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ORIGINAL PAPER

Petroleum geological characteristics and hydrocarbon accumulation patterns in the Melut Basin, South Sudan

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Abstract

The Melut Basin is a passive rift basin controlled by the Central African Shear Zone (CASZ), which contains numerous oil-rich rift sub-basins. After 20 years of large-scale hydrocarbon exploration, it has become increasingly difficult to find new discoveries, and it is necessary to deepen the understanding of petroleum geology, identifying new hydrocarbon accumulation patterns and establishing typical oil reservoir models to promote the future exploration in the Melut Basin. In the north Melut Basin, the far-source migration and accumulation pattern has been identified for the Paleogene main producing layer, which provided more than 95% oil reserves in the past years. For the Paleogene far-source accumulation pattern, the capability of hydrocarbon charge from the Al Renk source rocks and the development of oil-source faults connecting Al Renk source rocks and Paleogene reservoir rocks determine if the Paleogene traps can accumulate hydrocarbon. Using the model of the far-source accumulation pattern, numerous oil reservoirs have been discovered in the north Melut Basin, including the world-class Palogue oilfield. In addition to the Paleogene far-source accumulation pattern, three new near-source accumulation patterns have been identified in the Cretaceous, including the accumulation pattern of Galhak Formation, the accumulation pattern of Al Gayger Formation, and the accumulation patter of Al Renk Formation. Meanwhile, the typical oil reservoir models have been established for each near-source accumulation pattern. These new accumulation patterns and corresponding typical oil reservoir models should promote the exploration of the Cretaceous sequence in the Melut Basin. Compared to the north Melut Basin, the sub-basins in the south Melut Basin have smaller areas and coarser siliciclastic sediment infillings, which make the quality of Adar caprocks worse. Consequently, the Paleogene reservoir (Yabus and Samma Formations)-caprock (Adar Formation) pair is not an effective petroleum system combination in the south Melut Basin, and the near-source Cretaceous has better exploration potential. Affected by the movement of the East African Rift System in Paleogene, the Melut Basin widely developed inversion structures with numerous uplifts and faulted blocks, which provide good trap conditions for hydrocarbon accumulation. Three types of inversion structures have been identified, including the inner-basin inversion structures, the basin-margin inversion structures, and the inversion structures between sub-basins. The inner-basin inversion structures and the inversion structures between sub-basins have better oil-source and trap conditions and are important oil-bearing structures. However, the basin-margin inversion structure has big oil-source risk due to the long-distance migration from the basin center. The inversion movement makes the Cretaceous and basement shallower and therefore greatly increases the exploration potential of deep formations.

Keywords South Sudan · Melut Basin · Passive rift basin · Accumulation pattern · Far source · Near source

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Introduction

Rift basins are rich in oil and gas resources (Lowell 1985; Rosendahl 1987), e.g., Sirte Basin, South Turgay Basin, and Bohai Bay Basin. Among the 877 large oil and gas fields in the world, 271 fields are in rift basins, accounting for 30.9% (Mann et al. 2003; Jia et al. 2011), which indicates that rift basins play a valuable role in oil and gas exploration. For example, in the active rift basins of East China, such as the Bohai Bay Basin and the Songliao Basin, several mid-large oilfields, e.g., Daqing, Liaohe, and Shengli, have been discovered after decades of exploration. Moreover, petroleum geology theories on continental lacustrine have been developed in China, such as "theory of oil generation in terrestrial basins" (Pan 1941; Hu et al. 1991), "oil-source control theory" (Hu 1982; Li 2000; Hu 2005), "composite hydrocarbon accumulation zone" (Hu et al. 1986; Li 1995; Tian et al. 2002), "exploration theory of hydrocarbon-rich basin" (Zhao et al. 2004), "subtle reservoir theory" (Li et al. 2004), and "near depocenter exploration theory" (Meng et al. 2012). In recent years, with the increase of domestic demand, China has accelerated its pace of overseas exploration, and Chinese petroleum geologists have to face some petroliferous basins which have different petroleum geological conditions and hydrocarbon accumulation characteristics from the basins in China, such as the pre-salt carbonate rocks of the Caspian Basin, extensive thick braided river sandstones in the passive rift basins of Central and West African Rift Systems, and reef and beach carbonate rocks in the Indonesian back-arc rift basins. Deepening the petroleum geological research in these basins and gaining insights into the regularities behind hydrocarbon accumulation are of utmost importance for the rapid assessment and efficient exploration for overseas projects.

The petroleum geological conditions and hydrocarbon accumulation characteristics of the Melut Basin were systematically researched. Apart from the main producing layers of the Paleogene Yabus and Samma Formations, the hydrocarbon accumulation patterns and typical oil reservoir models of the Cretaceous formations also have been studied. Identification and establishment of these new accumulation patterns and new models would provide further understanding of hydrocarbon accumulation and promote the exploration of new potential pay zones and new types of reservoirs in the Melut Basin. Meanwhile, the investigation on hydrocarbon accumulation patterns in the Melut Basin may facilitate the exploration of other basins in the Central and West African Rift Systems.

Overview of the Melut Basin

The Melut Basin is the second largest sedimentary basin of the Central African Rift System in South Sudan, with an area of 3.3×10^4 km^2 (Schull 1988; Jorgensen and Bosworth 1989; Mchargue et al. 1992; Genik 1993). The Central and West African Rift System is a world-famous Mesozoic-Cenozoic rift system (Browne and Fairhead 1983; Bermingham et al. 1983; Genik 1992; Guiraud and Maurin 1992; Wilson and Guriaud 1992), with numerous petroliferous rift basins, such as the Termit, Bongor, Muglad, and Melut Basins (Fig. 1). Unlike the active rift basins in East China, these basins are passive rift basins (Dou et al. 2006). The formation of an active rift basin is related to the uplift of the mantle plume and the thermal subsidence of the crust, while the formation of a passive rift basin is mainly caused by the crust cracking under the regional tension to form a rift. The different formation mechanisms made the passive rift basins have different sedimentary infillings, reservoir-caprock pairs, and hydrocarbon accumulation patterns from the active rift basin, which are dominated by near-source accumulation. Research on the petroleum geological characteristics and hydrocarbon accumulation patterns in the Melut Basin may enrich the petroleum geological theory of passive rift basins and promote the exploration of the Melut Basin and other passive rift basins in Central and West Africa.

Exploration in the Melut Basin started in the 1970s. By the end of 2000, four exploration wells and one appraisal well were drilled in the Melut Basin, and as a result, only a small oilfield, Adar-Yale field, was found in the basin (Schull 1988; Dou al. 2007). Subsequently, some small companies carried out a few test production operations, and the exploration activities were completely stopped. In November 2000, CNPC (China National Petroleum Corporation) entered the Melut Basin, establishing the largest overseas exploration project of China at that time. Soon after, with scientific and reasonable exploration strategies and technical approaches, the Palogue oilfield, a world-class oilfield with the recoverable oil reserves of more than 900 million barrels (Dou et al. 2007), and several mid-large oilfields have been discovered. At that time, the far-source hydrocarbon accumulation pattern of the main producing layers of the Paleogene Yabus and Samma Formations was proposed, which guided the discoveries of numerous oil reservoirs (Dou 2005; Tong et al. 2006). However, after 20 years of exploration, the large-scale structural traps have been almost completely drilled, and it is becoming increasingly difficult to discover more Paleogene oil reservoirs. Under such circumstances, the research on the petroleum geological conditions and hydrocarbon accumulation patterns of new potential formations is particularly important, which would contribute to making new discoveries in the Melut Basin.

Petroleum geological characteristics of the Melut Basin

Structure

The Melut Basin has five sub-basins and one uplift, including the Northern sub-basin, the Eastern sub-basin, the Central sub-basin, the Western sub-basin, the Southern sub-basin, and the Central uplift (Fig. 2). These sub-basins have a half-graben basin framework presenting a main boundary fault in the west (Fig 3). The Northern sub-basin is the main exploration sub-basin of the Melut Basin, with the largest area of nearly 10,000 km^2. So far, almost all the discovered reservoirs are located in the Northern sub-basin, including the world-class Palogue

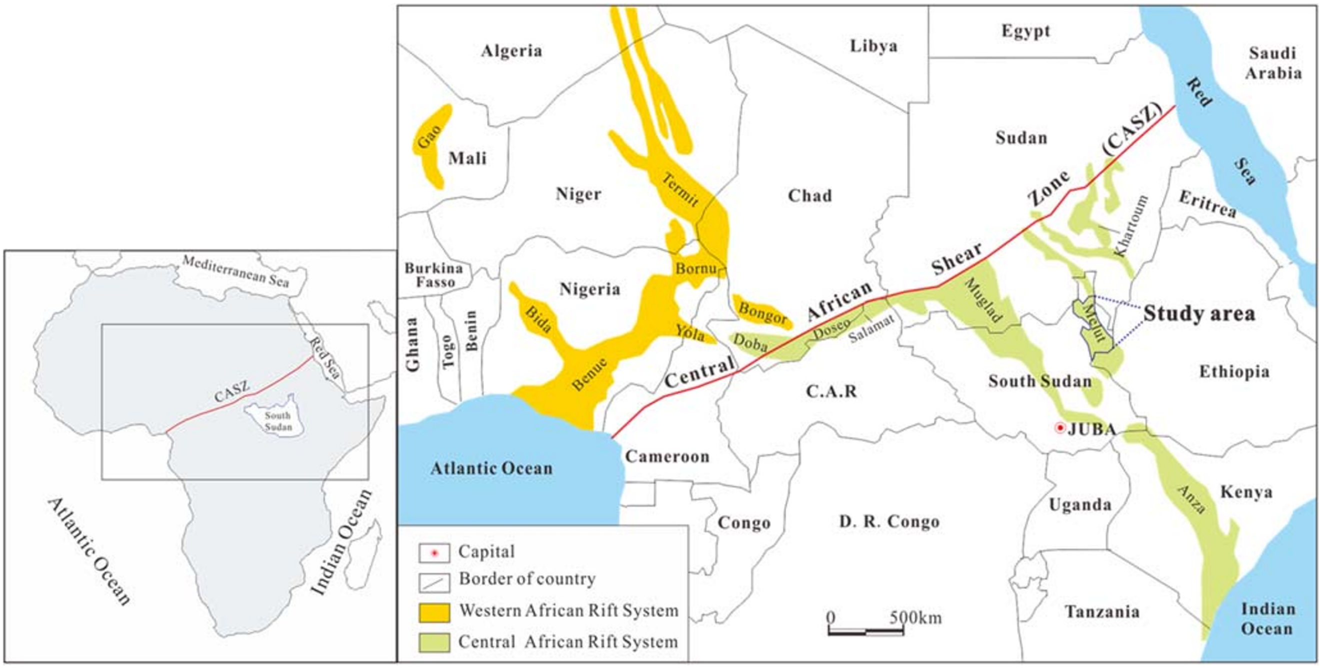

Fig. 1 Distribution of the Central African Shear Zone and Central and West African Rift Systems (modified after Genik1993)

oilfield. The other four sub-basins are smaller and mainly located in the south Melut Basin. Due to the swampy conditions on the surface and safety factors, these sub-basins have low exploration level, and there is hardly any discovery except the small oil reservoir in the Miyan area of the Central sub-basin.

The Melut Basin develops various extensional structures, including synthetic and antithetic faulted blocks, faulted horsts, faulted noses, and faulted anticlines. Furthermore, some inversion structures are also developed in the Melut Basin due to the compressive stress field from the movement of the East African Rift System in Paleogene, e.g., the Ruman and Kaka inversion structures in the Northern sub-basin and the Ghanam inversion structure in the Southern sub-basin (Fig. 2). These extensional structures and local inversion structures constitute the main structural styles of the Melut Basin.

The Melut Basin develops four types of faults, including the basin-controlling fault of half-graben, local sag-controlling fault in the gentle slope, the late-period fault formed in the Paleogene rifting stage, and the early-period fault formed in the Early Cretaceous rifting stage (Fig. 3). The basin-controlling fault of half-graben and local sag-controlling fault in gentle slope continuously moved from the initial rifting stage of Early Cretaceous to the third rifting stage of Paleogene and are important vertical hydrocarbon migration pathways connecting the Cretaceous source rocks and the main producing layers of Paleogene. The late-period faults formed numerous faulted blocks, faulted noses, and faulted horsts, which provided good trap conditions for the Paleogene target layers. Meanwhile, some late-period faults strongly moved and extended to Cretaceous source rocks and acted as the vertical migration pathways for the faulted blocks in the mid-shallow formations. The early-period faults mainly controlled the paleogeomorphology and sedimentary infillings of the Lower Cretaceous, and most faults terminated in the Lower Cretaceous. These faults had only minor effects on the hydrocarbon accumulation of the Paleogene and Upper Cretaceous.

Sedimentary infilling and source-reservoir-caprock assemblage

The Melut Basin experienced three rifting cycles and one sagging cycle from Cretaceous to present and developed four corresponding tectonostratigraphic successions and four sets of reservoir-caprock pairs (Fig. 4). The first rifting cycle in the Early Cretaceous is the initial rifting activity of the Melut Basin, and the coarse clastic sediments of Al Gayger Formation and thick shales of Al Renk Formation deposited during this pronounced rifting activity, which formed the first set of reservoirs (Al Gayger Formation)-caprock (Al Renk Fm.) pair. Due to the deep buried depth (4–7 km), it attracted less attention in the early exploration, and only a few wells were drilled in the basin margin, with some oil shows and low testing production. Being close to the source rocks of Al Renk Formation, the Al Gayger Formation has good oil-source and caprock conditions and is an important potential formation for the future exploration.

The Al Renk Formation is a set of deep lacustrine shale sediments of Lower Cretaceous and acts as the primary source rocks of the Melut Basin, with the thickness of 1000 m in the

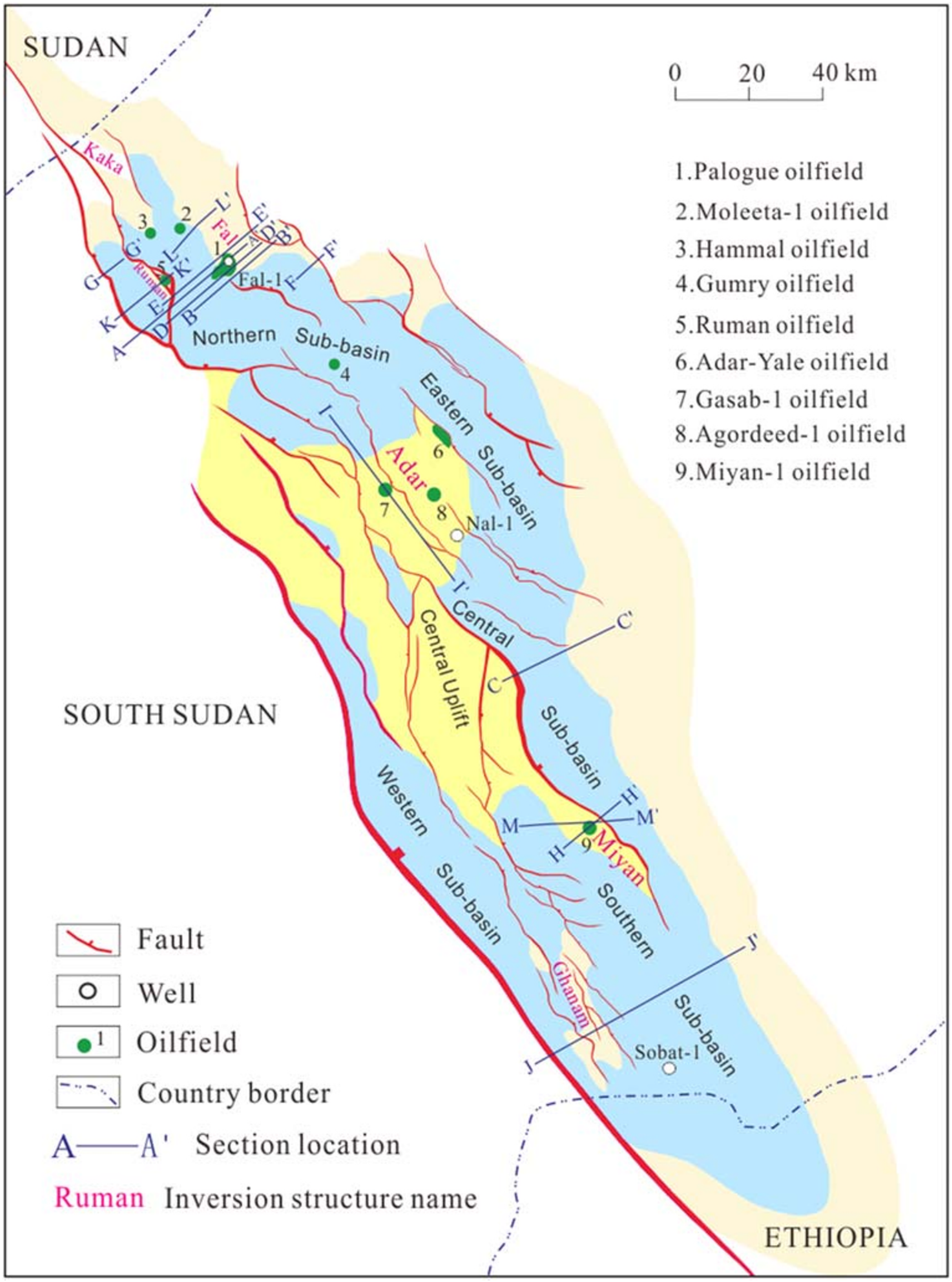

Fig. 2 Structural units of the Melut Basin; for location see Fig. 1

depocenter and 200–500 m in the slope area. The TOC of the Al Renk Formation shows good to very good levels, with a maximum value of 3.24% and an average value of 2.08%. Meanwhile, the S1+S2 ranges from 0.25 to 19.53 mg HC/g TOC and the average value arrives to 9.96 mg/g TOC (Dou et al. 2007; Mohamed et al. 2016). The organic matter type of the Al Renk Formation is dominated by type II kerogen (Fig. 5).

The Melut Basin is a passive rift basin originated from the strike-slip movement of CASZ, so the volcanic activity is not developed in the early stage of basin evolution, which makes the geothermal gradient low in the early period of basin development. However, in the late stage of the basin evolution, influenced by the activity of the East African Rift System in Cenozoic, the geothermal gradient gradually rose and now the average value of geothermal gradient is 2.94 °C/100 m, which is still lower than the value of 3.4–3.6 °C/100 m of the Bohai Bay active rift basin in East China (Gong et al. 2003; Qiu et al. 2007). Consequently, the generation and expulsion were late in the Melut Basin. The thermal evolution history modelling of source rocks demonstrated that the Al Renk Formation entered the oil window in the Late Cretaceous, and the

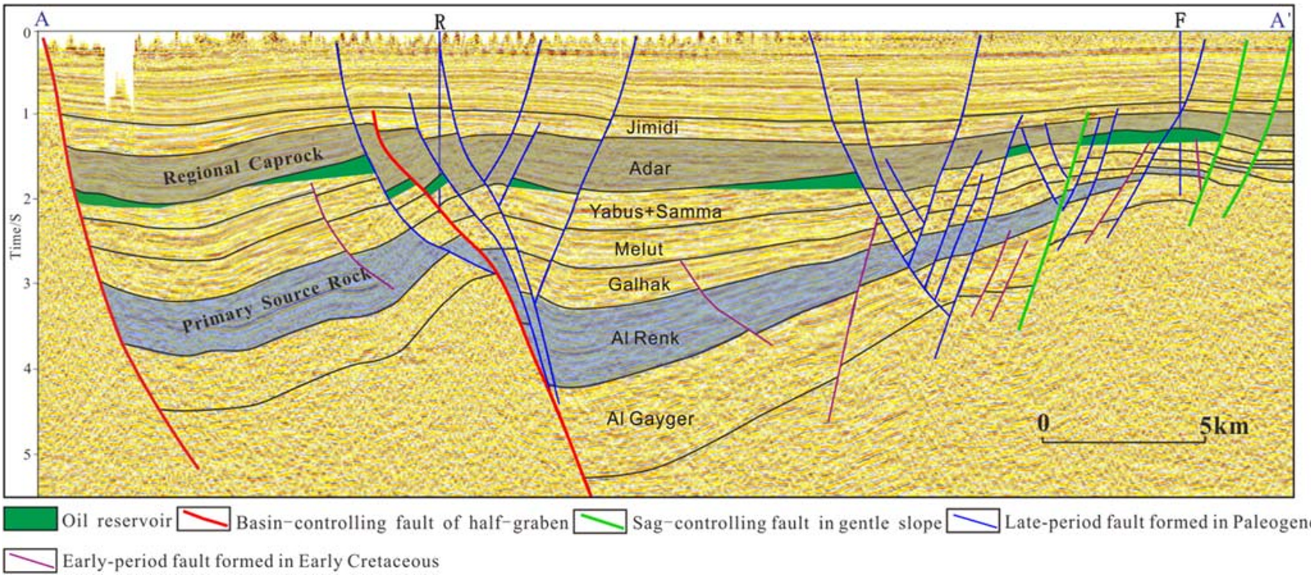

Fig. 3 Seismic profile across the Northern sub-basin, the Melut Basin; for location see Fig. 2

massive generation and expulsion commenced in the Paleogene and continued to present (Dou et al. 2007; Mohamed et al. 2016), which provided continuous oil supply for the hydrocarbon accumulation in the Melut Basin.

The second rifting cycle was relatively weaker and is dominated by the sand-rich sequences in the Upper Cretaceous. These sequences are characterized by braided river and braided river delta deposition with high sand content. The Galhak Formation is in the lower part of the Upper Cretaceous and is the product of a regression after the extensive flooding in the period of Al Renk Formation deposition. The Galhak Formation is a set of interbedded sequence of sandstones with the thickness of 500–600 m and 50–70% sand content. Since the Galhak Formation is adjacent to the Al Renk source rocks, and the shore-shallow lacustrine mudstones in the lower Galhak Formation also possess certain hydrocarbon generation potential (Fig. 5), the Galhak Formation has good oil-source condition. The interbedded sandstones and mudstones formed the internal reservoir-caprock pair of Galhak Formation, and under the control of oil-source faults cutting through the Galhak Formation and Al Renk source rocks, Galhak Formation may develop fault-block and stratigraphic oil reservoirs. At present, some oil reservoirs have been discovered in Galhak Formation, and some wells had high production. Consequently, the interbedded reservoir-caprock pair of the Galhak Formation is an important exploration target. Conversely, although the Melut Formation is also a set of sandy sequence and develops good reservoir rocks, the lack of internal mudstones and regional caprocks make the Melut Formation to have bad lateral and top sealing conditions. So, the Melut Formation is not a favorable exploration target.

The third rifting cycle in the Paleogene includes two parts with different rifting intensity and sedimentary features. The lower part has weak rifting activity and mainly deposited sandy formations of Samma and Yabus Formations. The Upper part has strong rifting activity and deposited thick mudstones of Adar Formation. So, the reservoir rocks of Samma and Yabus formations and the caprocks of Adar Formation formed the major reservoir-caprock pair of the Melut Basin, and more than 95% discoveries are in this set of pair (Dou 2005).

From Neogene to Quaternary, the Melut Basin entered the sagging evolution stage. The braided river sandstones of the Jimidi Formation and the floodplain mudstones of the Miadol Formation constitute the Neogene reservoir-caprock pair. As this set of reservoir-caprock pair is far from Al Renk source rocks, it is difficult for hydrocarbon to penetrate thick Upper Cretaceous and Paleogene formations and accumulate in the Jimidi Formation. So far, only some small reservoirs have been discovered near the basin-controlling fault, and no reservoir was discovered in the inner basin. In addition, as the burial depth of the Jimidi Formation is only several hundred meters, the oil of Jimidi Formation has very low API, which made it difficult to produce. So, the Neogene reservoir-caprock pair of Jimidi and Miadol Formations is not a favorable pair.

On the whole, the Paleogene reservoir (Yabus and Samma Formations)-caprock (Adar Formation) pair is the major reservoir-caprock pair of the Melut Basin; the internal reservoir-caprock pair of the Galhak Formation and the upper-caprock and lower-reservoir pair of the Al Renk and Al Gayger Formations are two sets of potential pairs; the Melut and Jimidi Formations have relatively poor petroleum geology conditions.

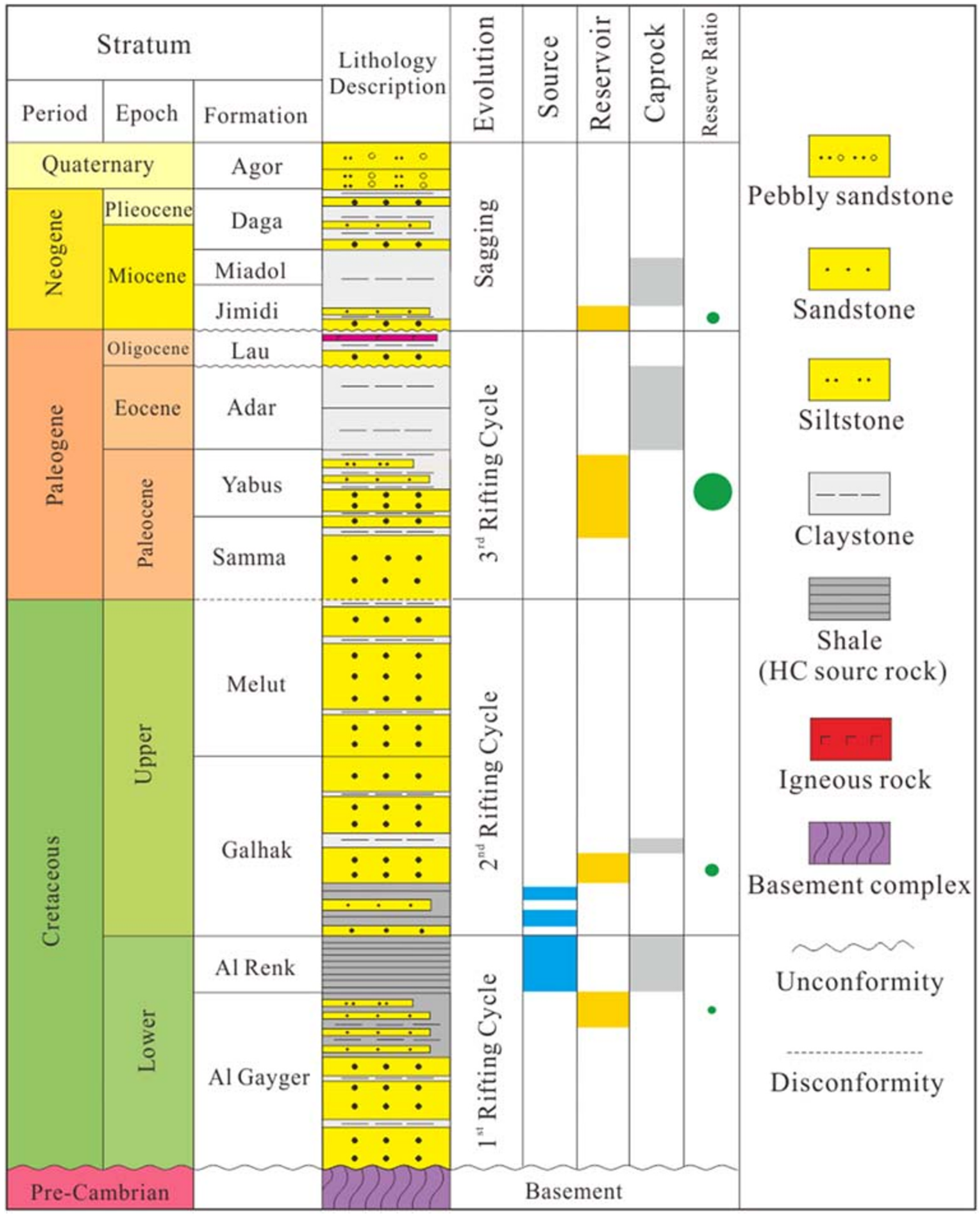

Fig. 4 Stratigraphic summary of the Melut Basin

Hydrocarbon accumulation patterns in the Melut Basin

Investigation of hydrocarbon accumulation patterns are crucial for deepening the understanding of hydrocarbon accumulation rules, reasonably forecasting reservoir distribution, effectively guiding exploration deployment, and improving the drilling success rate. Tong et al. (2006), Dou (2005), and Dou et al. (2007) proposed the far-source migration and accumulation patterns for the main producing layers of the Paleogene Yabus and Samma Formations based on the oil reservoir analysis of Palogue oilfield. Their work effectively guided the discoveries of several mid-large oilfields, such as Moleeta, Hammal, and Gumry oilfields (Fig. 2). However, with the deepening of exploration, it is becoming difficult to discover new oil reservoirs in the Paleogene producing layers, and it is urgent to explore new exploration layers and new reservoir-caprock pairs. Consequently, the petroleum geological characteristics and hydrocarbon accumulation patterns of the Melut Basin have been systematically researched, and the typical oil reservoir models corresponding to each accumulation pattern have been built, which would contribute to promoting the exploration.

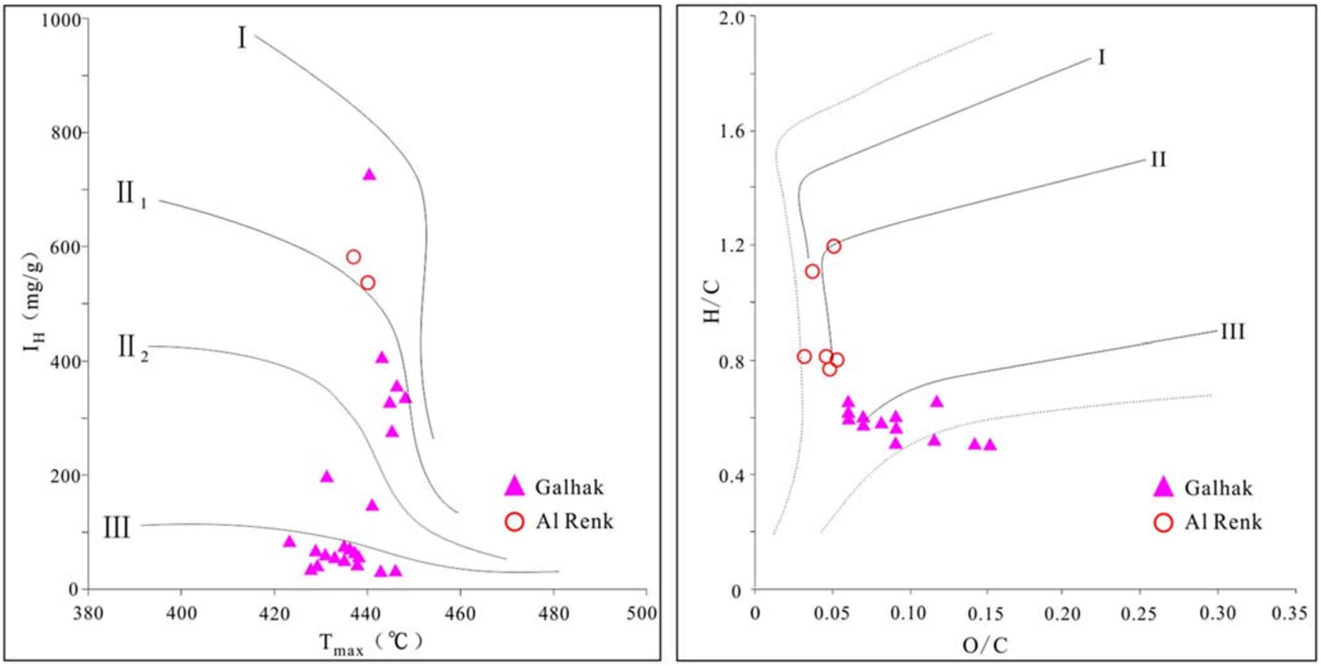

Fig. 5 Organic matter types of the source rocks in the Melut Basin

Far-source migration and accumulation pattern of the Paleogene main producing layers

The far-source migration and accumulation pattern of the Paleogene Yabus and Samma Formations is the main accumulation pattern of the Melut Basin, and more than 95% discoveries are from this pattern. The development of this hydrocarbon accumulation pattern is related to the basin forming mechanism and sedimentary infilling features of passive rift basin. Studies show that the rifting-sagging differentiation is stronger in passive rift basins than in active rift basins (Dou et al. 2006; Ouyang et al. 2007), and the sand-rich formations deposited in the sagging and weak rifting stage extend thousands of square kilometers, which explained why the Melut Basin develops multiple sets of sand-rich formations, including the Upper Cretaceous Galhak and Melut Formations, Paleogene Samma and Yabus Formations, and Neogene Jimidi Formation. The existence of sand-rich formations in the Upper Cretaceous made it possible for the hydrocarbon from the Al Renk source rocks to migrate long distance and accumulate in the Yabus and Samma Formations and form the far-source oil reservoirs sealed by the Adar regional caprocks (Fig. 6).

Fault-block reservoirs associated with the oil-source faults are the main oil reservoir types of far-source accumulation pattern. The capability of hydrocarbon charge from the Al Renk source rocks and the development of oil-source faults connecting source rocks and Paleogene reservoir rocks are two key factors for the oil reservoir formation of far-source accumulation pattern. The discoveries of the Palogue oilfield and other mid-large oilfields have confirmed that the Northern sub-basin develops abundant oil resources and has good capability of hydrocarbon supply. Meanwhile, the multi-stage rifting movements make the Melut Basin develop numerous faults connecting Cretaceous source rocks and Paleogene reservoir rocks. Hence, the far-source accumulation pattern successfully guided the exploration of the Northern sub-basin. Conversely, the sub-basins in the south Melut Basin are smaller, and the capability of hydrocarbon supply is a big risk for the far-source migration pattern of the Paleogene producing layer. That is why only a few small oil reservoirs of Paleogene have been discovered in south Melut Basin. Consequently, the far-source accumulation pattern is not an effective accumulation pattern for the south Melut Basin, and it is necessary to identify new hydrocarbon accumulation patterns and built new oil reservoir models to promote the exploration in the south Melut Basin.

Near-source migration and accumulation patterns of the Cretaceous

The near-source formations include Al Renk and Al Gayger Formations of the Lower Cretaceous, and Galhak Formation of the Upper Cretaceous. Since near-source formations are close to the source rocks of Al Renk Formation, they have good oil-source condition. The near-source Cretaceous formations develop 3 types of reservoir-caprock pairs, including the interbedded reservoir-caprock pair of Galhak Formation, upper-caprock and lower-reservoir pair of Al Renk and Al Gayger Formations, and the internal reservoir-caprock pair of Al Renk subaqueous fans and Al Renk source rocks. These 3 reservoir-caprock pairs

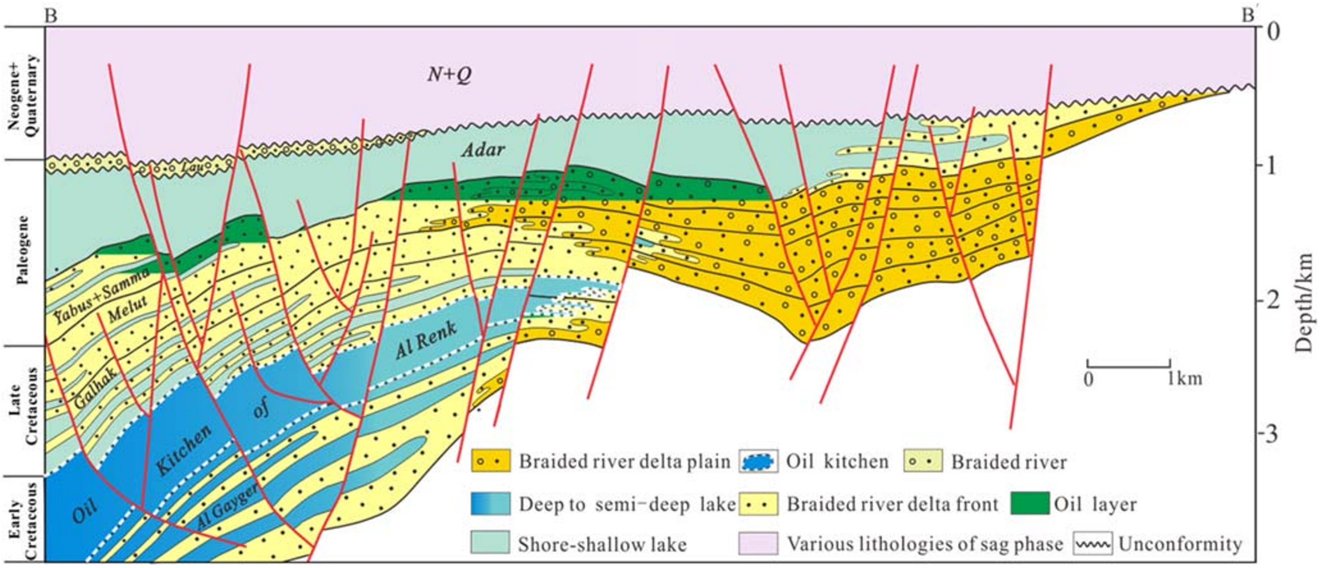

Fig. 6 Typical reservoir model of the far-source accumulation pattern of the Paleogene main producing layer in the Melut Basin(see Fig. 2 for location)

formed 3 types of near-source migration and accumulation patterns: lower-generation and upper-accumulation pattern of Galhak Formation, upper-generation and lower-accumulation pattern of Al Gayger Formation, and internal-generation and internal-accumulation of Al Renk Formation (Fig. 7). At present, the near-source Cretaceous reservoir-caprock pairs are relatively new exploration targets in the Melut Basin, and only a few wells penetrated Cretaceous with some discoveries. For example, a few wells achieved high production in the Galhak Formation in the east gentle slope of the Northern sub-basin, and some wells encountered commercial oil flow in Abyat fan delta of Cretaceous in steep slope. So, the near-source Cretaceous formations have good hydrocarbon accumulation conditions and good exploration potential. The identification of accumulation patterns and establishment of typical oil reservoir models will promote the exploration of Cretaceous.

Lower-generation and upper-accumulation pattern of Galhak Formation in gentle slope

The lower-generation and upper-accumulation pattern means that the oil kitchen is beneath the reservoir rocks, and the oil generated by the source rocks migrates upward and accumulates in the reservoir rocks on the oil kitchen. The Galhak Formation is above the Al Renk source rocks and has good oil-source condition. Although it is overlaid by the regional sand-rich Melut Formation, the interbedded sandstones and mudstones in Galhak Formation formed the internal reservoir-caprock pair. Moreover, the buried depth of Galhak Formation is in the drillable depth of 2000–3500 m in most areas. So, Galhak Formation is an important exploration target. So far, some wells have got commercial oil flow in Galhak Formation, but most wells failed. So,

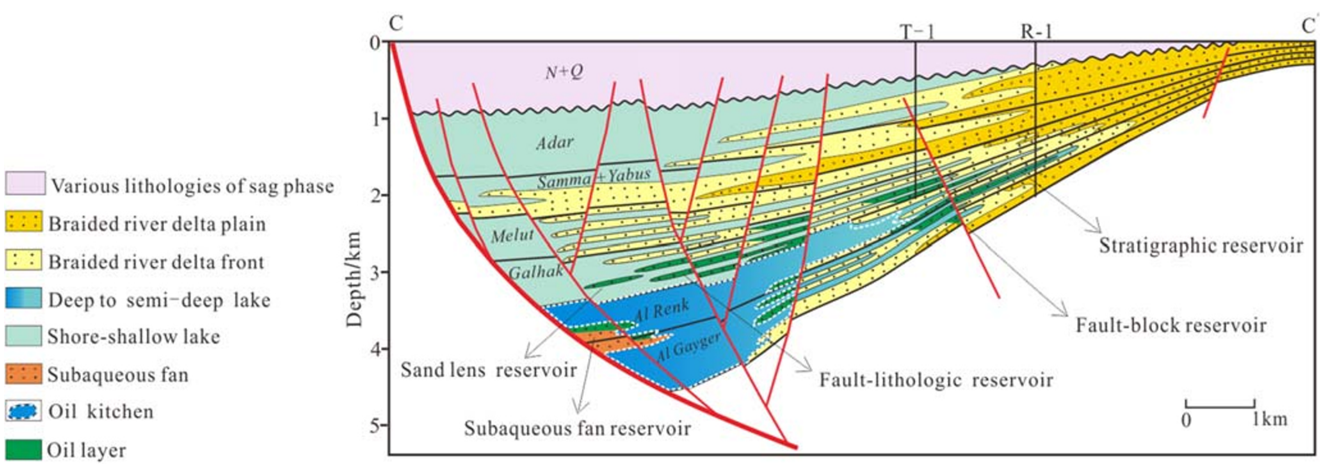

Fig. 7 Typical oil reservoir model of the near-source migration and accumulation patterns in Cretaceous (see Fig. 2 for location)

clarifying the main controlling factors of the hydrocarbon accumulation and improving the exploration success rate are the key issues to carry out the exploration of Galhak Formation.

The overall sand-rich and locally mud-bearing lithology features make the local flooding mudstones be the key factor of controlling the hydrocarbon accumulation of Galhak Formation. The distribution and thickness of flooding mudstones determine the distribution and thickness of oil layers. Vertically, the oil layers mainly occur in the lower part of Galhak Formation, where the flooding mudstones are relatively developed. Horizontally, the oil reservoirs mainly developed in the mid-lower part of the gentle slope. The upper Galhak Formation and the Galhak Formation in the upper part of gentle slope have high sand content, and the lack of local mudstones made the Galhak Formation have poor caprock condition. Furthermore, the sedimentary facies study showed that the inner braided delta front of Galhak Formation develops thick sandstones of distributary channels and thick flooding mudstones that made the inner braided delta front be the best region for seeking the thick fault-block oil reservoirs. In the outer delta front and prodelta, the Galhak Formation has the "sand wrapped by mud" lithology features, with about 30% or even lower sand content. In these areas, the Galhak Formation mainly develops sand lens or structural-stratigraphic combination oil reservoirs. Overall, from the depocenter to the high part of gentle slope, the Galhak Formation develops sand lens reservoirs, structural-stratigraphic combination reservoirs, fault-block reservoirs, and stratigraphic reservoirs (Fig. 8). The understandings of hydrocarbon accumulation pattern and the establishment of accumulation model will increase the success rate of Galhak exploration.

Upper-generation and lower-accumulation pattern of Al Gayger Formation in gentle slope

The upper-generation and lower-accumulation pattern means that the oil kitchen is on the reservoir rocks. For the formation mechanism of this type of pattern, a lot of researches have been carried out to explain how the source rocks expelled hydrocarbon downward to the underlying reservoirs (Chi et al. 2000; Cui and Cui 2004; Liu et al. 2009; Fu and Feng 2012). In general, there are two main views: the first view is that under the control of the overpressure in the source rocks, the hydrocarbon will be injected into the underlying reservoir rocks through the oil-source faults connecting the source rocks and underlying reservoir rocks. The second view is that under the action of synthetic faults, the source rocks of hanging wall directly contact with the underlying reservoir rocks in the footwall, and the hydrocarbon will laterally migrate to the underlying reservoir rocks. In any case, the accumulation of the underlying reservoirs is closely related to the oil-source faults. Consequently, the oil-source fault is the key factor for the upper-generation and lower-accumulation pattern, and without the development of oil-source faults, the hydrocarbon cannot enter the underlying reservoir rocks.

The Al Gayger Formation is a set of sandy sequence deposited in the initial stage of the basin evolution. After the deposition of Al Gayger Formation, Melut Basin experienced the strongest rifting activity and deposited the primary source rocks of Al Renk Formation. The Al Renk Formation not only provided hydrocarbon, but also acted as regional caprocks for Al Gayger Formation. Consequently, the Al Gayger Formation has good oil-source and caprock conditions, and some wells have encountered oil shows and low testing production oil layers, which indicated that the upper-caprock and lower-reservoir pair of Al Renk and Al Gayger Formations is

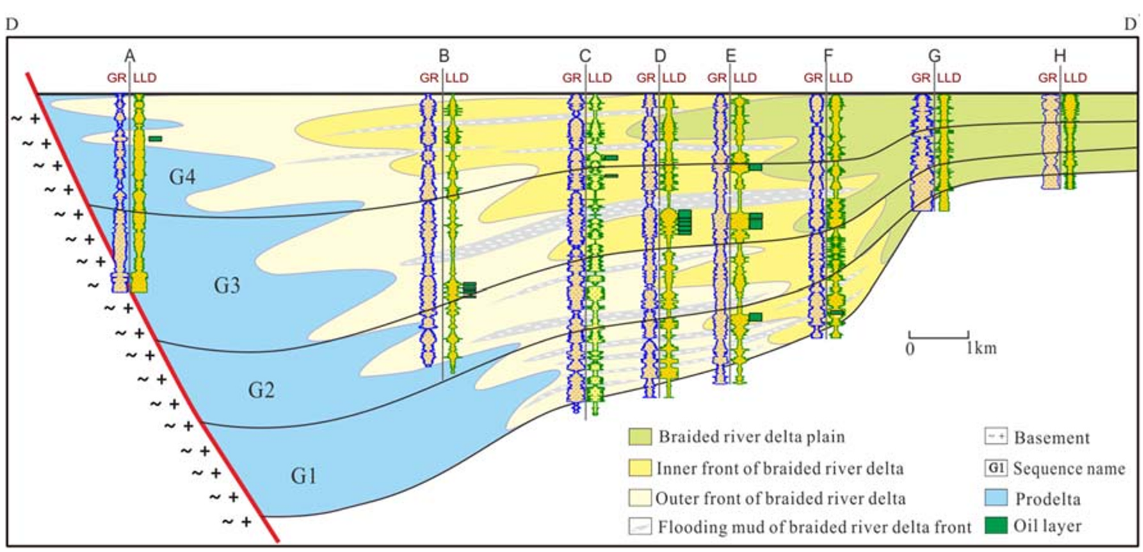

Fig. 8 Sedimentary facies section and oil layers distribution of Galhak Formation(See Fig. 2 for section location)

an effective reservoir-caprock pair. Strengthening the research on the mechanism of the upper-generation and lower-accumulation pattern and establishing the typical oil reservoir model will promote the exploration of Al Gayger Formation.

The fault-block reservoir controlled by the oil-source fault is the main reservoir type of the Al Gayger Formation. According to the fault type and fault throw, the faulted blocks of Al Gayger Formation may be divided into 2 types (Fig. 9). Type I faulted block is controlled by the antithetic fault. Under the control of antithetic fault, the sandstones of Al Gayger Formation directly contact with Al Renk source rocks in lateral, which makes the faulted blocks of Al Gayger Formation have good oil-source and good lateral sealing conditions. Type II faulted block is controlled by synthetic fault. The synthetic fault makes the Al Gayger Formation of hanging wall contact with the Al Gayger Formation of footwall, so this type of faulted blocks of Al Gayger Formation have poor lateral sealing condition. For the Upper Al Gayger Formation, the interbedded sandstones and mudstones lithologic association makes it possibility develop thin oil layers when the thin sandstones in the hanging wall are laterally sealed by the internal mudstones of upper Al Gayger Formation in the footwall. The lower Al Gayger Formation mainly develops massive sandstones, and if the fault throw is big enough to make the lower Al Gayger sandstones contact with basement, the hydrocarbon accumulation of lower Al Gayger Formation depends on the sealing capability of the basement. Conversely, if the fault throw is small, the lower Al Gayger sandstones of the hanging wall will contact with the lower Al Gayger sandstones of the footwall, which makes the faulted blocks of Al Gayger Formation in the hanging wall have poor sealing condition (Fig. 9). Overall, the antithetic faulted blocks with big fault throw are the most favorable drilling targets for Al Gayger Formation, and the synthetic faulted blocks have big lateral sealing risk.

Internal-generation and internal-accumulation pattern of Al Renk Formation in steep slope

The internal-generation and internal-accumulation pattern means the reservoir rocks develop in the oil kitchen, and the hydrocarbon generated by the source rocks directly accumulates in the reservoir rocks. So, the internal-generation and internal-accumulation pattern has low hydrocarbon charging risk. For a rift basin, the strong rifting activity makes the steep slope zone not only develop thick source rocks but deposit subaqueous fans or fan deltas along the basin-controlling fault. The subaqueous fans or fan deltas usually are wrapped by the source rocks, so they have good oil-source and sealing conditions. These fans, together with the source rocks, form the internal-generation and internal-accumulation pattern, which is a favorable drilling target for a rift basin.

The Abyat fan delta controlled by the basin-controlling fault has got commercial oil flow in the Melut Basin. The investigation on the hydrocarbon accumulation rules revealed that the sedimentary characteristics control the oil reservoir types and distribution in the Abyat fan, and different part of the fan develops different type oil reservoir (Fig. 10). The proximal fan mainly develops fan delta plain deposition dominated by thick braided river channel sandstones, which is conducive to forming thick structural oil reservoirs (e.g., well A-1). The middle part of the fan is characterized by the fan delta front deposition with the interbedded sandstones and mudstones. The sandstones of the distributary channels are the main reservoir rocks. Compared to the proximal fan, the thickness of the sandstones in the middle part of the fan are thinner, but the mudstones are thicker, which make the sandstones have better top and lateral sealing conditions. Consequently, the middle part of the fan primarily develops layered fault-block reservoirs or layered structural-stratigraphic combination reservoirs (e.g., well S-1 and well S-2). The distal part of the fan is far from the sediment source

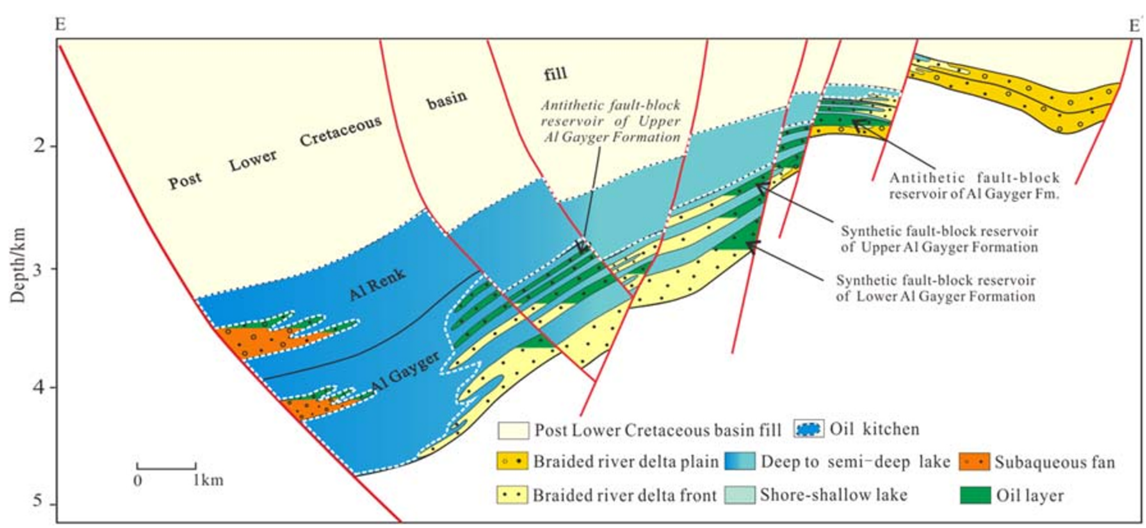

Fig. 9 Typical oil reservoir model of the Al Gayger Formation in the gentle slope(see Fig. 2 for location)

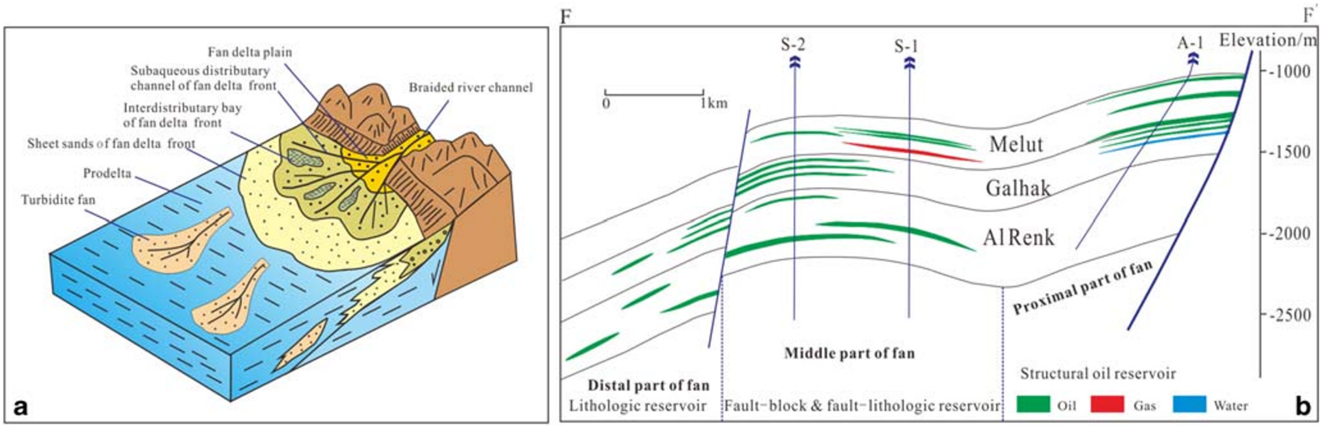

Fig. 10 Depositional model (**a**) and hydrocarbon accumulation pattern (**b**) of the Abyat fan delta (Shi et al. 2015), and the location of section F-F' is shown in Fig. 2

and has high mud content, which makes it mainly develop sand lens reservoirs. Overall, the fan delta usually develops in the initial rifting stage and directly contacts with the source rocks, which makes it develop multi-type oil reservoirs.

Besides the Abyat fan, several other subaqueous fans have been identified in the steep slope of the Ruman sag (Fig. 11). These fans also develop in the initial rifting stage and are interbedded with the Al Renk source rocks. So, they have better oil-source and sealing conditions. The exploration on the subaqueous fans or fan deltas in the steep slope will further increase the exploration potential of Cretaceous in the Melut Basin.

Tectonic-sedimentary effects on hydrocarbon accumulation in the Melut Basin

Paleogene inversion movement and hydrocarbon accumulation

The inversion structure is an important hydrocarbon-bearing structure, and many oil and gas reservoirs associated with inversion structures have been discovered in the world (Chen and Chen 1995; Liu 1995; Wang et al. 2001; Hu et al. 2004; Charlton 2004). The inversion structures have multiple formation mechanisms, including the thin-skinned thrust, strike-slip deformation, and the regional compression, so the inversion structures may develop in many tectonic settings, such as the orogenic belts, rift basins, intra-cratonic basins and passive margins (Cooper and Warren 2010; Granado and Ruh 2019). The inversion structure is a type of common structure in the Melut Basin and originated from a compressive stress field during the late Eocene, which is from the extensional movement of the East African Rift System in Cenozoic. The Melut Basin mainly develops local inversion structures, and the overall uplift of the basin is small, so the inversion movement has limited impact on the hydrocarbon generation of the basin. The burial history and source rock evolution history modeling in the Adar and Fal inversion structures and Moleeta slope of the Northern sub-basin from Dou et al. (2007) and Mohamed et al. (2016) indicated that the Northern sub-basin of the Melut Basin is still in the oil generation stage in present (Table 1), and the inversion movement occurred in the late Eocene and Oligocene did not shut down

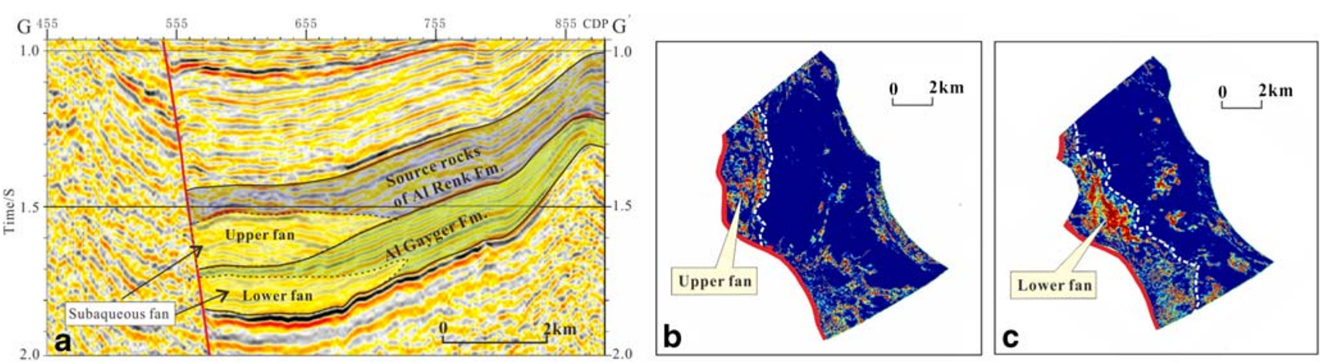

Fig. 11 Seismic characteristics of Ruman subaqueous fans (Shi et al. 2015; Shi et al. 2014). **a** Reflection features of Ruman subaqueous fans in seismic section (the section location was shown on Fig. 2), and two sets of subaqueous fans develop in the near-source formations; **b** RMS amplitude map of Upper fan, and the time window ranged from bottom to top Al Renk Formation; **c** RMS amplitude map of Lower fan, and the time window ranged from bottom to top Al Gayger Formation

Table 1 The source rock evolution modeling results of different inversion structures and slope in the Northern sub-basin (Dou et al. 2007; Mohamed et al. 2016)

Well		[a]Moleeta-1	[a]Fal-1	[a]Gasab-1	[a]Agordeed-1
Location		Slope	Fal inversion structure	Adar inversion structure	
Oil window depth (m)	Onset	1727	1730	1619	2500
	Peak	3345	Not reached	3211	3400
	End	3900	Not reached	3715	4500
Oil generation time (Ma)	Start	84	51	86	66
	End	Generating	Generating	Generating	Generating

[a] Data from Mohamed et al. 2016; [b] data from Dou et al. 2007

the hydrocarbon generation, which provided good oil-source condition for the hydrocarbon accumulation of inversion structures. So far, some reservoirs associated with inversion structures have been discovered in the Melut Basin, such as the fault-block reservoirs in Adar inversion structure and the basement fracture reservoirs in Ruman inversion structure (Fig. 2). Consequently, the inversion structure is a favorable oil-bearing structure in the Melut Basin.

According to the development position in the basin, the inversion structures can be classified into three types: basin-margin inversion structure, inner-basin inversion structure, and inversion structure between sub-basins. These inversion structures have good trap conditions, and the oil-source, caprock, and preservation conditions are the main controlling factors for the hydrocarbon accumulation. The basin-margin inversion structure is far from the basin center, and the oil-source is the biggest risk for the hydrocarbon accumulation. For instance, the Kaka inversion structure in the north margin of the Melut Basin (Fig. 2), although it develops a big anticline structure, no any reservoir has been discovered due to the poor oil-source condition. Compared to the basin-margin inversion structure, the inner-basin inversion structure and the inversion structure between sub-basins have better oil-source and reservoir-caprock pair conditions. For instance, the Ruman and Adar inner-basin inversion structures have got good oil discoveries in the Northern sub-basin, and the Miyan inversion structure between the Central and Southern sub-basins got the only discovery in the south Melut Basin (Fig. 12). Consequently, the inner-basin inversion structure and the inversion structure between sub-basins are two types of favorable oil-bearing structures in the Melut Basin.

For the inner-basin inversion structure and the inversion structure between sub-basins, the inversion magnitude and erosion extent determine the exploration target formation. For the weak inversion structures, the uplifting magnitude and erosion extent is light, which make the major reservoir-caprock pair of Paleogene Yabus+Samma and Adar formations well preserved. For example, the Adar inner-basin inversion structure experienced weak uplifting and eroding in the end of the Paleogene, and the Yabus+Samma-Adar formations are still an effective reservoir-caprock pair (Fig. 13a), which led to the discoveries of Adar and Gasab oilfields. Conversely, the strong inversion structure experienced significantly uplifting and eroding, which made the Paleogene reservoir-caprock pair severely destroyed and the Cretaceous and basement became favorable drilling targets. For example, the Adar Formation is almost completely eroded in the Ghanam inner-basin inversion structure in the Southern sub-basin (Fig. 13b), and the internal reservoir-caprock pair of Galhak Formation is the favorable exploration target. The inversion structures between sub-basins look like an uptilted basement footwall blocks (Figs. 12 and 13c) and formed due to the continuing extension on the large bounding master fault and the regional compression from the extensional movement of the East African Rift System in the late Paleogene. Due to the relatively shallow burial depth and thin formation

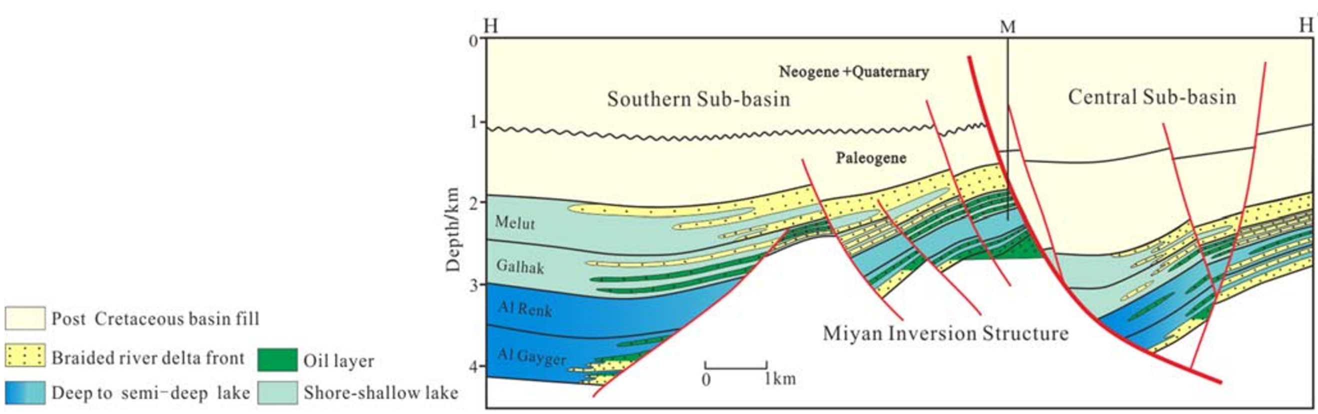

Fig. 12 Typical oil reservoir model of the Miyan inversion structure (see Fig. 2 for section location)

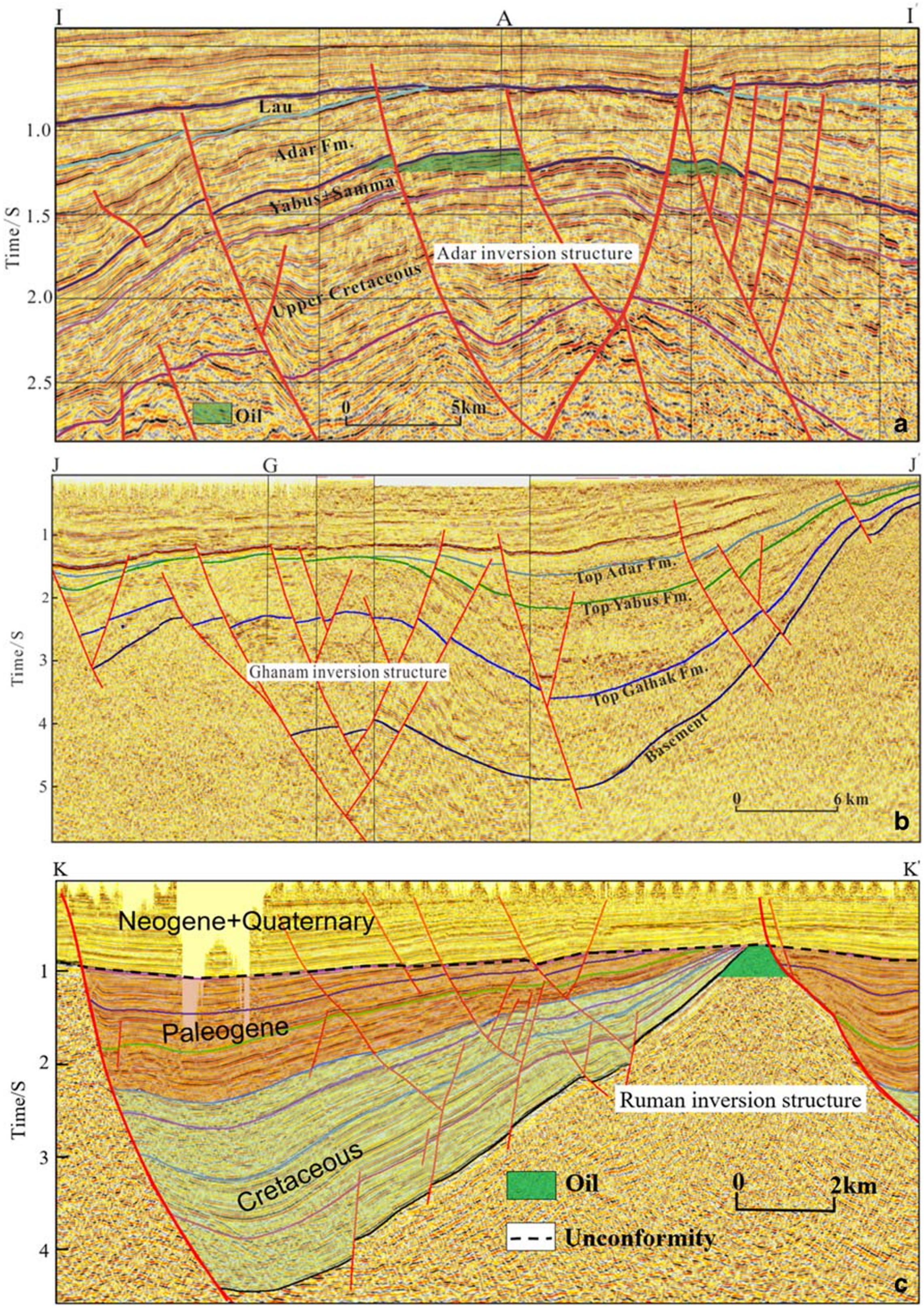

Fig. 13 Adar inversion structure of section I-I'(**a**), Ghanam inversion structure of section J-J'(**b**), and Ruman inversion structure of section K-K'(**c**). The section locations are shown in Fig. 2, and the approximate vertical exaggeration on these sections is 3.7

thickness than the inner-basin inversion structures, the inversion structures between sub-basins usually develop strong erosion and the Cretaceous and basement are favorable exploration targets. For instance, the Miyan inversion structure between the Central and Southern sub-basins has shallow burial depth, which made the Cretaceous formations shallower and be drillable, and some wells have got oil flow in Galhak and Al Renk Formations (Fig. 12). Similarly, the Paleogene and Cretaceous formations are totally eroded in the Ruman inversion structure between sub-basins (Figs. 4 and 13c), and the basement became an important target. Consequently, the Cretaceous and basement are potential exploration targets for the strong inner-basin inversion structures and the inversion structures between sub-basins.

Sedimentary infilling and hydrocarbon accumulation

Compared to the Northern sub-basin, the other sub-basins in the south Melut Basin are smaller, with areas of 2000–3000 km^2, and have coarser sedimentary infillings, which make the quality of Adar caprocks worse. The Adar Formation in most uplifts and slope areas of the south Melut Basin no longer presents thick mudstones, but of high sand content sequence (Fig. 14), which makes the reservoir-caprock pair of Yabus+Samma-Adar Formations get worse. That explained why most wells failed in the exploration of Yabus and Samma Formations in the south Melut Basin. Instead, the near-source Cretaceous formations develop better reservoir-caprock pair and have better oil-source and preservation conditions, and some wells have got oil flow in Cretaceous (Fig. 14). Compared to the Northern sub-basin, the buried depth of Cretaceous in the south Melut Basin is shallower due to the relatively small basin scale. Meanwhile, the widespread inversion structures make the Cretaceous formations uplifted, such as the Miyan inversion structure and the Ghanam inversion structure. Consequently, the near-source Cretaceous have better accumulation conditions and are the most favorable potential targets in the south Melut Basin.

Conclusions

(1) The Paleogene far-source migration and accumulation pattern is the primary hydrocarbon accumulation pattern in the Northern sub-basin, which accounted for 95% discoveries. The capability of hydrocarbon charge from the Al Renk source rocks and the development of oil-source faults are two controlling factors for the far-source accumulation pattern. The identification of Paleogene far-source migration and accumulation pattern successfully guided the exploration of the north Melut Basin. In the south Melut Basin, due to the coarse deposition of Adar Formation, the Paleogene far-source Yabus+Samma-Adar formations are not an effective reservoir-caprock pair. Conversely, the near-source Cretaceous and basement are favorable exploration targets due to the development of inversion structures.

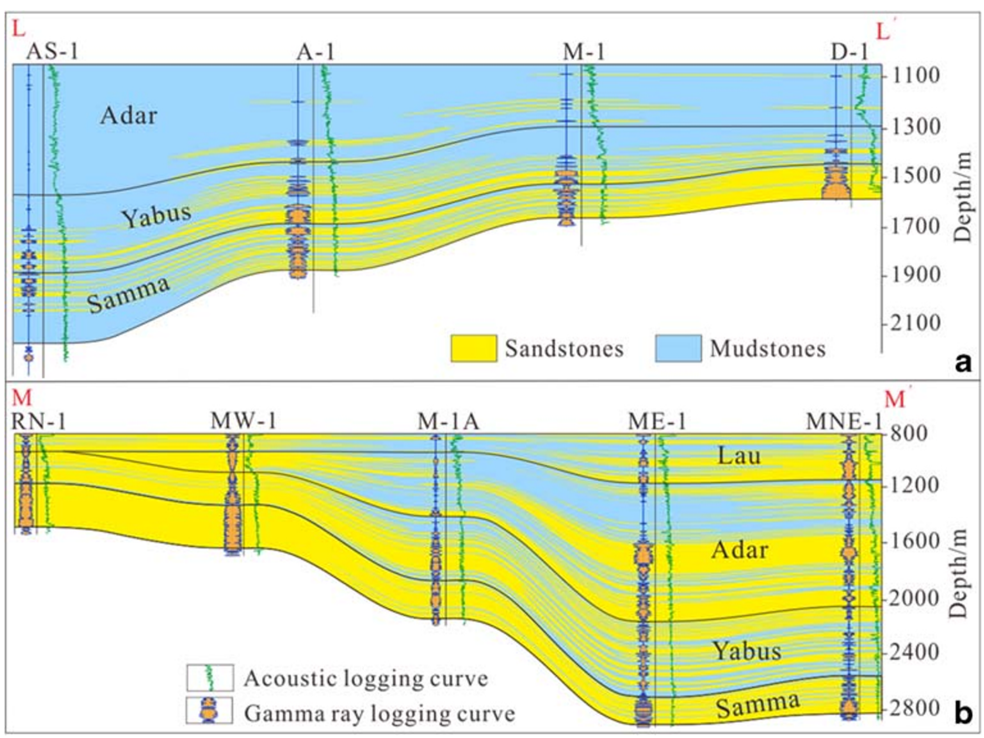

Fig. 14 Lithological features of the Adar Formation in the north (above) and south (below) Melut Basin, and the section locations are shown in Fig. 2.

(2) Three near-source Cretaceous accumulation patterns have been identified, including the lower-generation and upper-accumulation pattern of Galhak Formation, the upper-generation and lower-accumulation pattern of Al Gayger Formation, and the internal-generation and internal-accumulation pattern of Al Renk Formation. Moreover, the typical oil reservoir models of each accumulation pattern have been established. The identification and establishment of these hydrocarbon accumulation patterns and models would greatly promote the exploration of Cretaceous in the Melut Basin.

(3) The Melut Basin mainly develops local inversion structures, and the overall uplift of the basin is small, which made the inversion movement have limited impact on the hydrocarbon generation. The inversion structures made the Melut Basin develop favorable structural traps, meanwhile the continuous generation and expulsion of source rocks from Later Cretaceous to present is conducive to the hydrocarbon accumulation. Consequently, the inversion structures are generally favorable oil-bearing structures. The basin-margin inversion structure has poor oil-source condition, and the inner-basin inversion structure and the inversion structure between sub-basins are two types of favorable oil-bearing structures. For the weak inversion structures, the uplifting magnitude and erosion extent is light, and the Paleogene reservoir-caprock pair is well preserved. Inversely, for the strong inversion structures, the Paleogene reservoir-caprock pair is severely destroyed, and the Cretaceous and basement become potential drilling targets.

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