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Characteristics of Oil and Gas Distribution and Controlling Factors of Hydrocarbon Accumulations in the Eocene Pinghu Formation of the Xihu Depression, East China Sea

(Ciri Pengagihan Minyak dan Gas serta Faktor Pengawalan Pengumpulan Hidrokarbon dalam Formasi Pinghu Eosen di Kelekukan Xihu, Laut China Timur)

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ABSTRACT

The Xihu Depression at the shelf of the East China Sea is a petroliferous basin with excellent exploration potential. The Eocene Pinghu Formation has become a recent oil and gas exploration target and as the critical hydrocarbon-bearing stratigraphic layer in the basin. However, studies specifically examining the characteristics of hydrocarbon distribution and the controlling factors of reservoirs in the Kongqueting area remain limited. The lack of in-depth hydrocarbon accumulation model research restricts subsequent exploration. In this paper, based on data from drilling, 3D seismic, well test, and geochemical analysis, we found that coal bed-related hydrocarbon source rocks were widely occurred in the Pinghu Formation in the Kongqueting area. The source rocks provide good hydrocarbon supply of near-source and distant-source to reservoir. The river sands were connected laterally and stacked vertically, forming a pattern characterized by 'lateral succession and vertical superposition' indicative of good quality of reservoir. During the deposition period of the Pinghu Formation, two large sets of regional cap rock (P3 and P7) were excellent sealing rock. The sand reservoir was interbedded with shale layers, forming a Mille-feuille type of reservoir-seal pair. Faults formed at the early stage of the formation of basin serve as conduits for hydrocarbon migration, governing both the spatial distribution of hydrocarbon-bearing strata and the types of hydrocarbon accumulations. These faults were instrumental in facilitating the formation of extensive oil and gas accumulations. This paper establishes a hydrocarbon accumulation model in the Kongqueting area, characterized as 'dual hydrocarbon supply from source, upper oil, and lower gas, good reservoir-seal pair, hydrocarbon migration through fault conduit'.

Keywords: Controlling factors on hydrocarbon accumulation; hydrocarbon accumulation model; Kongqueting area; oil and gas distribution; Xihu Depression

ABSTRAK

Kelekukan Xihu di pelantar Laut China Timur ialah satu lembangan berpetroleum dengan potensi penjelajahan yang sangat baik. Formasi Pinghu Eosen telah menjadi sasaran penjelajahan minyak dan gas yang terkini dan sebagai lapisan stratigrafi galas hidrokarbon kritikal dalam lembangan. Akan tetapi, kajian khusus meneliti ciri taburan hidrokarbon dan faktor kawalan reservoir di kawasan Kongqueting masih terhad. Kekurangan penyelidikan model pengumpulan hidrokarbon yang mendalam menghalang penjelajahan seterusnya. Dalam kertas ini, berdasarkan data daripada penggerudian, seismos 3D, ujian telaga dan analisis geokimia, kami mendapati bahawa batuan sumber hidrokarbon yang berkaitan dengan dasar batu arang adalah terwujud secara meluas dalam Formasi Pinghu di kawasan Kongqueting. Batuan sumber membekalkan bekalan hidrokarbon yang baik sebagai sumber dekat dan sumber jauh untuk reservoir. Pasir sungai yang bersambungan secara sisi dan disusun secara menegak, membentuk corak yang

dicirikan sebagai '*succession* sisi dan superposisi menegak' yang menunjukkan kualiti reservoir yang baik. Semasa pemendapan Formasi Pinghu, dua set batuan tukup serantau yang besar (P3 dan P7) merupakan batuan pengedap yang sangat baik. Reservoir pasir adalah saling lapisan dengan lapisan syal, membentuk satu pasangan reservoir-kedap jenis Mille-feuille. Sesar yang terbentuk pada awal pembentukan lembangan berfungsi sebagai saluran untuk penghijrahan hidrokarbon yang mengawal kedua-dua taburan ruang strata yang mengandungi hidrokarbon dan penumpukan hidrokarbon. Sesar ini memainkan peranan penting dalam memudahkan pembentukan penumpukan minyak dan gas yang meluas. Kertas kerja ini mewujudkan model penumpukan hidrokarbon di kawasan Kongqueting, dicirikan sebagai 'bekalan hidrokarbon dwi daripada sumber, minyak atas, dan gas bawah, pasangan reservoir-kedap yang baik, penghijrahan hidrokarbon melalui saluran sesar'.

Kata kunci: Faktor kawalan pengumpulan hidrokarbon; kawasan Kongqueting; lekukan Xihu; model penumpukan hidrokarbon; pengagihan minyak dan gas

Introduction

The shelf basin of the East China Sea is one of the largest Mesozoic and Cenozoic hydrocarbon-bearing sedimentary basins in the offshore area of China (Figure 1(A)). The abundant hydrocarbon reserves, complex petroleum geology, and important strategic location attract many domestic and abroad petroleum geologists. The Xihu Depression is the most significant hydrocarbon-rich depression and the most important oil and gas-producing area in the East China Sea shelf basin (Figure 1(B), 1(C)) (He et al. 2008; Ye, Gu & Jia 2008; Zhang 2013). During almost 50 years of exploration, studies on the Xihu Depression have focused on hydrocarbon source rock characteristics (Abbas et al. 2018; Jiang, Diao & Zeng 2020), tectonic evolution characteristics (Hu et al. 2018; Zhang et al. 2016), reservoir characteristics (Qian et al. 2020; Sun et al. 2019), sedimentary system (Liu et al. 2023; Yu et al. 2017), pressure anomalies genesis (Li et al. 2021), trap type (Zhang et al. 2022), fault characteristics (Sun et al. 2022), and hydrodynamics. However, only a few discussions are on the main controlling factors of the hydrocarbon accumulations in the structure belt. More in-depth research is needed. By considering the controlling factors of the hydrocarbon accumulations, we could advance the understanding of the comprehensive mechanisms driving hydrocarbon accumulation. The research will offer a valuable geological reference for further exploration endeavors in the Kongqueting area and across other blocks within the Xihu Depression, potentially unlocking new prospects and optimizing resource exploitation.

Previous scholars did significant studies on the hydrocarbon accumulation model of the Xihu Depression. In these studies, accumulation models such as tower structure (Yu et al. 2022), overpressure control (Zhang & Jiang 2013), and evaporative fractionation are proposed, which have effectively guided the exploration of the Xihu Depression from different levels. However, most of the research emphasized a single controlling factor without consideration for the spatial-temporal coupling relationship of the main controlling factors on hydrocarbon accumulation. The lack of insightful study on the hydrocarbon accumulation model hinders the progress of hydrocarbon exploration. In this paper, the Eocene Pinghu Formation in the Pinghu Slope area of the Xihu Depression is selected as the research topic. Using seismic data, logging data, well-test and production test data, and pre-acquired geochemical analysis, we explored the formation mechanism of hydrocarbon accumulation and established its model in the Pinghu Slope area of the Pinghu district. Our investigation commences with an examination of reservoir distribution patterns, the key geological elements contributing to reservoir formation, and the controlling factors influencing reservoir development. The study will provide a geological reference for further exploration in the Kongqueting area and guide the hydrocarbon exploration of the Pinghu Formation in other blocks of the Xihu Depression.

Geological Setting

The East China Sea shelf basin is a Mesozoic and Cenozoic basin that developed above the Precambrian basement along the continental margin (Figure 1(A), 1(D))(Cui et al. 2021). It is located at the intersection of Asian and the western Pacific subduction zone, mainly impacted by the subduction of the Philippine plate to the Eurasian plate during the Eocene-Oligocene period (Zhang et al. 2023; Zhu et al. 2021). The basin is oriented

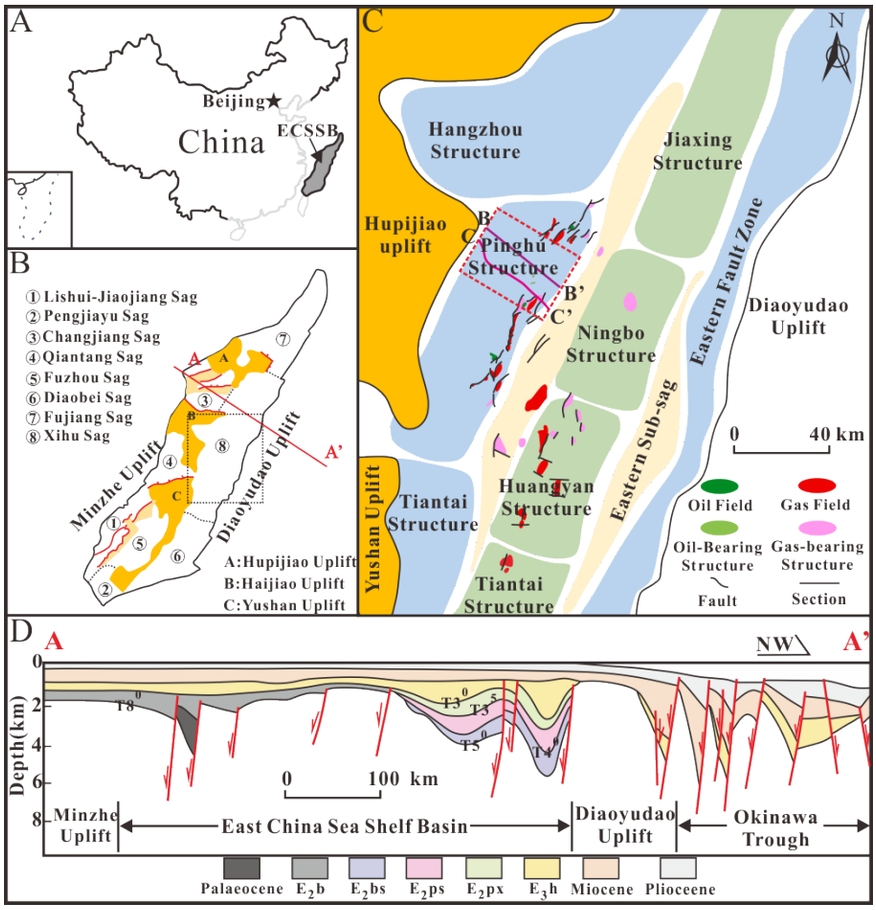

FIGURE 1. (A) Location map of the East China Sea shelf basin; (B) Sub-tectonic unit segmentation map of the East China Sea shelf basin (according to Zhu et al. 2019); (C) Structural unit segmentation map of West Lake sag; (D) Cross-section of the East China Sea shelf basin (Modified from Wang et al. 2018)

in the NNE (north-northeast) direction with a gross length of 1400 km, and width of 90-300 km, and a total area of up to 24×10^4 km^2 (Li et al. 2018; Zhu et al. 2022). During the Paleocene, the post-arc rifting process generated topographic highs and lows in the East China Sea shelf basin (Shao et al. 2019). The Xihu Depression is the most extensive topographic low in the area, which connects to the Haijiao Uplift and the Yushan Uplift in the west and the outer edge of the shelf in the east (Figure 1(B)). The depression is narrowly distributed and generally NNE-oriented, with a total area of about 4.5×10^4 km^2. There are five divided tectonic units from west to east, including the western slope zone, the western sub-depression, the central inversion zone, the eastern sub-depression, and the eastern fault zone. The western slope belt can be divided into three secondary tectonic units (Figure 1(C)): Hangzhou slope belt, Pinghu slope belt, and Tiantai slope belt from north to south. The stratigraphy of the Pinghu Slope Belt (Figure 1(D) and Figure 2) includes the Eocene Baoshi Formation (E2bs) and Pinghu Formation (E2p), Oligocene Huagang Formation (E3h), Miocene Longjing Formation (N1lj), Yuquan Formation (N1yq), Liulang Formation (N1ll), Pliocene Santan Formation (N2s) and Pleistocene Donghai Formation (Qd). This study focuses on the Pinghu Formation within the northern segment of the Pinghu Slope Belt, situated in the Kongqueting area.

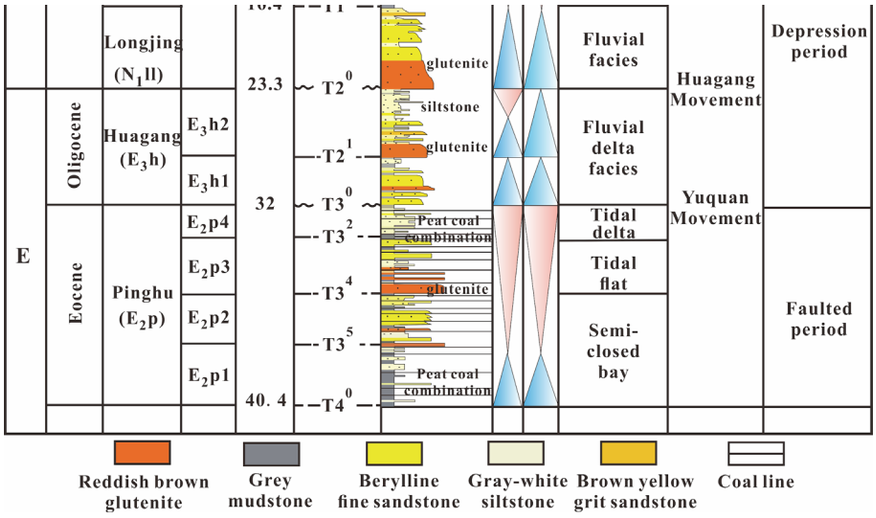

FIGURE 2. Comprehensive stratigraphic column of the Pinghu slope belt in the Xihu Depression. Sys.-System; Gp.-Formation; Fm.-Formation; Mbr.-Member

From bottom to top, the Pinghu Formation comprises stratigraphic units distributed as follows: two members in its lower section (the Lower Pinghu Member, comprising P9 and P10), two members in the middle and lower subsections of the formation (Lower Pinghu Member, P7-P8), two members in the middle and upper subsections (Upper Pinghu Member, P5-P6), and finally, four members in the upper part of the formation (Upper Pinghu Member, P1 through P4).

The depositional environment in the Kongqueting area evolved from the early littoral and neritic faces, through semi-enclosed bays, deltas, rivers, and marine-terrestrial transitions, to the present tidally influenced delta-barrier island depositional system (Figure 2) (Cai, Qin & Liu 2019; Liu et al. 2023). The Pinghu Formation develops three source rock types: marine-terrestrial transitional coal beds, carbonaceous mudstone, and mudstone. Coal and carbonaceous mudstone developed in the tidal flat-barrier island depositional environment (Cai, Qin & Liu 2019), with a broad distribution and remarkable thickness. The source rocks have reached the mature evolutionary stage and are the primary hydrocarbon source rock in the slope area. Tidal deltas developed in the middle and upper part of the Pinghu Formation, while tidal flat deposits dominated in the middle and lower part of the Pinghu Formation. Tidal channels, sand flats, and other sand bodies developed in the tidal flats.

Materials and Methods

In this paper, our study is based on the 3D seismic data and drilling data from 12 wells, including logging data, geochemical data, flow test and production test data, and core photos of the Pinghu Formation in the study area, provided by China National Offshore Oil Corporation Shanghai Branch. The 3D seismic is a powerful tool that enables us to visualize and interpret the subsurface geology in three dimensions. This high-resolution imagery provides critical insights into the structural framework of the reservoirs, fault systems, and stratigraphic architectures, which are instrumental in guiding exploration efforts and deciphering hydrocarbon entrapment mechanisms. Well logs offer a detailed profile of physical properties such as resistivity, porosity, and acoustic velocity of the drilled formations. These parameters are crucial for characterizing reservoir quality, identifying hydrocarbon-bearing zones, and understanding the vertical and lateral continuity of reservoir rocks.

Analysis of hydrocarbon fluids and source rocks through geochemistry provides vital clues about the maturity, type, and origin of the hydrocarbons. Stable isotopes (e.g., carbon and hydrogen isotopes in methane) help trace the migration pathways and differentiate between biogenic and thermogenic gas, while biomarker compounds give insights into the thermal history

and depositional environments of the source rocks. Flow Test and Production Test Datas are conducted to evaluate the productivity and deliverability of the reservoir. By measuring the rate and pressure responses during controlled production or injection, we can assess reservoir permeability, potential flow rates, and estimate recoverable reserves. Rock cores, when available, provide the most direct sample of the subsurface geology. High-resolution images and descriptions of cores from the Pinghu Formation reveal sedimentary structures, grain size, mineralogy, and the presence of hydrocarbons, offering unparalleled ground-truthing for seismic interpretations and log analyses. Based on these data, we analyzed oil and gas distribution characteristics in the Kongqueting area of the Xihu Depression, summarized four factors controlling hydrocarbon accumulations, and established a hydrocarbon accumulation model for the Kongqueting area.

Results and Discussion

Characteristics of oil and gas distribution in the Kongqueting area

The dominant types of hydrocarbon accumulation in the Kongqueting area include condensate, oil, and wet gas reservoirs, which account for 65%, 17.5%, and 17.5% of the proven reserves, respectively (Shan et al. 2015). Stratigraphically, the sandstone reservoirs of the Eocene Pinghu and Oligocene Huagang Formations provide the main storage spaces for oil and gas accumulation (Figure 3(A)). Horizontally, there are significant variations in the hydrocarbon distribution characteristics of the different layers in the same area. Huagang Formation is principally an oil reservoir, and the Pinghu Formation is mainly a condensate gas reservoir (Figure 3(B)). Most of the proven reserves are concentrated in the low-porosity and low-permeability sandstone reservoirs of the Eocene Pinghu Formation with a burial depth of 3800 - 4600 m. In addition, several oil and gas-bearing layers are discovered in the sandstone reservoirs of the Pinghu Formation below 4600 m, classified as tight gas reservoirs (Figure 3(C)). In general, the hydrocarbon trap of the Kongqueting area is a structural-stratigraphic combination trap with hydrocarbon discoveries from multiple stratigraphic layers. Following the increasing amounts of oil and gas-bearing layers from the structure high to low (from west to east in the slope area of the Kongqueting area) (Figure 4(A), 4(B)), the gas column height grows (Figure 4(C)). The distribution of the explored hydrocarbon accumulation becomes progressively shallower from the high-structured areas to the low-structured belt within the slope region. The leading oil and gas-bearing layers are the lower part of the Pinghu Formation and the Baoshi Formation in the structure high belt, the middle and upper part of the Pinghu Formation in the central belt, the upper part of the Pinghu Formation and the lower part of the Huagang Formation in the low belt, respectively (Figure 4(B)).

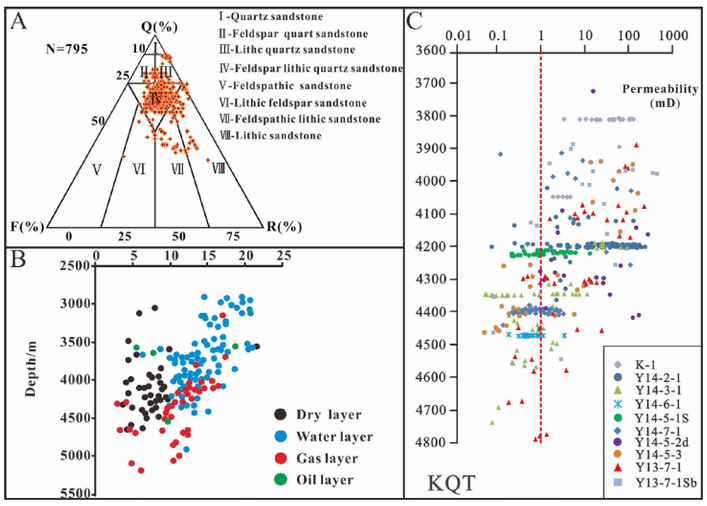

FIGURE 3. Analysis of physical properties and hydrocarbon content of the sandstone reservoirs in the Kongqueting area (A) Triangle map of sandstone types of Pinghu Formation in Kongqueting area; (B) Stratigraphic variation in fluid properties of the hydrocarbon accumulations in Kongqueting area (according to Zhao et al. 2018); (C) Permeability characteristics of Kongqueting area

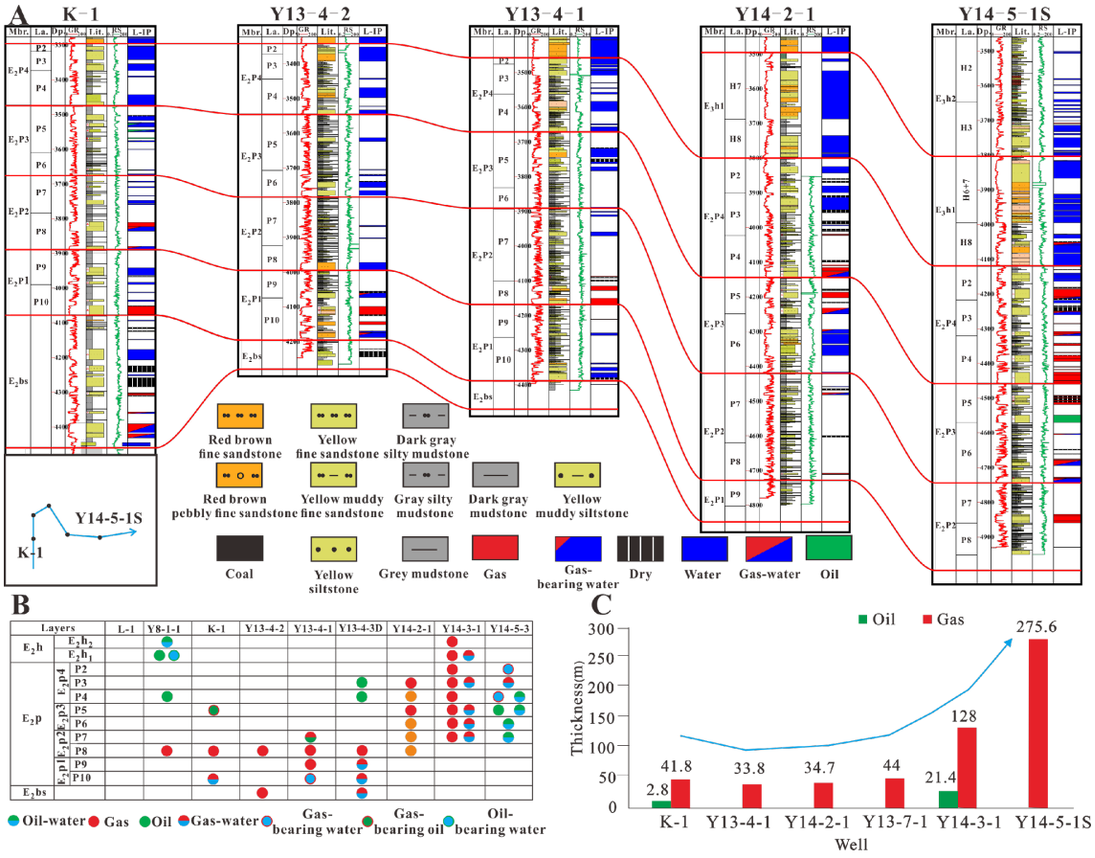

FIGURE 4. Schematic diagram of the hydrocarbon accumulations in the Kongqueting Area (A) Stratigraphic cross-section of the strata with hydrocarbon accumulations in Kongqueting area; (B) Oil and gas distribution characteristics map in Kongqueting area; (C) Oil and gas layer thickness map in Kongqueting area. Mbr.-Member;La.-Layer;Dp.-Depth;Lit.-Lithological;L-IP-Log interpretation

Meanwhile, the degree of oil and gas enrichment is observed to steadily increase from the high belt towards the low belt (Figure 4(B)). The low belt is dominated by gas discovery, whereas oil and gas are found in the central belt. Stratigraphically, oil and gas are mainly enriched in the Pinghu Formation, followed by the Baoshi and Huagang Formations (Figure 4(B)). The oil and gas reservoirs demonstrate the characteristics of upper oil and lower gas. In the central-high structure belt, hydrocarbons mainly developed below the P7 layer in the middle and lower part of the Pinghu Formation. In contrast, oil and gas in the central-low structure belt mainly concentrated in the upper part of the Pinghu and the Huagang Formations.

CONTROLLING FACTORS OF THE HYDROCARBON ACCUMULATION IN THE KONGQUETING AREA

Regarding the distribution characteristics of the discovered oil and gas in the Kongqueting area, the hydrocarbon distribution exhibits a characteristic of multi-layer system. The scale of the lower overpressure and low permeability tight gas reservoir in the upper oil-lower gas system is much larger than that of the upper conventional oil and gas reservoir (Alias 2022). Based on an array of data including geochemical, 3D seismic well logs, drilling cores, and additional data, we analyzed the distribution characteristics of hydrocarbon source rocks in the study area. This investigation encompassed the assessment of storage properties associated with river

sand bodies, deep faults, and other factors. To conclude, the controlling factors of hydrocarbon accumulations in the Kongqueting area are 'multi-source hydrocarbon supply, developed river sand bodies, good reservoir-seal pair, multistage faults that control hydrocarbon migration and enrichment'.

Abundant hydrocarbon supply from multi-source

Hydrocarbon source rock is the basis for hydrocarbon accumulation in a sedimentary basin. The hydrocarbon generation and supply capacity are the key factors determining the formation of accumulation and hydrocarbon filling degree in the sand bodies (Magoon 1995). The hydrocarbon source rocks in the Kongqueting area were mainly situated in the Pinghu Formation, which was deposited in a continental shelf and marsh environment in a semi-enclosed bay context. Coal-related hydrocarbon source rocks developed, comprising lithologies such as coal, carbonaceous mudstone, and mudstone. From the plot of S1+S2-TOC (Figure 5(A)), the variations of the organic matter abundance in the study area are relatively similar, high in the coal and carbonaceous mudstone and poor-good in the dark mudstone. The distribution of hydrocarbon source rocks is relatively uniform. Pinghu Formation's mudstone has a higher abundance of organic matter and generally belongs to the high-quality hydrocarbon source rocks (Figure 5(B)). To study the organic matter type, the hydrogen index (HI)-maximum pyrolysis peak temperature (Tmax) map is commonly plotted based on the available analytical and laboratory data of hydrocarbon source rocks of the Pinghu Formation. The hydrocarbon source rocks of most formations are type III kerogen, except that some Pinghu Formation samples are type II1 and II2 kerogen (Figure 5(C)). The thermal maturity of hydrocarbon source rocks in the Huagang Formation is generally characterized as low. Notably, there is a gradual increase in maturity observed from the Oligocene Huagang Formation towards the younger Eocene Pinghu Formation (Figure 5(D)). With the exception of the shallow upper section of the Pinghu Member, which predominantly resides in a low maturity stage, the majority of hydrocarbon source rocks within the middle Pinghu Member and subsequent underlying strata attain a moderate maturity level. They are treated as effective source rocks with confident in situ hydrocarbon generation and supply capacity (Figure 5(D)). In addition, the eastern part of the Kongqueting area is adjacent to the western sub-lying hydrocarbon-rich sub-depression, which can also provide some hydrocarbons.

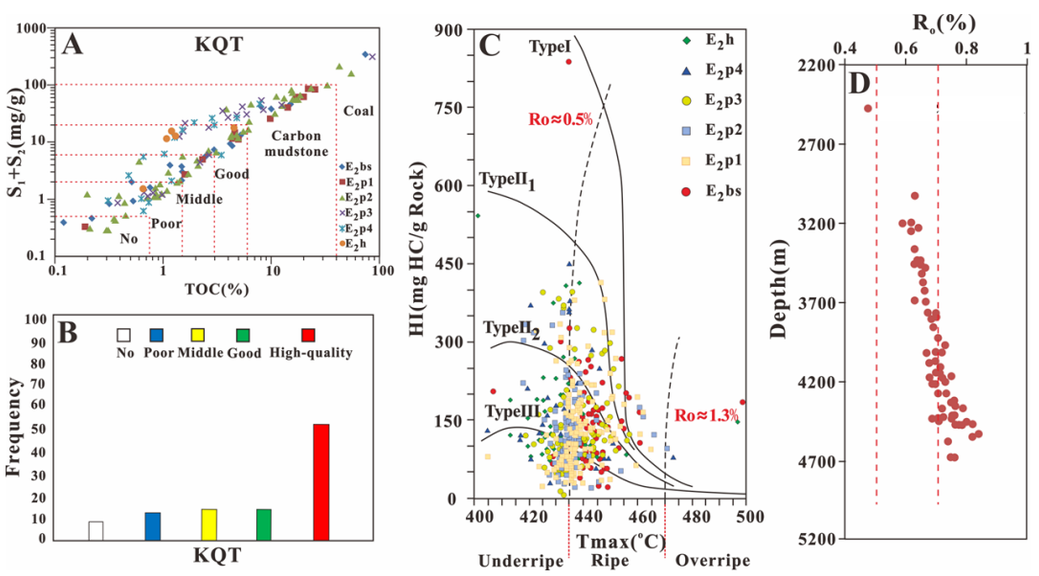

FIGURE 5. Characteristic map of the source rocks of Pinghu Formation in Kongqueting area (A) Variation maps of the organic matter abundance of the different stratigraphic members in the study area; (B) Integrated evaluation map of the organic matter in the study area; (C) Map of source rock types in the study area; (D) Analysis map of organic matter maturity in the study area

According to the limited analysis of geochemical data, the hydrocarbon source rocks in the Kongqueting area are mainly distributed in the lower and middle members of the Pinghu Formation. Based on the distance from the source, they are divided into near source type (local hydrocarbon source rocks) and distant source type (low-belt West Sub-parallel hydrocarbon source rocks). The area with proximity to the source rock is extensive and predominantly contributes oil, whereas the distal source distribution zone is more limited and mainly supplies gas. In the process of oil and gas migration, some indicators of oil and gas will change regularly along the migration pathway due to the Geoehromatograph (Seifert & Moldowan 1981). In addition, some indicators reflecting the maturity of oil and gas can also be used to indicate the direction of oil and gas migration. The maturity of oil and gas generated in the early stage is lower than in the late stage, so the maturity changes from higher to lower following the migration direction. From the geochemical data of natural gas in this area, the carbon isotope value (δ13C1) of natural gas methane has a trend from large to small from well Y27-5-2 (-32.1‰) → well Y14-3-1 (-37.7‰) → well Y14-2-1 (-37.8‰). The natural gas δ13C1 value generally becomes more prominent with increasing maturity. The variation of natural gas δ13C1 value in this unit may reflect the migration of natural gas from well Y27-5-2 to well Y14-2-1, which indicates the gas is relocated from the deep depression zone to the higher part. The drying factor of natural gas (C1/(C1+C5)) is also an indicator of maturity. The drying coefficient of natural gas in this unit is from well Y27-5-2 (0.95) to well Y14-3-1 (0.90) to well Y14-2-1 (0.87) to well Y13-4-2 (0.86), where the trend is from large to small. This trend also indicates that the gas is transported from the deep zone to the higher unit.

Superior river sandstone at deep strata

Past exploration has demonstrated that reservoir development is closely related to the sedimentary facies (Radzir et al. 2023). Decent reservoirs are favorable for the formation of hydrocarbon accumulations (Yin et al. 2021). Heterogenous conventional reservoirs dominate the Pinghu Formation in the Kongqueting area. The sandstone porosity is mostly between 10-20%, with an average of 13.2%. The permeability is mainly between 1×103 μm^2-100×103 μm^2, with an average of 30×103 μm^2. In addition, conventional low-permeability and low-permeability formations account for one-third, and non-reservoirs or dense formations have few occurrences (Xie et al. 2021). Developing secondary porosity helps maintain good physical properties in large deep sandstone reservoirs, making them the primary exploration targets (Hao et al. 2002). The depositional period of the Pinghu Formation is characterized by the deposition of a multi-phase deltaic complex with a bi-directional sediment supply affected by rivers and tides (Liu et al. 2023; Zhang et al. 2012). For example, the depositional period of the Pinghu Formation in the Y14-2-1 well area mainly consists of tidally influenced deltaic-tidal flat deposits. Based on the core photos obtained, the P5 layer in the upper part of the Pingzhong member is a tidally influenced and submerged delta front channel deposit, displaying an overall anticyclonic feature. The lower part of the P5 layer is a tidal channel deposit in the delta front environment. The upper part of the P5 layer is gravelly sandstone and sand conglomerate, which has a weak tidal influence. The delta plain distributary channel and the delta front submerged distributary channel microfacies developed in the upper member of the Pinghu Formation. The entire Pinghu Formation is characterized by medium and fine sandstones interbedded with mudstones. The cumulative thickness of sandstone is 488.3 m, accounting for 51.2% of the member, and the cumulative thickness of mudstone is 412.2 m, accounting for 43.1% of the total drilled thickness of the Pinghu Formation. The mudstone of this layer is dense and can act as an effective regional seal.

The sedimentary facies in different strata were obtained (Figure 6) by integrated analysis of drilling cores, logging curves, seismic profiles, and seismic attributes. During the deposition period of the lower Pinghu member (Figure 6(A)), there are multiple sediment sources. The overall water body is shallow, and faults control sand deposition. Deltaic deposition influenced by tides developed, with sediments advancing toward the depression center from the southwest and west directions, respectively. As a result, multiple deltas formed in the low structure zone near the well Y14-3-1. Multiple composite sand bars of different sizes can be observed parallel to the shoreline with developed tidal channels. In the lower part of the Pinghu Formation (Figure 6(B)), the western material decreased, and the entire water body started to rise rapidly. The tidal channel deposition brings the primary sediment source. The size of deltas gradually decreases in the upper part of the Pinghu Formation (Figure 6(C)). The process of deltaic accretion was notably evident, resulting in the formation of smaller, tidally-influenced delta front facies in the upper portion of the Pinghu Formation (Figure 6(D)). The

overall environment tends to be stable, and a large-scale delta plain subfacies start to develop. The sand bodies are horizontally contiguous and vertically superimposed. The developed river sand bodies can become large-scale and high-quality reservoirs. The reservoirs and hydrocarbon source rocks of the Pinghu Formation are stacked with each other. Therefore, once oil and gas are generated, they can enter the adjacent reservoirs and form efficient autogenous self-storage reservoirs.

Decent sealing capacity in the Mille-feuille type of the reservoir-seal pair Cap rock is one of the most significant geological elements of the petroleum system, because it

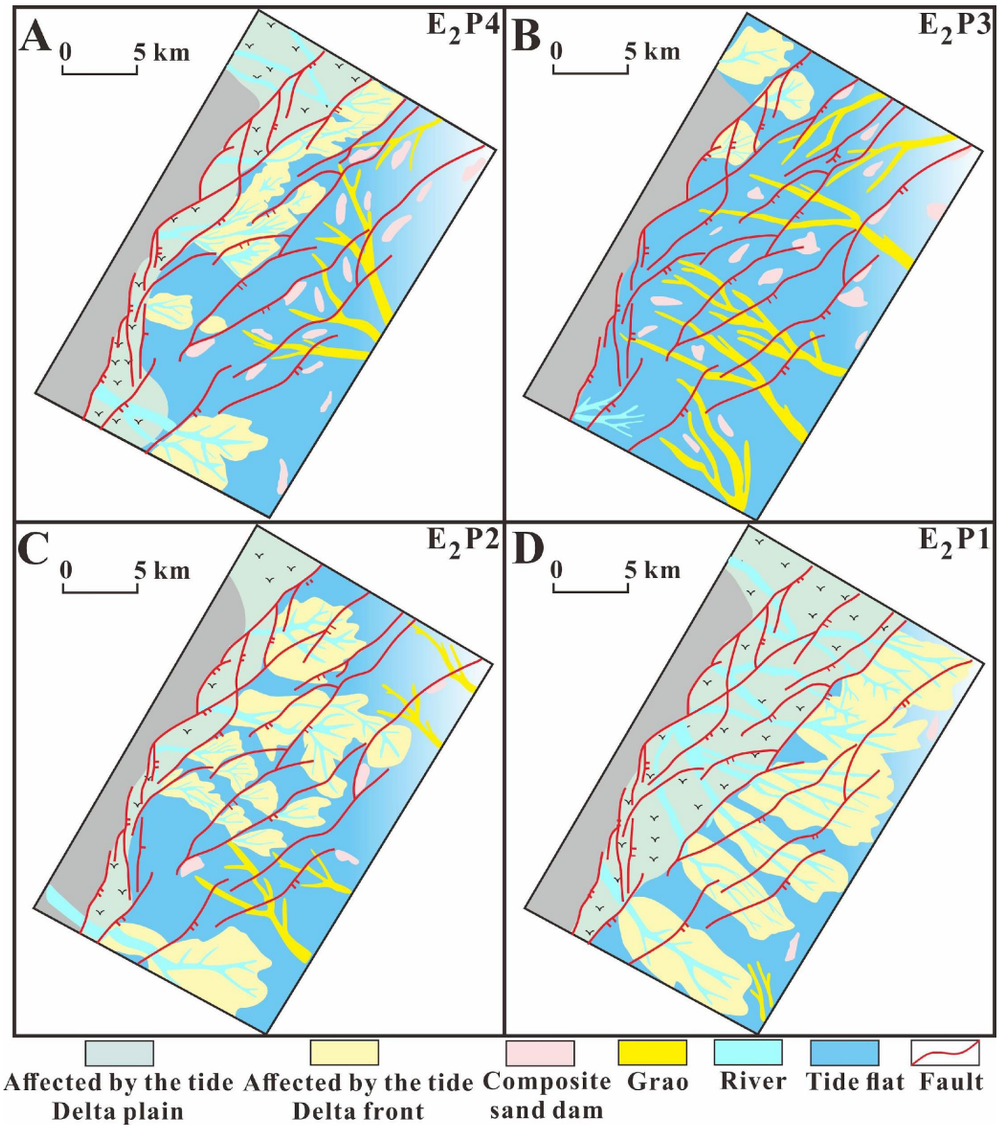

FIGURE 6. Facies map of the different members of the Pinghu Formation Facies map of the lower member; (B) facies map of the middle to lower member; (C) facies map of the middle to upper member; (D) facies map of the upper member

can prevent the destruction and leakage of hydrocarbons in the trap. For the Kongqueting area, mudstone cap rock is the critical factor controlling hydrocarbon distribution. Zhang et al. (2012) suggested that the mudstone cap rock of the Pinghu Formation formed in a semi-enclosed bay, mud flat, and pre-delta depositional environment. The Eocene Pinghu Formation experienced two large-scale marine floods during deposition. The first was during the early deposition of the Pinghu Formation (P7 in the middle member of the Pinghu Formation), forming a set of dark mudstones with a thin siltstone layer. The thickness of the cap rock is about 180 m and is widely distributed, making it an excellent deep regional seal. The second one appeared in the late deposition of the Pinghu Formation (P3 in the upper member of Pinghu Formation), with about 50 m thick mudstone intercalated with flat tidal mud (Figure 7(A)). The sandstone units within the Huagang Formation exhibit more prominent development, featured by a greater single-layer thickness and higher stacking frequency. Therefore, they have better physical properties than those of the Pinghu Formation. However, due to the localized distribution of cap rock in the Huagang Formation, it fails to seal large-scale oil and gas accumulations. The sandstone reservoirs of the Pinghu Formation are interbedded with mudstone, with high mud content - the overall lithological combination pattern of 'mud enclosing sand', which has better seal properties. The sandstone and mudstone are frequently interbedded, forming a 'thousand-layer cake' type reservoir and seal pair (Zhao et al. 2018). The oil and gas generated from the mudstone of the Pinghu Formation are transported to the adjacent sandstone layer for accumulation, which is conducive to the formation of autogenous self-storage reservoirs.

Hydrocarbon migration and distribution controlled by multistage faulting

The Xihu Depression has experienced multiperiod tectonic events, such as Keelung, Yuquan, Huagang, and Longjing movements, forming numerous normal faults. The faults are interconnected with sand bodies and unconformities, constituting a hydrocarbon migration system and controlling hydrocarbon-bearing strata distribution (Mei et al. 2020). Based on systematic interpretation of seismic profiles, we identified that the faults in the study area are mainly planar faults and listric faults. Ramp-flat faults, however, are conspicuously underdeveloped, suggesting that the faults in this region are in an early evolutionary stage. In addition, we have discerned five types of fault combinations: Y-shaped, herringbone, nested V-shaped, inclined en echelon, and listric. The listric or micro-listric fault combination style commonly has long-term activity.

In the northern part of the Kongqueting area, synthetic faults, graben, and antithetic faults are predominantly observed. The middle of the strata is thicker due to a composite graben. In the southern part of the Kongqueting area, synthetic faults dominate. Secondary antithetic listric faults developed in the lower part of the slope. The thickness of the Pinghu Formation varies significantly, with thicker deposits in the west and thinner ones in the east. Despite both regions falling within a synthetic stepped fault zone, they exhibit distinguishing features. The northern area displays a pattern of strong initial tilting followed by less pronounced later tilting, as shown by seismic lines, whereas the southern region is characterized by linear displacement patterns. The syn-sedimentary activity develops syngenetic faults from the Paleocene to the end of the Miocene. These faults break up to the top of the Pinghu Formation and down to the basement and control the Paleocene and Eocene deposition. The fault throw is significant at the bottom and small at the top, mostly between 50-300 m. The early faults have become great conduits for oil and gas migration. Many hydrocarbon source faults have been developed to build a three-dimensional migration pattern from the hydrocarbon source rock to the trap, which controls the oil and gas-enriched layers and types of accumulations. Faults also control the stratigraphic distribution of hydrocarbon accumulations. When faults reach the hydrocarbon source rock, the degree of trap filling is higher, and hydrocarbons are gathered into reservoirs. When the faults do not impact the source rock, hydrocarbons cannot be transported upward during the peak hydrocarbon generation and discharge period due to the lack of migration pathways. As a result, the degree of trap filling is low. The late fault plays a role in transforming and destroying the oil and gas accumulations formed in the early stage, causing oil and gas to escape. Therefore, the filling degree of oil and gas is low, and the upper shallow oil and gas are only enriched at the structure high, leading to more dispersal than the hydrocarbon supply.

HYDROCARBON ACCUMULATION MODE OF THE KONGQUETING AREA

The Kongqueting area features a synthetic stepping fault zone. It is supplied with hydrocarbons from near

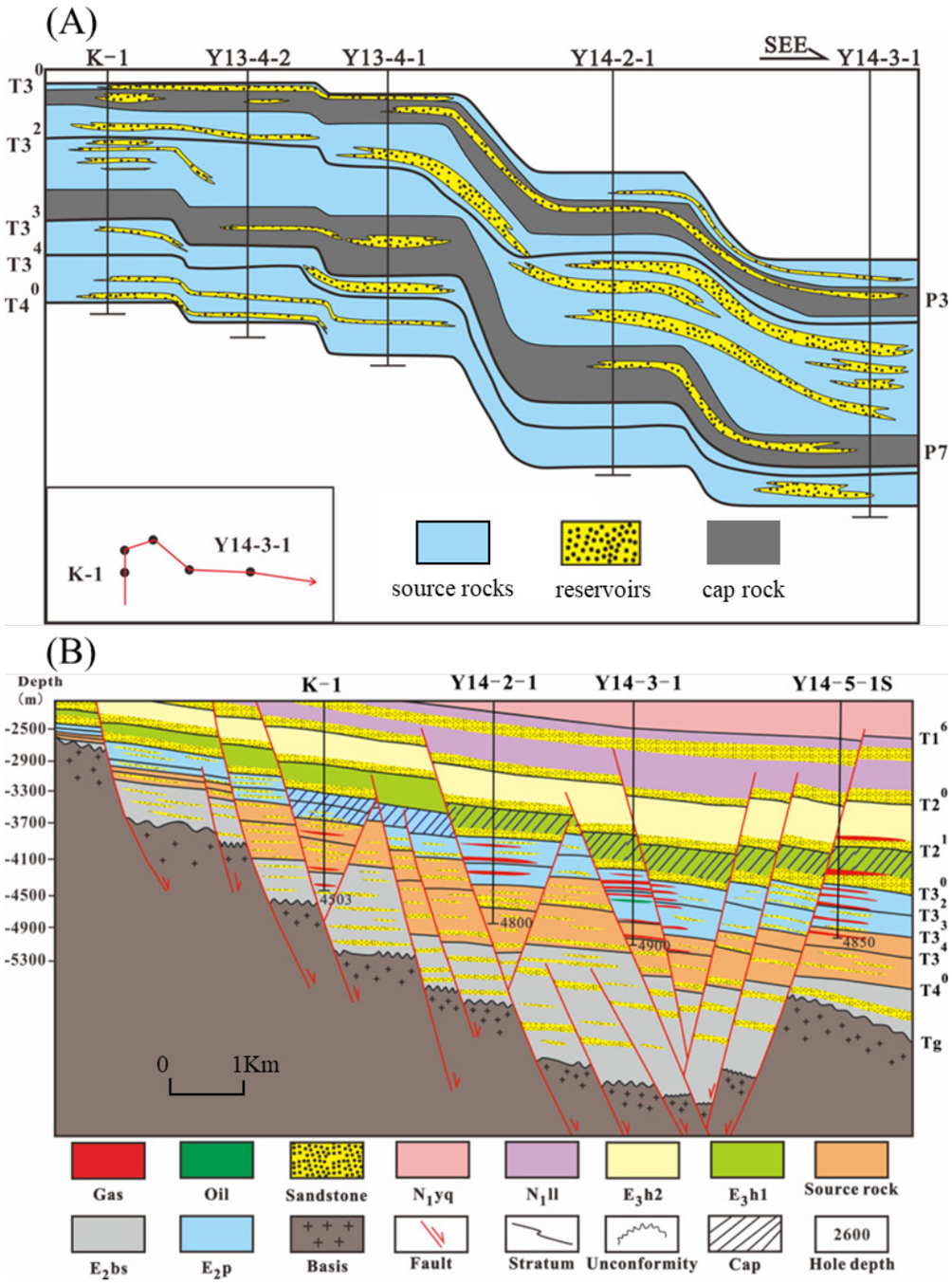

FIGURE 7. (A) Schematic diagram of the reservoir-seal pair of the Kongqueting area Schematic diagram of the hydrocarbon accumulation of the Pinghu Formation in the Kongqueting area

sources (local hydrocarbon source rocks) and distant sources (deep depressional hydrocarbon source rocks). The river-controlled-tidally influenced deltaic deposits develop in the study area. The western structure high belt is highly influenced by river input. The central to high belts are strongly influenced by tidal action. Tidal sand bars in this area exhibit good reservoir properties. Oil and gas migration and reservoir conditions are better in the area with a more developed river sand body. In this case, oil and gas enrichment factors are mainly the development of regional cap rock and fault seal. From the perspective of seal development, the middle and shallow regional cap rock is more stable, formed by the docking of the localized mudstone in the highland system tract during the lower member of the Huagang Formation and the localized mudstone in the upper member of the Pinghu Formation. The middle and deep regional cap rock development is stable with developed oil and gas layers under them. Therefore, more reservoir layers are above the upper member of the Pinghu Formation. Regarding fault activity, it is less pronounced in the middle and lower structural belts. Parts of the oil and gas are transported into the reservoir, while parts migrate through the fault. The late preservation conditions of hydrocarbon are good. This explains the significant oil and gas abundance in the NB14-2-1 well and NB14-3-1 well close to the central depression. In contrast, oil and gas are limited in distribution in the KQT-1 and NB13-4-1 wells in the middle and high-structure belt. Intense late activity and weak lateral sealing capacity result in lower hydrocarbon abundance than the eastern lower structure belt. Therefore, the hydrocarbon accumulation pattern is characterized as a 'dual-source hydrocarbon supply, lower oil and upper gas, good reservoir seal pair, and migration through faults' in the Kongquoting area (Figure 7(B)).

Conclusions

The hydrocarbon accumulations of the Pinghu Formation in the Kongqueting area prevalently consist of condensate gas and oil reservoirs. Multiple hydrocarbon-bearing layers develop. In this area, the majority of stratigraphic intervals targeted by drilling exhibit a characteristic distribution pattern with oil deposits occurring at lower levels and gas accumulations found above. From the structure high to low blet, the amounts of hydrocarbon-bearing layers increase with growing gas column height in the shallower accumulations.

Coal-related hydrocarbon source rocks widely develop in the Pinghu Formation in the study area, which provides both near-source and distant-source hydrocarbon supply. The near-source supply area mainly provides oil, while the distant-source supply area is small and mainly provides gas. During the deposition period of the Pinghu Formation, river-controlled and tide-controlled deltaic deposits developed. The river sand bodies carry the architecture of 'laterally continuous and vertically stacked', which quickly forms good reservoirs. During the deposition period of the Pinghu Formation, two large sets of regional cap rocks (P3 and P7) were formed with sealing capability. The sand layers are interbedded with mud layers to form a lasagna-type reservoir-seal pair, which is conducive to forming large-scale oil and gas accumulations. Faults in the Kongqueting area widely develop. The early faults become desirable hydrocarbon migration pathways, which control the distribution of hydrocarbon-rich strata and the type of hydrocarbon accumulations. The late faults also play a role in modifying and destroying the hydrocarbon accumulations formed in the early stage, which assists the escapement of oil and gas escape easily and results in more dispersion than supply.

Based on our analysis of the factors controlling the formation of hydrocarbon accumulations in the study area, we summarized that the Kongqueting area shows a hydrocarbon accumulation pattern of 'dual-source hydrocarbon supply, upper oil, and lower gas, good reservoir-seal pair, and migration through fault'.

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