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Key factors controlling the accumulation of oil reservoir in the Gaosheng area of Western Depression, Liaohe Basin, Northeastern China

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The Proterozoic oil in Gaosheng area of the Western Depression of Liaohe Basin has great potential and is an important exploration field. However, the study about control factors of Gaosheng reservoir needs to be improved. The source rocks are characterized by using geochemical techniques and the structural evolution history is restored by using 2D-Move software. The characteristics of reservoirs and caps are clarified, and the controlling factors of reservoir formation are summarized. The oil generation intensity of Es4 and Es3 is generally 5×10^6–10×10^6 t/km^2, indicating that the oil source is sufficient. The sandstone reservoir has fracture and dissolution porosity, which provide storage space for oil accumulation. Faults and unconformities provide pathways for oil migration. The dense Fangshenpao and Mesozoic basalt is a good cap layer to preserve the reservoir, which effectively prevents the upward migration of oil. According to the comprehensive analysis of main controlling factors, the favorable exploration areas are pointed out. The research results are of great significance to guide the future oil and gas exploration in Liaohe Basin.

KEYWORDS

controlling factors, buried-hill reservoir, hydrocarbon accumulation, favorable zones, Gaosheng oilfield, Liaohe Basin

Highlights

- The characteristics of source rocks and tectonic evolution are revealed.
- The condition of sandstone reservoir and cap rock are clearly clarified.
- The factors controlling oil reservoir accumulation were summarized systematically.

1 Introduction

Unconventional oil and gas attract wide attention in the world due to its success of exploration and development in North America (Hein et al., 2019). According to the statistics of relevant scholars, the amount of unconventional oil resources in the world is about 4495 × 10^8t, which is roughly equivalent to that of conventional oil resources (IEA, 2013). By 2030, global oil production is expected to increase by 16.1 million barrels per day compared to today, with nearly half of that coming from tight oil, which will meet nearly 10% of global energy demand by then (IEA, 2012).

The distribution of tight oil in China is characterized by a wide range, multiple blocks, and large series span. In addition, tight sandstone in the Quang 4th member Formation in Songliao Basin (Huang et al., 2017), Jurassic Formation of the Tuha Basin (Feng et al., 2021), Yanchang Formation in Ordos Basin (Xu et al., 2017), Cretaceous tight limestone of the Jiuquan Basin (Chen et al., 2018) and the dolomites of Permian Lucaogou Formation in Junggar Basin (Liu et al., 2023) all have geological conditions for forming tight oil reservoir. In terms of geological background, source rock quality, reservoir quality, formation overpressure, source-reservoir communication and crude oil quality, the Bakken oil formation in Williston Basin in North America is comparable to the Bakken and Eagle Ford tight oil in North America. Even in terms of source-reservoir combination, the Bakken oil formation in Williston Basin in North America is inferior to the tight oil of Yanchang Formation in Ordos Basin (Zou et al., 2012; Zhang et al., 2013). Previous studies mainly focused on geochemical characteristics (El Diasty et al., 2016; Kobraei et al., 2019; Wu et al., 2021), accumulation conditions (Xu et al., 2021; Szatmari and Schaffer, 2023), physical properties (Busch et al., 2019; Zhao et al., 2021; Odrzygóźdź et al., 2023), diagenesis (Higgs et al., 2007; Alsuwaidi et al., 2022; Er et al., 2022), charging period (Han et al., 2022; Liu et al., 2022), fractures (Chen et al., 2022; Zhao et al., 2022; Panara et al., 2023) and so on. However, due to the rare research literature on tight gas reservoir control, the comprehensive understanding of control factors still needs to be further improved.

The exploration and development of the buried hill reservoir in Liaohe Basin is early, and the buried hill reservoir accounts for a major proportion of the reserves and production of Liaohe oilfield, which is the important oil exploration field (Luo et al., 2005). After oil test, a high oil flow rate of 22.47 tons per day was obtained in the well section of 2680 m–2714.07 m in Proterozoic in Gaogu (GG) 2 well, thus the Gaosheng Proterozoic buried hill reservoir was discovered. Gaosheng oilfield has shown great potential in the process of exploration (Yu, 2016).

In recent years, we have a consensus view of the formation conditions of tight oil reservoirs in Gaosheng area. Reservoir formation is influenced by fractures, high quality source rocks and good preservation conditions of volcanic cover in Gaosheng area (Yu, 2016). It is also basically clear that the structure is the main migration channel of reservoir formation (You et al., 2006). However, the systematic summary of reservoir controlling factors and the prediction of favorable areas are relatively scarce and there is still room for improvement in the in-depth understanding of reservoir controlling factors. Lack of understanding of control factors has limited exploration progress. Therefore, it is significant to explore the main controlling factors of Gaosheng reservoir.

The main goals of the study are: 1) describe the characteristics of Es3 (Shahejie Member 3) and Es4 (Shahejie Member 4) source rocks and sandstone reservoirs; 2) reveal the characteristics of tectonic evolution and cover layer in Gaosheng area; 3) discuss the controlling factors of reservoir formation. The results can be used for reference to guide oil and gas exploration, and have practical application value in areas similar to the Western Depression in the world. In addition, it also has reference value for the exploration of other similar reservoirs.

2 Geological setting

Gaosheng area is in the northeast of the Western Depression of Liaohe Basin, Bohai Bay Basin. Liaohe Depression is a Cenozoic continental rift basin developed over the Mesozoic Basin, including several secondary structural units, such as the Eastern Depression, Western Depression, Damintun Depression, Shenbei Depression, Eastern Bulge, Western Bulge and Central Bulge (Hu et al., 2005). In the Paleogene, the Western Depression was a long and narrow half graben-like fault depression with a northeastward distribution and a steep slope in the east and a gentle slope in the west (Figure 1). The Western Depression is rich in oil and gas and the exploration degree of conventional oil and gas is high. The target strata studied in this paper are Proterozoic strata.

The Liaohe Basin was a part of the North China platform before the Early Triassic, and was uplifted for a long time after the Paleozoic, resulting in the loss of some strata. During the Mesocenozoic period, under the influence of the Pacific plate subduction to the northwest, several depressions spread north and east, and thick Mesozoic-Cenozoic sand-mudstone strata were deposited. Most of the Western Depression is based on Archeozoic strata, and the Shuguang area is based on Proterozoic and Paleozoic strata. The maximum thickness of the Cenozoic cap layer is thousands of meters and it is relatively widely distributed (Figure 2).

In terms of regional structure, Liaohe Basin is a part of the Bohai Bay oil and gas belt, belonging to the Middle and Cenozoic rift basin and located in the northeast of the North China platform, bordering the Liaodong Platform anticline to the east, the Yanshantai fold to the west and the eastern edge of the Inner Mongolia axis to the north (Zhang et al., 2014). The Liaohe Depression is characterized by a high geothermal field, regional shallow gravity negative anomalies, narrow geological features, frequent volcanic activity, and a fault system dominated by normal faults. It is a product of the uplift of the upper mantle and the extension of the upper crust. Its formation and development can be divided into three periods: the expansion period, the deep sag stage, and the suture period (convergence period) (Ge, 2018).

The source rocks in the Western Depression are mainly Es3 and Es4 strata and they have excellent oil generation potential to form large oil reservoir (Yu, 2016). The reservoirs are mainly Es3, Es4, Pz, Pt and Ar. The reservoir of Gaosheng oilfield is mainly concentrated in Pt.

3 Samples and methods

3.1 Samples

The samples of 4 wells were obtained to clarify the characteristic of source rocks and sandstone reservoir (Table 1). The source

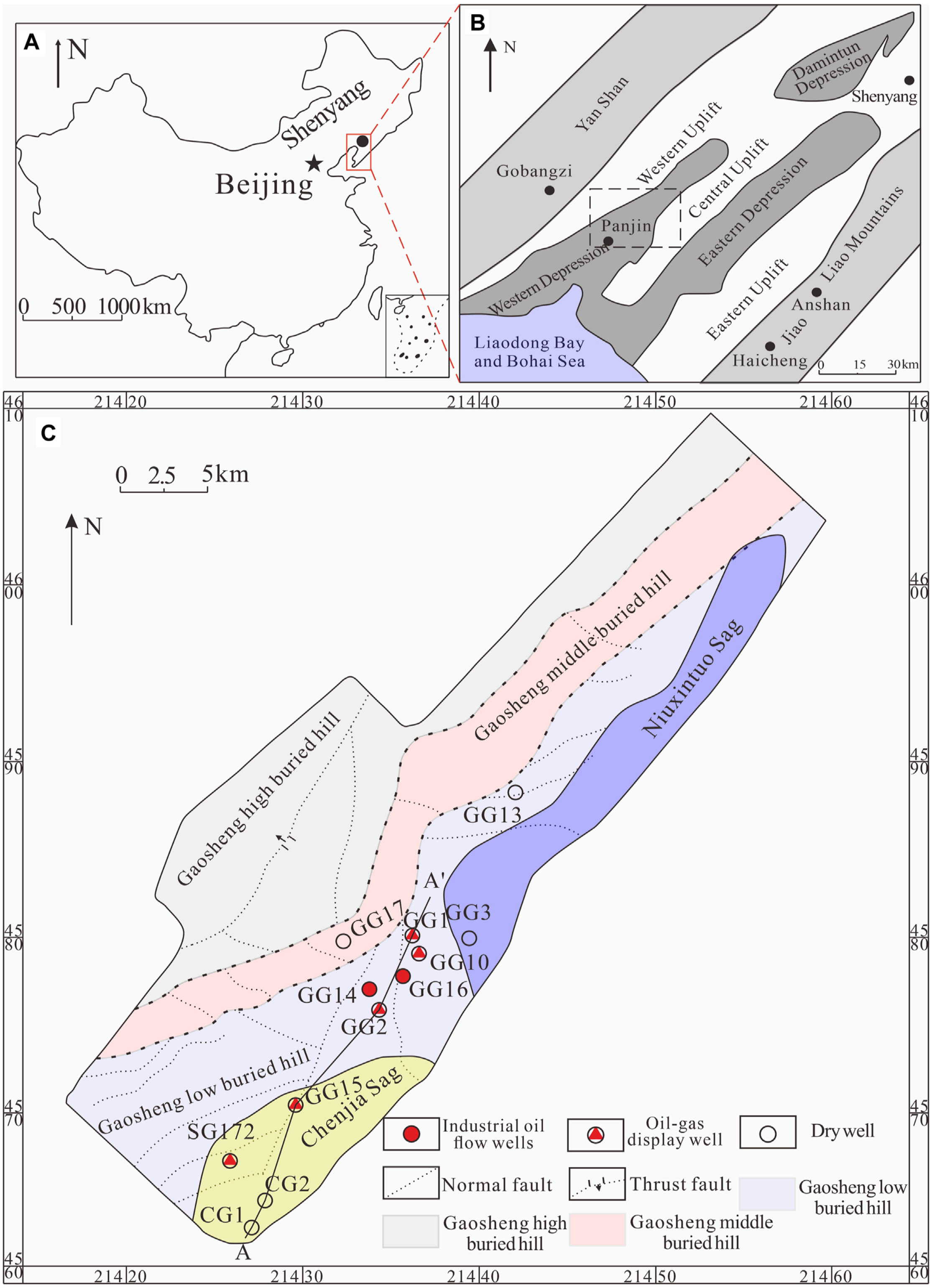

FIGURE 1
Location map of Gaosheng area in Western Depression of Liaohe Basin (modified from Hu et al., 2005). **(A)** Location of the Liaohe Basin in eastern China; **(B)** Location of the Gaosheng area in the Liaohe Basin; **(C)** The geological map the Gaosheng structural belt.

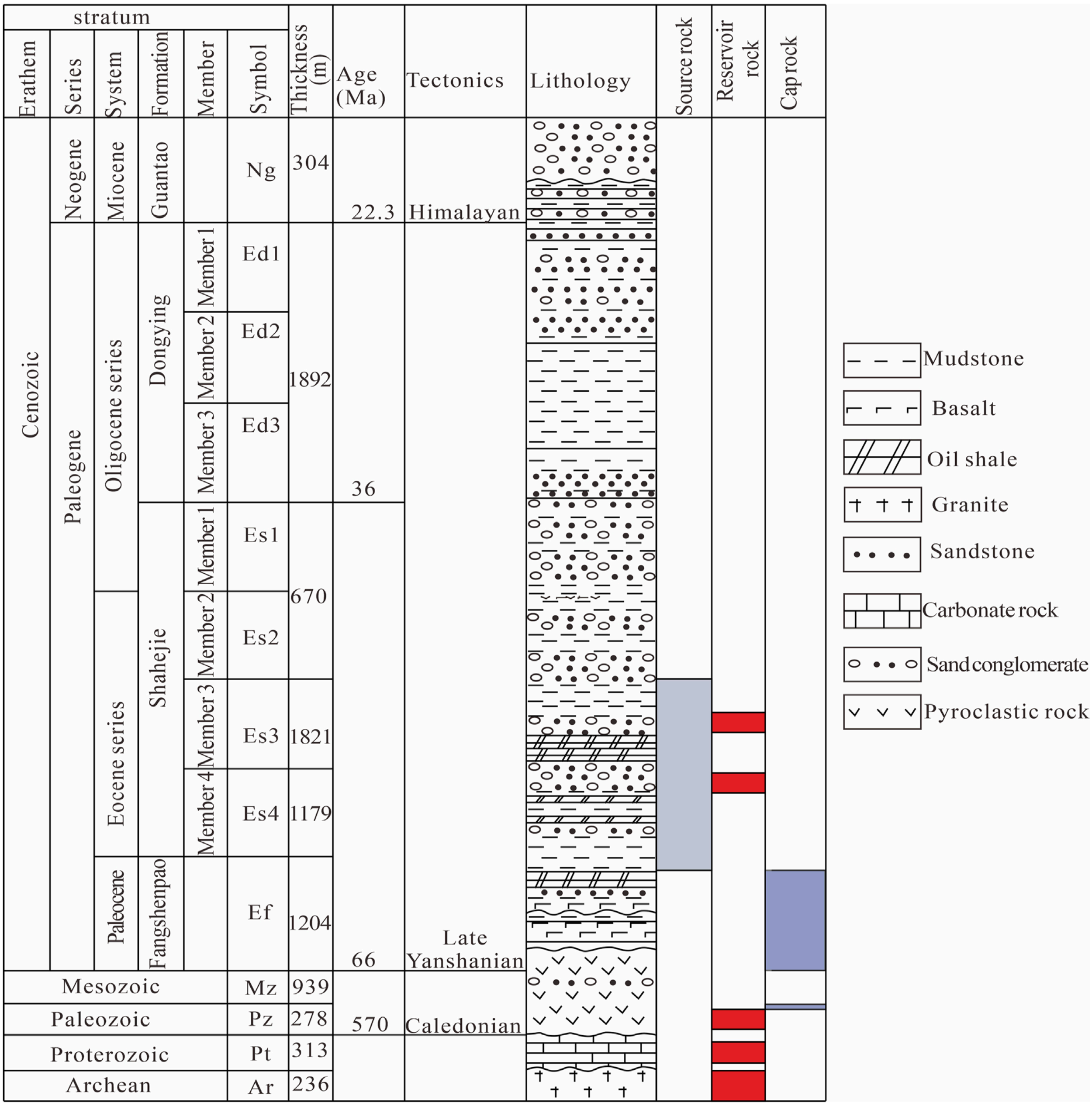

FIGURE 2
Comprehensive column chart of Gaosheng area in Western Depression of Liaohe Oilfield (modified from Leng et al., 2008).

rock samples were tested for geochemical characteristics. And the sandstones were for physical properties of reservoir.

3.2 Methods

3.2.1 2D-move was used to make structural evolution profile

According to 2D seismic profiles, geological and drilling data, the evolution history of a typical profile is recovered using 2D-Move software, which is implemented by the balanced profile method. The restoration of profile evolution provides a basis for explaining the evolution of structure and sedimentation in the study area. At the same time, these data are comprehensively utilized to establish the hydrocarbon accumulation model in the Gaosheng area.

3.2.2 Analysis of geochemical characteristics

The pyrolysis analysis method is to crush the sample to about 100 mesh, and the instrument used is YY3000A comprehensive evaluation instrument for source rocks. The analysis method is referred to GB/T 18602-2012 (Rock Pyrolysis Analysis). The organic geochemical parameters are mainly total organic carbon content (TOC), maturity (*Ro*), generation potential (S_1+S_2) and so on.

TABLE 1 Data of the obtained samples.

Well	Layer	Depth (m)	Lithology	Type of sample
GG2	Es3	1259.2	Mudstone	Source rock
GG2	Es4	1318.5		
GG14	Es3	1247.9		
GG14	Es4	1458.3		
GG15	Es3	1274.7		
GG15	Es4	1468.4		
GG16	Es3	1327.6		
GG16	Es4	1489.8		
GG2	Pt	3049.2	Sandstone	Sandstone reservoir
GG14	Pt	2941.88		
GG15	Pt	2869.26		
GG16	Pt	2656.5		

3.2.3 Experiment of reservoir

The porosity was measured by JS100007 helium porosity meter, and the permeability was measured by A-10133 gas permeability meter, utilizing standard industrial methods (Li et al., 2019). The resin or liquid glue dyed blue is poured into the pore space of the rock under a vacuum to solidify the resin or liquid glue, and then the rock is ground into thin slices, and finally the pore structure is observed under a polarizing microscope. The pore types and measurement parameters of reservoir rock can be clearly shown in the scanning electron microscopy (SEM). The SEM images were produced by China University of Petroleum (Beijing). The diameter of the sample is 0.5–3.0 cm, and the thickness is 0.2–1.0 cm. The observation instrument was Zeiss SUPRA 55 sapphire scanning electron microscope. Samples of quartz sandstone are cut into thin slices and then viewed through instruments.

4 Results

4.1 Characteristics of source rock

The source rocks of Es4 developed in the initial rifting stage of the rift valley, mainly in the western slope of the northern and southern parts of the depression, with a thickness of 0–700 m, generally about 300 m. The dark mudstone and sandy mudstone account for the majority. The contour map of source rocks (Figure 3A) indicates that the source rocks in Niuxintuo Sag in the northeast of Gaosheng area are the most developed, with a thickness of up to 700 m. According to the evaluation criteria of source rocks, the TOC of source rocks in Es4 Member ranges from 0.14% to 8.02% (average 2.35%), and the organic matter is mainly II_1 and II_2 types. The *Ro* ranged from 0.3% to 1.26% (average 0.76%).

The source rock of Es3 member is dark mudstone rich in organic matter, which is widely distributed and produced in the deep depression period. The isocontour map of source rock thickness (Figure 3B) indicates that the source rocks of Niuxintuo Sag, Chenjia-Panshan Sag and Qingshui Sag are relatively developed, and the most developed is Qingshui Sag with the maximum thickness of 1,500 m, followed by Chenjia Sag and Panshan Sag with the thickness of source rock up to 1,200 m, and the thickness of Niuxintuo Sag source rock is only 700 m. Generally speaking, this set of source rocks is the best source rock with the widest distribution and the largest thickness in the Western Depression. The TOC of the source rocks in Es4 ranges from 0.03% to 1.19% (average 0.19%). The organic matter is dominated by types II_1 and II_2, and the *Ro* ranges from 0.28% to 1.29% (average 0.68%).

4.2 Tectonic evolution

According to the structural development history, this area is mainly composed of three major structural layers: Paleogene pre-structural layer, Paleogene structural layer and Neogene structural layer. In the Mesozoic to early and middle Paleogene, fault activity was intense and frequent, showing obvious inheritance and neogenesis (Figure 4). In the middle and late Paleogene, fault activity gradually weakened, and there was basically no new fault development in the Neogene, showing stages of tectonic evolution. The reservoir formation model of the established Gaosheng reservoir is shown in Figure 5, which is conducive to revealing the formation mechanism of the reservoir.

4.3 Characteristics of the reservoir

The reservoirs include siliceous quartz sandstone, quartzite sandstone, glauconitic quartz sandstone, generally greyish-gray and dark gray, widely distributed in this area. The debris consists of fine particles, coarse and medium particles, sorting is generally good, roundness is mainly subroundness. The clastic composition is mainly monocrystalline quartz and feldspar and siltstone debris are occasionally seen. The content of quartz is generally 95%–99% of the detritus (Figure 6).

According to the porosity experiment, the porosity of quartz sandstone ranges from 0.4% to 22.1%, the porosity of less than 10% accounts for about 50%, the permeability ranges from 0.03 to 10.2 mD, and the permeability of less than 0.1 mD accounts for about 32% (Figure 7). It indicates that the quartz sandstone in Pt formation has a certain degree of density, but the heterogeneity is obvious.

Based on the data of core observation and cast thin sections, the pore types of Proterozoic reservoir rocks in this area are mainly secondary pores and fractures. Among them, the pore types mainly include: residual intergranular pores, intergranular dissolved pores, and intragranular dissolved pores.

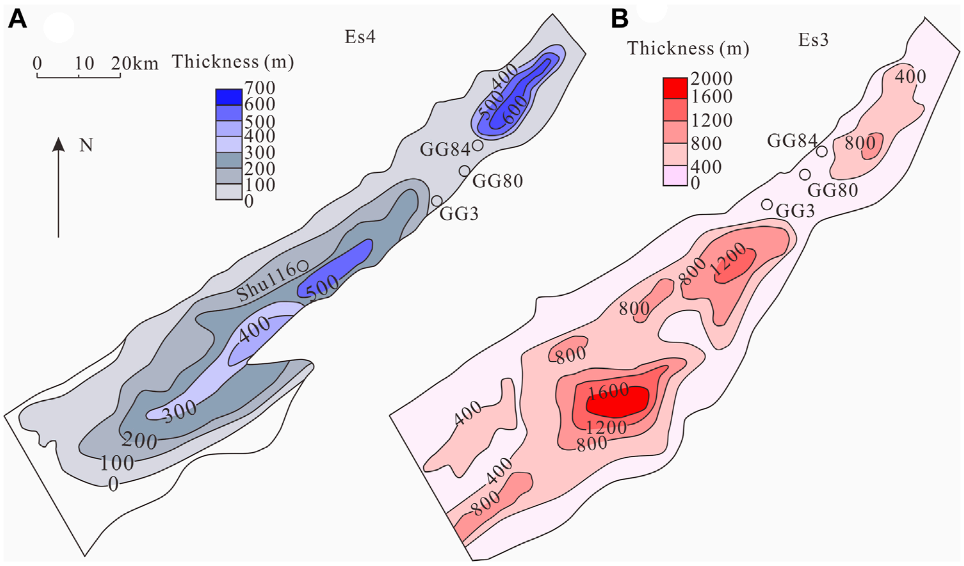

FIGURE 3
Isopach map of source rocks in the Western Depression of Liaohe Basin (The data are from Liaohe Oilfield). **(A)** Es4 source rocks; **(B)** Es3 source rocks.

Most of the fractures are open fractures, and the fracture surface extends longer, and most of them cut the whole core. Multiple groups of fractures develop and are distributed in a macroscopic network, so the core is often broken into small pieces. The presence of a lot of fractures in the core indicates that microfractures in the quartz sandstone are well developed (Figure 8).

4.4 Characteristics of the cap rock

This map is based on data collected from drilling Wells. Since Cenozoic, the subduction of the Pacific plate to the Eurasian plate led to the influence of Tanlu fault activity in the early stage of Liaohe Depression. During the Paleocene period, under the action of regional tensile stress, the fault activity was extremely strong, represented by the deep fault activity. The Tai' an major fault was strongly active and broke off the upper mantle. Then mantle materials poured out along the fracture and erupted to the surface, forming a thick basalt blanket in the Gaosheng—Leijia area (Figure 9).

The Fangshenpao Formation and the Mesozoic basalts are strongly controlled by the main fault and have a large thickness near the fault. It is analyzed that the eruption center is formed in the Gaosheng area, the thickness is larger in the main part of the buried hill, and it is thinner toward the low part of the buried hill (Figure 9). The basalt of this group has the characteristics of large single-layer thickness, multiple layers and large cumulative thickness. And the lithology is dense, which is a good cap layer. For example, the cumulative thickness of basalt in GG 2 well is 632 m, the cumulative thickness of basalt in GG 1 well is 1199 m, and the cumulative thickness of basalt in GG 1 well is 1189 m (Wu, 2012).

5 Discussion

5.1 The influence of source rock on accumulation

Proximity to the hydrocarbon generating center is conducive to oil migration and accumulation, which is the basic guarantee of reservoir formation (Zhao et al., 2019). The isocontour thickness maps of Es3 and Es4 in the Western Depression indicate the source rocks are thick (Figure 3). According to Section 4.1 of the results, the Es3 and Es4 source rocks have high abundance, good types, and their *Ro* are at the oil generation window, indicating that the source rocks have the potential to provide a large amount of crude oil and thus form large reservoirs. High hydrocarbon generation intensity is conducive to reservoir formation and the value of large reservoirs is generally greater than 350×10^4 t/km^2 (Hu et al., 2017; Feng et al., 2021; Song et al., 2021). The hydrocarbon generating intensity of Es4 is generally 5×10^6–10×10^6 t/km^2, and that of Es3 is generally greater than 5×10^6–15×10^6 t/km^2, which also indicates that the hydrocarbon generating potential of source rocks is good (Wu, 2012). It should be pointed out that proximity to the hydrocarbon generating depression is not a sufficient condition for hydrocarbon accumulation. The possibility of accumulation increases only in the dominant direction of oil and gas migration (Guo et al., 2017) and Gaosheng Oilfield meets this requirement (Figure 5).

5.2 Palaeouplift controls the direction of hydrocarbon migration

Palaeouplift area is the location of oil and gas accumulation, which is beneficial for the formation of various reservoir traps, such as structure, lithology-stratigraphy. The systematic analysis of

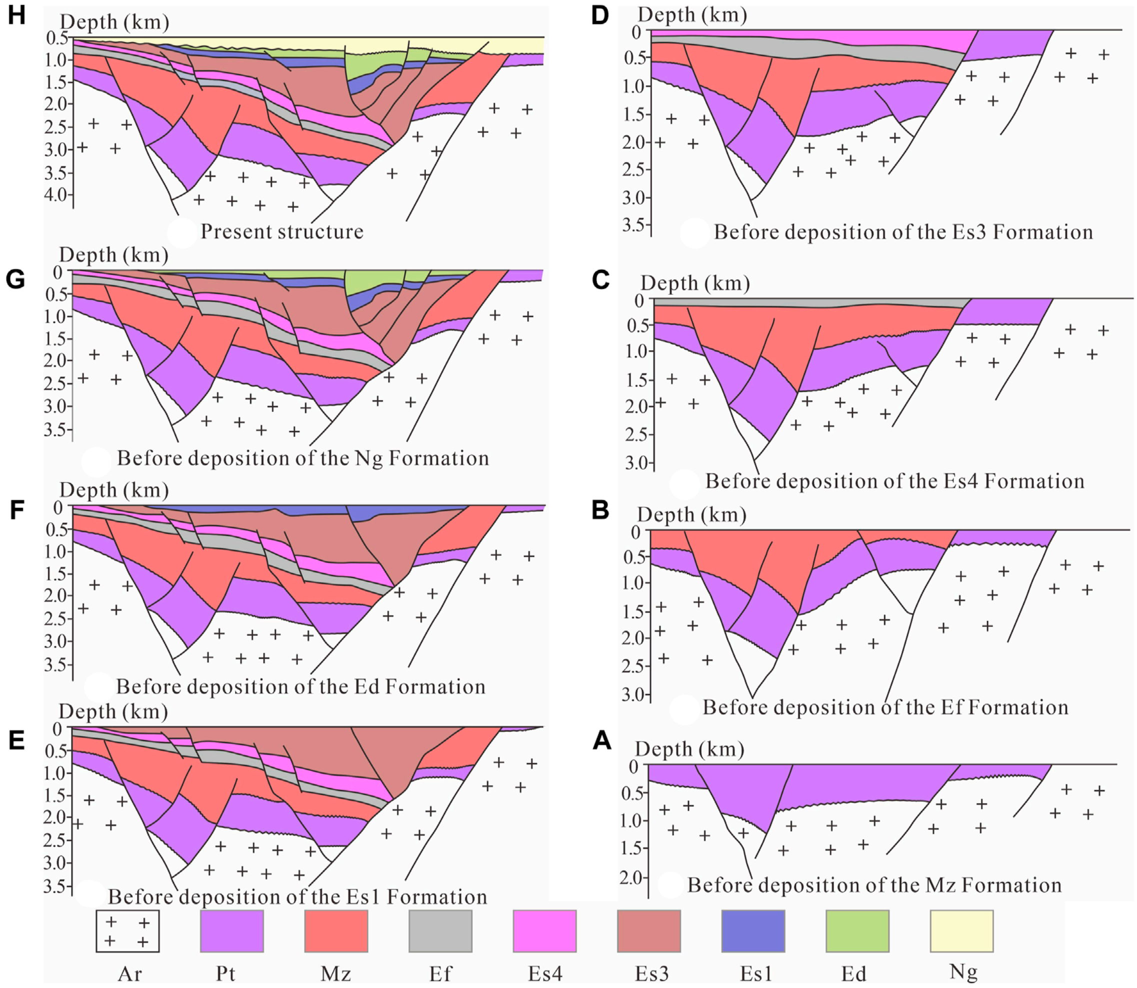

FIGURE 4
Structural evolution history of typical profiles in Gaosheng area of Liaohe Basin. (**A–H**) respectively indicate the sedimentary periods of Pt, Mz, Ef, Es4, Es3, Es1, Ed, and Ng strata.

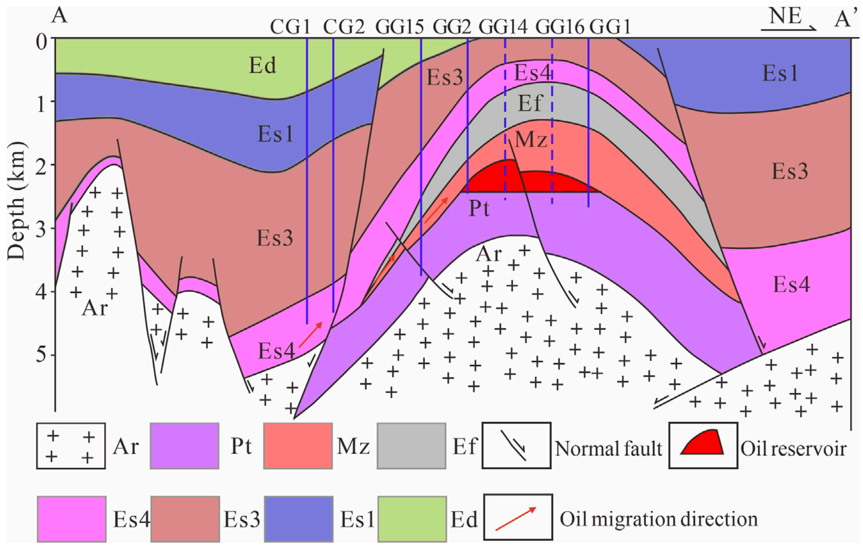

FIGURE 5
Accumulation model of Gaosheng area in Liaohe Basin.

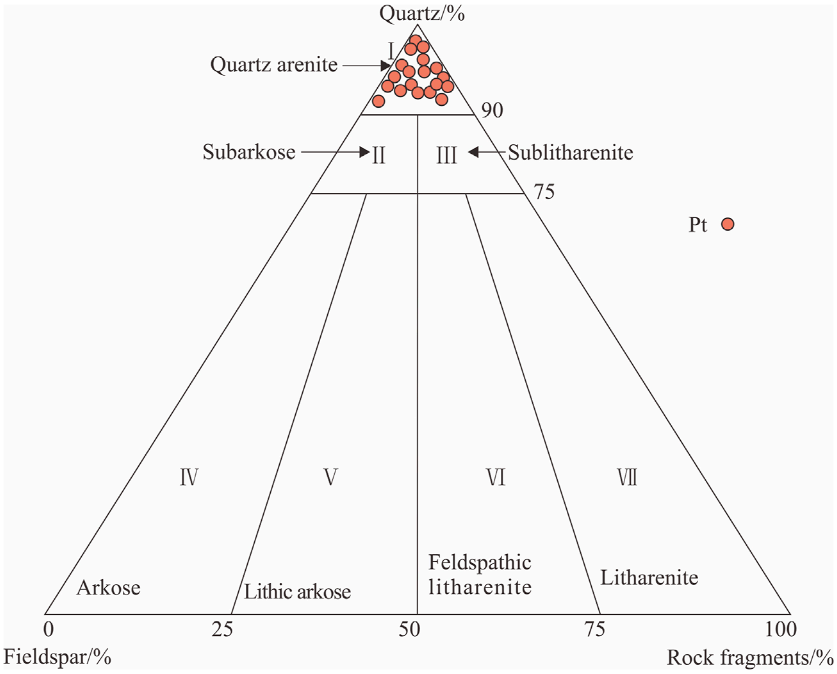

FIGURE 6
Compositional classification of Pt sandstone in Gaosheng area of Liaohe Basin.

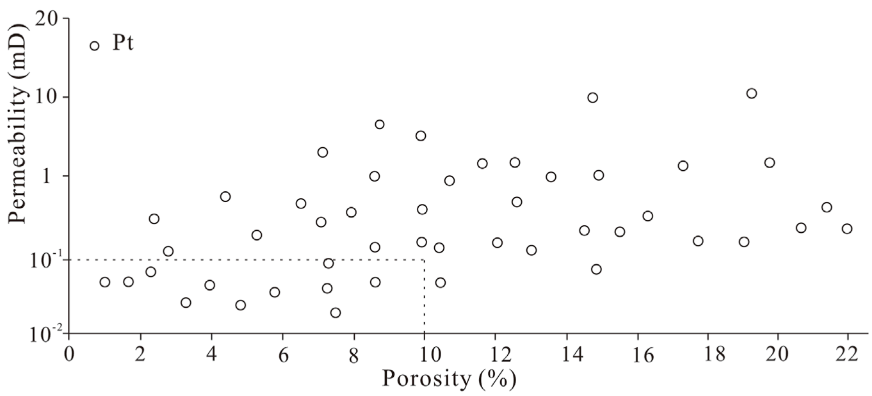

FIGURE 7
Pore permeability relationship of Pt reservoir in Gaosheng area of Liaohe Basin.

reservoir development characteristics in palaeouplift area is of great significance for oil and gas exploration. If the palaeouplift is in the dominant direction of oil and gas migration, it is conducive to accumulation (Jiang et al., 2023).

The archetype of Gaosheng buried-hill palaeouplift was formed at the end of Mesozoic, and it was basically formed in the middle of Eocene (late sedimentation of Es3 Member) (Wu, 2012).

Uplift is a positive tectonic unit (Jin, 2012). In the oil-gas accumulation unit, uplift is located in the low potential area of hydrocarbon fluid migration, which is a favorable place for oil-gas accumulation. At the same time, the traps formed during the formation and evolution of uplift are mainly anticlinal traps. The migration of oil and gas in such traps is more affected by buoyancy and tends to converge to the apex. Therefore, this type of reservoir is formed by the movement of oil from the deep to the shallow layer through faults and unconformities under the action of buoyancy. The oil migrated to the direction of regional uplift and accumulated in the suitable trap (Figure 5) (Liu et al., 2015).

5.3 The influence of reservoir on hydrocarbon accumulation

Reservoir physical property is an important factor affecting the formation of oil and gas reservoirs, especially for tight sandstone reservoirs. The development degree of reservoir

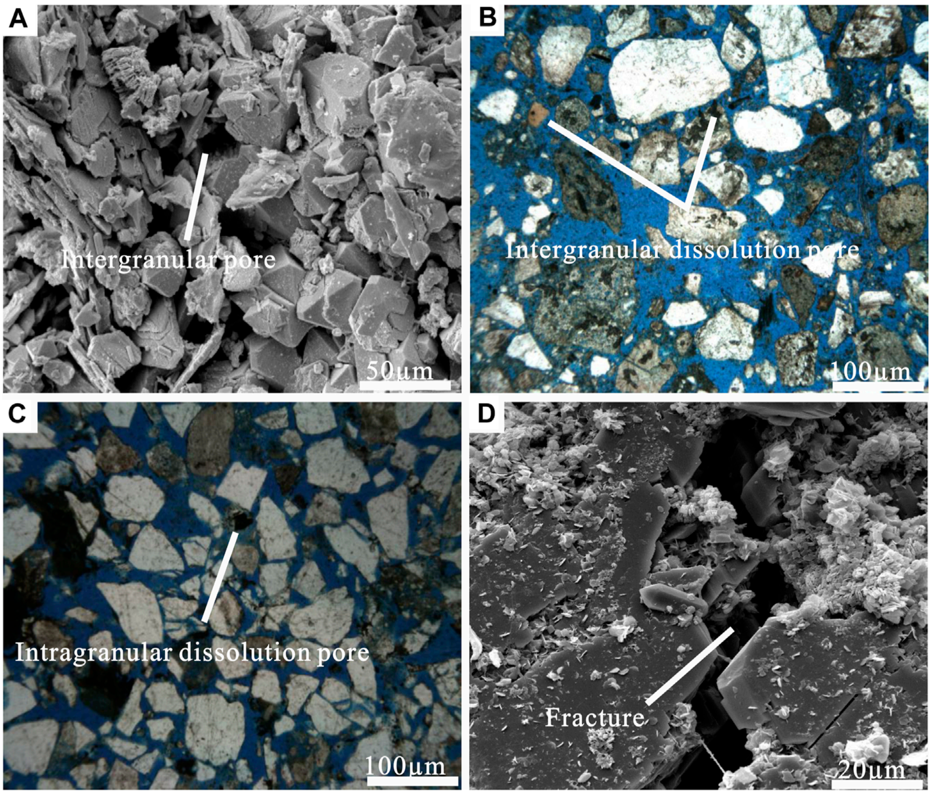

FIGURE 8
Pore structure characteristics of quartz sandstone in Gaosheng area. **(A)** Intergranular pore, SEM, GG2, 3049.2 m (Pt quartz sandstone); **(B)** Intergranular dissolution pore, cast thin section, GG14, 2941.88 m (Pt quartz sandstone); **(C)** Intragranular dissolution pore, cast thin section, GG15, 2869.26 m (Pt quartz sandstone); **(D)** Fracture, SEM, GG16, 2656.5 m (Pt quartz sandstone).

porosity, permeability and fracture have an influence on the formation of hydrocarbon reservoirs (Liu et al., 2017; Liu and Xiong, 2021).

The main reservoir in the study area is the sandstone of Pt formation. The pore types mainly include residual intergranular pores, intergranular dissolved pores, intra-granular dissolved pores and fractures (Figure 8), which provide sufficient space for the accumulation of crude oil.

Fracture can improve the permeability and the physical properties of the reservoir, and also seriously influence on the distribution of the reservoir (Jiang et al., 2015; Zhao et al., 2022)

From the analysis of failed wells in and around this area, it can be concluded that undeveloped reservoir or poor reservoir physical properties are the main factors leading to failure, accounting for the largest proportion. In the favorable sand body distribution area, good exploration results have been obtained in recent years. This is also evidenced by the high oil flow rates of wells GG14, SG169, and SG158. On the contrary, good result was not achieved due to poor reservoir conditions in the wells GG1 and GG15.

The distribution of sand body and the physical properties of reservoir restrict the enrichment and high production of oil and gas, so the comprehensive study on the distribution of reservoir and sand body should be strengthened.

5.4 Cap rock influence the preservation of reservoir

The formation of a large number of reservoirs requires an overlying layer as a good preservation condition (Guo et al., 2017; Liu et al., 2017; Jiang et al., 2022). The thickness of cap layer is positively correlated with oil and gas reserves (Liu et al., 2017). The basalt cap layer with large thickness is developed in the Gaosheng area, and the largest area can reach 2100 m. For example, the cumulative thickness of basalt in GG 2 is 1903 m, and the cumulative thickness of basalt in GG 1 is 1189 m. The cap layer has large thickness and stable distribution, so it is a regional cap layer to preserve the reservoir. In addition, the reservoir and overlying basalt constitute a good reservoir-cap combination.

5.5 Favorable zones and belts

On the basis of comprehensive analysis of main controlling factors of accumulation in Gaosheng area, favorable exploration

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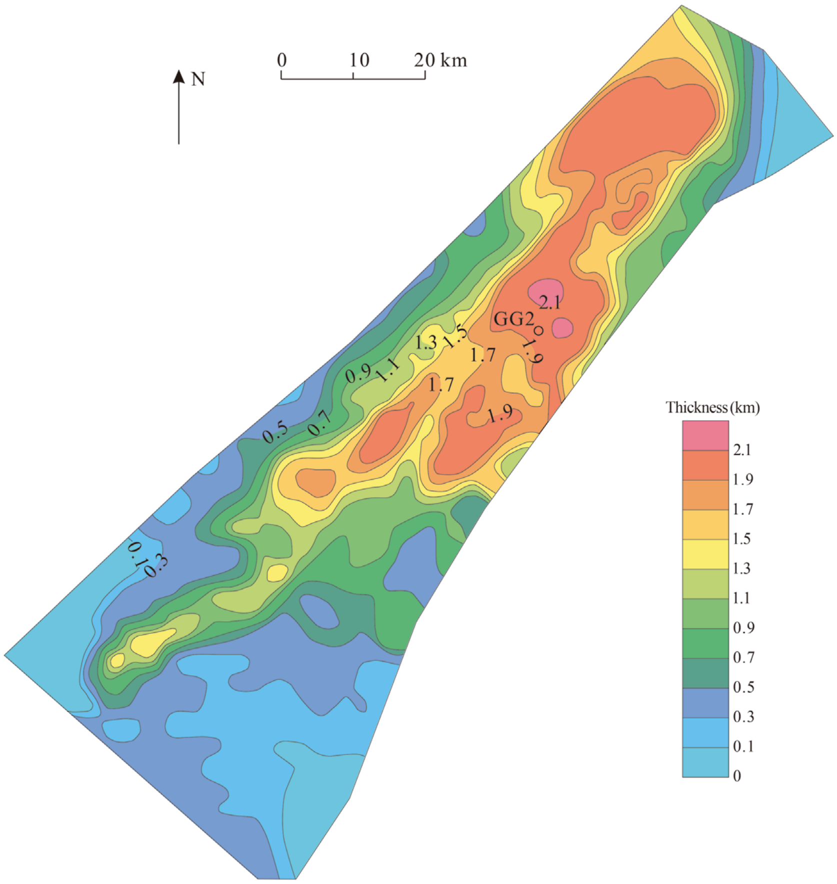

FIGURE 9
Ef+Mz basalt isopach map in the Western Depression of Liaohe Basin (The data are from Liaohe Oilfield).

zones are pointed out. According to the evaluation ideas and indicators, the reservoir forming factors such as structural conditions, source rock conditions, reservoir development, preservation conditions and trap development in Gaosheng area are evaluated. Combined with previous studies (You et al., 2006; Yu, 2016), it is considered that the formation conditions of the Gaosheng area are superior and the Proterozoic and Mesozoic oil-gas accumulation associations are the most promising in the Gaosheng area. Due to the small number of drilled wells, the low degree of exploration and the poor quality of seismic data, the development of fault system and the connection between reservoir and source rock are not fully evaluated. The Proterozoic and Mesozoic oil and gas accumulation associations in the middle-buried hill belt are the direction of oil and gas migration, and are potential exploration fields with great potential, which must be paid sufficient attention to.

In addition, the formation high pressure caused by hydrocarbon generation may also be one of the main controlling factors of oil and gas accumulation, but there is a lack of related research, so this should be one of the future research focuses.

6 Conclusion

Buried-hill reservoir is a reservoir different from conventional reservoirs. This kind of oil and gas reservoir needs the accumulation conditions of conventional reservoirs. In addition, the reservoir with abundant dissolved pores and fractures and the special migration channels formed by faults and unconformities are also critical. The source rock, reservoir and structure were analysed by geochemical method, reservoir experiment and 2D move software. Buried-hill reservoirs are mainly controlled by the following factors: 1) hydrocarbon generating depressions control the overall distribution of buried-hill reservoirs, 2) paleo-uplift and paleo-slope control the direction of oil and gas migration, 3) faults and unconformity constitute the system of oil and gas migration channels, and 4) reservoirs with dissolved holes and fractures control hydrocarbon enrichment.

The reservoir is close to the main hydrocarbon-generating depression. These areas have paleouplift background, deep faults and unconformities formed migration channels, and reservoirs with solution holes and fractures developed and suitable cap beds. The hydrocarbon accumulation association of Proterozoic and

Mesozoic in the middle buried-hill belt is the direction of hydrocarbon migration.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: None. Requests to access these datasets should be directed to QZ; 904836105@qq.com.

Author contributions

GZ: Conceptualization, Writing–original draft, Writing–review and editing. FJ: Writing–original draft. QZ: Project administration, Writing–review and editing. HP: Conceptualization, Writing–review and editing. XL: Software, Writing–original draft. DC: Funding acquisition, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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