The lithology of buried hills in the Bozhong sag consists mainly of igneous, carbonate, and metamorphic rocks. These three lithologies were affected by multi-stage tectonic movements including the Indosinian, Yanshan, and Himalayan movements, leading to fractures that developed into three-dimensional reticulation reservoirs that provided large-scale storage space for natural gas. Overall, the thick overpressure mudstone “quilts” in the Bozhong sag, the area that generated the largest gas volume, were distributed continuously in the region. The scale of natural gas resources was predicted to reach trillions of cubic meters in the low-buried hills of the central Bohai Sea. Therefore, in addition to the large-scale condensate gas field of Bozhong 19–6, other areas in the Bozhong sag are favorable targets in the exploration of natural gas fields.

The Liaozhong sag is in the Liaodongwan Depression in the northern part of the Bohai Sea. The Jinzhou 20–2 gas field was discovered in the northern part of the Liaozhong sag and is currently the largest natural gas producing area in the Bohai Sea. The degrees of development of Paleogene mudstone in the southern and northern Liaozhong sag were different. The Paleogene in the southern area mainly comprises interbedded sand and mudstone, and the degree of overpressure is low, making it difficult to preserve a large volume of natural gas effectively. The northern Paleogene is dominated by thick mudstone, with a pressure coefficient up to 1.8, providing sealing conditions for large-scale natural gas preservation. The Shahejie Formation in the Liaozhong sag developed high-quality hydrocarbon source rocks with type II_1-II_2 kerogen at a high degree of thermal evolution, providing a good source rock foundation for the generation of a large amount of natural gas. The buried hill reservoirs in the sag, slope, and adjacent uplift areas had good conditions to support the formation of large-scale reservoirs, which also formed the conditions for large-scale natural gas preservation. Together, the thick overpressure mudstone “quilts” developed by the Paleogene in the northern part of the Liaozhong sag and the Shahejie Formation source rock with a relatively large burial depth that can generate a large amount of gas for the reservoirs in buried hills indicate a favorable area for natural gas field exploration.

Conclusions

1) The Bohai Bay Basin is a typical Cenozoic continental rift basin that has the following characteristics that commonly support the formation of gas reservoirs: 1) rapid maturation and high-intensity gas generation in the late stage; 2) a buried hill reservoir that is less affected by burial depth but rather by multi-stage structural uplift, deep fluids, atmospheric fresh water, weathering crust, and inner fractures; and 3) an overpressure mudstone "quilt" in the developed area that replaces the gypsum layer to promote sealing.
2) Enrichment and depletion models for natural gas accumulation in the Bohai Bay Basin were established and divided into the following types: regional overpressure mudstone enrichment, local overpressure mudstone depletion, sand-rich sedimentary depression depletion, and late fault strong development depletion.
3) The areas with high-quality reservoirs and the thick Paleogene overpressure mudstone "quilts" were closed to hydrocarbon generation in both center and buried hills, such as in the surrounding zone of the Bozhong sag and the northern part of the Liaozhong sag.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

In this study, YX contributed to the key geological conditions for the formation of large natural gas fields in the continental lacustrine basin of the Bohai Bay; HY contributed to natural gas accumulation law and depletion and enrichment modeling in continental lacustrine basins of Bohai Bay; PX contributed to exploration cases and favorable exploration directions; and SX contributed to discussion of how buried hill large-scale reservoirs provide large storage space.

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Conflict of interest

YX, HY, PX, and SX were employed by the company CNOOC Co., Ltd.

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