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The hydrocarbon accumulation potential of Upper Cretaceous to Paleogene in the northern Kaikang trough, Muglad Basin

Congsheng Bian[1] · Yongxin Li[1] · Bin Bai[1] · Xuexian Zhou[1] · Jiguo Liu[1]

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Abstract
This paper investigates the characteristics of sedimentary faces, source rocks, and hydrocarbon accumulation in detail within the Paleogene and Upper Cretaceous in the northern Kaikang trough, Muglad Basin. Analysis shows that the fluvial floodplain, delta, and shore-shallow lake facies are well developed in the main formations and several reservoir-cap assemblages are formed. Research on geochemical indicators, hydrocarbon generation, and expulsion potential of source rocks indicated that the thickness of good source rocks in Paleogene ranges from 50 to 200 m and TOC value can reach 0.5–1.3%, but it is immature and has no hydrocarbon generation potential. Nevertheless, the Upper Cretaceous source rocks are mostly matured, but its hydrocarbon generation is limited because of lower TOC (only 0.5–0.8%) and thinner thickness (only 10 m). The main effective source rock is the AG Group in the Lower Cretaceous, which is distributed throughout the area. The evolutionary history shows that most of structures in the central troughs lack hydrocarbon potential, because they were formed since the Paleogene, which are later than the main accumulation period of the AG source rock. The fault terrace zones on both sides of the Kaikang trough have obtained petroleum discovery, but the distribution of oil layers is much complicated. Hydrocarbon accumulation is controlled by formation dips, fault activity intensity, and fault lateral docking characteristics. The weaker active fault block in late period and more effective trap are the key factors to hydrocarbon enrichment at the fault terrace zones. There are two typical reservoir-forming modes; one is the small fault distance reservoir-forming mode of the lower primary reservoir, and the other is the secondary reservoir-forming mode of the upper and middle combination.

Keywords Sedimentary face · Source rocks · Hydrocarbon accumulation · Upper Cretaceous · Paleogene · Kaikang trough · Muglad Basin

Introduction

Kaikang trough is located in the middle of the Muglad Basin and can be divided into the north and the south subdepressions (Dou 2005; Tong et al. 2004). The area of the north subdepression is approximately 7000 km^2. It is a narrow sag with a long axis distance of more than 30 km and a short axis distance of 5–10 km. The thickness of the strata in the sag is over 10,000 m, which mainly includes Cretaceous, Paleogene, and Neogene formations (Mohamed et al. 2002; Ran et al. 2014; Hong et al. 2019). It belongs to continental river-delta and lacustrine deposits. In recent years, many large-scale oil and gas reservoirs have been discovered successively in the Cretaceous on both sides of Kaikang trough, which proves that the hydrocarbon accumulation conditions in this area are superior and the potential of reservoirs is great. However, the depth of the Cretaceous in the depression is relatively deep, especially the Lower Cretaceous, which is more than 5000 m. Therefore, the Upper Cretaceous and Paleogene with shallower depth than Cretaceous are the main exploration targets in the depression (Zhang and Chen 2002).

After intensive hydrocarbon exploration, only a few of reservoirs have been discovered within the Upper Cretaceous and Paleogene in the central depression, which made explorer lose their confidences (Dou 2005; Zhang et al. 2018). It is unclear whether the upper Cretaceous and Paleogene in the Kaikang

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✉ Congsheng Bian
biancongsheng@126.com

1 Research Institute of Petroleum Exploration & Development, PetroChina, Beijing, China

trough are capable of hydrocarbon generation or whether secondary reservoirs can be formed. In view of this geological problem, this paper has investigated the characteristics of stratigraphic sediments, the development history of source rocks, the tectonic evolution, and the main controlling factors of hydrocarbon accumulation in detail within the Paleogene and Upper Cretaceous formations, and a detailed and comprehensive geology understanding has been obtained.

Geologic setting

Muglad Basin is a typical passive rift basin in the eastern part of the Central African giant strike-slip fault zone (CASZ) (Emmanuel et al. 2008; Adissin et al. 2014). Generally, the basin is a triangle of "wide north and narrow south" and terminated in the Central African shear zone in the NW direction and converges in the interior of the African plate in the SE direction (Zhang et al. 2015; Zhang et al. 2018) (Fig. 1). It is a Cretaceous extensional rift basin with an area of about 112,000 km^2. The study area in the basin has a structural pattern of "one depression, two fault steps, and two slopes," which are Kaikang depression, east and west fault step zone of Kaikang, and east and west slope zone. It underwent three large-scale rifting and depression activities in the Early Cretaceous, Late Cretaceous, and Early Paleogene-Neogene, forming three sets of sedimentary cycles (Tong et al. 2004; Shi et al. 2014): (1) AG rift deposits and Bentiu-Aradeiba depression deposits, (2) Zarqa-Ghazal-Baraka rift deposits and Amal depression deposits, and (3) Nayil-Tendi rift deposits. The AG formation deposited in the first rift period is a set of proven source rocks, which together with the overlying Bentiu sandstone reservoir and the mudstone caprock of the Aradeiba formation constitute a complete source-reservoir-cap combination. The Bentiu sandstone is the important reservoir in this area and a lot of oil fields were found (Dou et al. 2006). However, seismic profiles and drilling results confirm that multi-stage tectonic activities have developed in the study area, resulting in complex fault systems (Mohamed et al. 2001), oil-bearing multi-layers, and distinct hydrocarbon differential

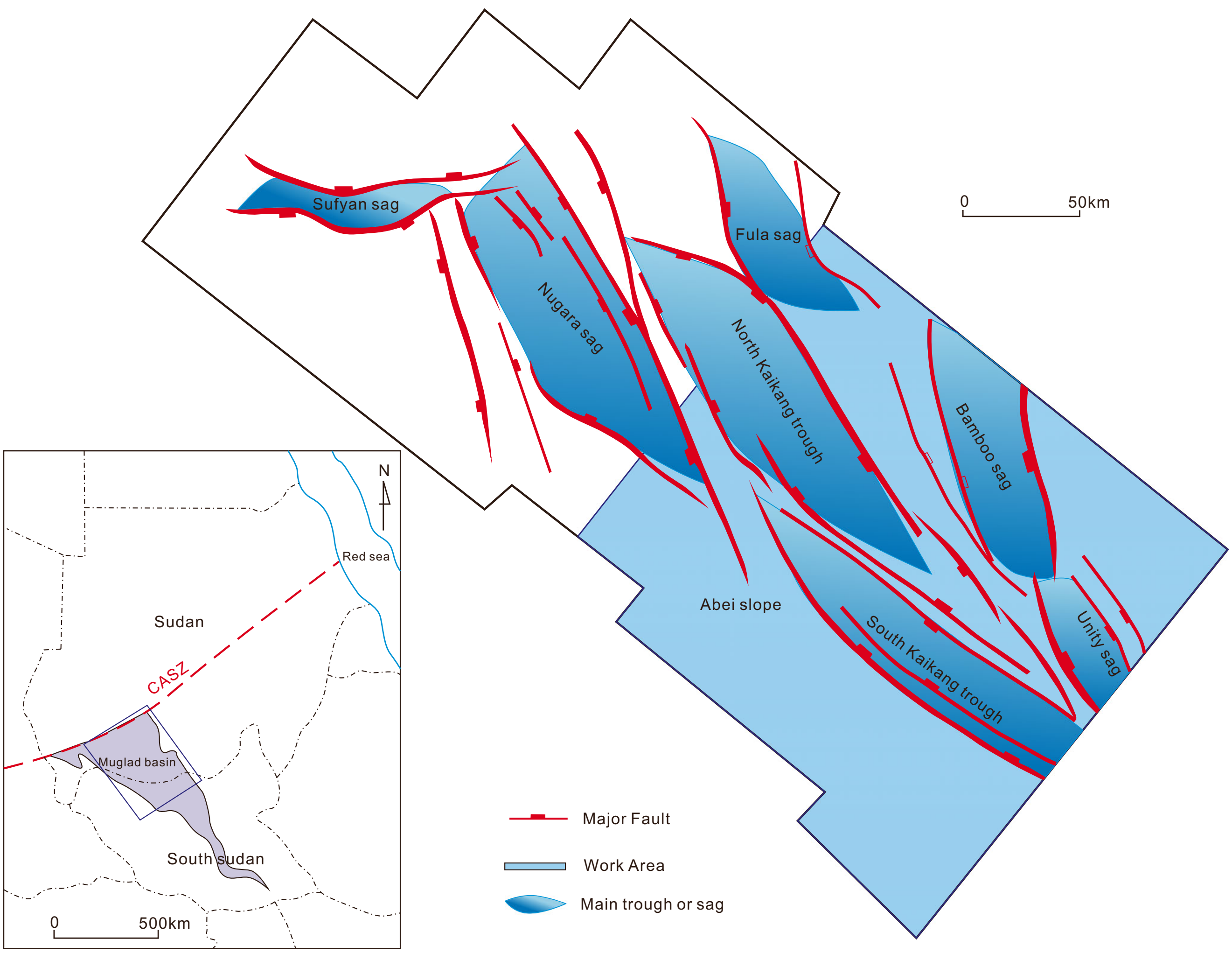


Fig. 1 Location map of the Kaikang trough and work area in the Muglad Basin, Sudan (altered from Yousif et al. 2015)

accumulation characteristics (Yousif et al. 2015, 2016). Due to the poor quality of seismic data and lack of wells, the understanding of deep geological structure is relatively lacking. The secondary and Tertiary sedimentary assemblages in the middle and shallow layers are the main target layers (Fig. 2).

Methods

In view of the problems of whether the Upper Cretaceous and Paleogene in the Kaikang trough are capable of hydrocarbon generation, the paper has investigated the stratigraphic characteristics of sediments, hydrocarbon generation potential of source rocks by conferences and well data, and the main controlling factors of hydrocarbon accumulation in detail within the Paleogene and Upper Cretaceous of the area by seismic and well data as well as typical sections.

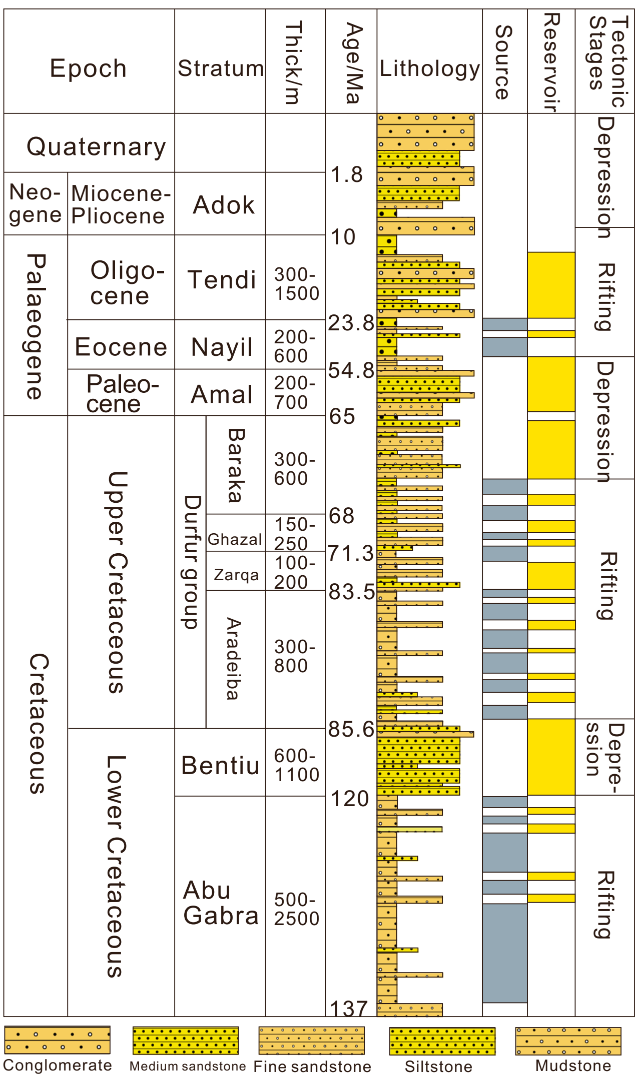


Fig. 2 Lithostratigraphic column map of the Kaikang trough in the Muglad Basin, Sudan

The log data and core data of 8 wells in the area were analyzed, and the well logging method was utilized to calculate the TOC value of the source rock in every well, due to the lack of core geochemistry analysis in this area. By restoring the history of regional tectonic evolution, the formation period of the tectonic structure in the trough and its relationship with the hydrocarbon generation history of the source rocks are inferred. The reservoir types and structural features of reservoirs and failure wells are analyzed, to study the main controlling factors of reservoirs, and the future exploration direction and key issues that need attention are proposed.

Results

Sedimentary facies characteristics

Through the analysis of logging curves and sedimentary assemblages, it is cleared that the Upper Cretaceous, Paleogene, and Neogene in Kaikang trough mainly developed fluvial floodplain, delta, and shore-shallow lake facies. (1) River-flood plain facies: mainly developed in Amal-Nayil formation. The fluvial sediments are mainly composed of coarse sandstone, gravel sandstone, and red and green mudstone, with scouring surface at the bottom. Natural gamma also has the characteristics of toothed box. Because the study area is located in the center of Kaikang trough, which is far from the provenance, the sedimentary sequence showed the meandering river sediments characteristics. It indicates that the grain size of rivers is relatively fine and there is no large amount of conglomerate. The floodplain deposits are mainly developed on the edge of Nayil formation and lakeside, which are mainly a set of positive and negative cycles composed of red mudstone and sandstone. (2) Delta deposits: mainly developed in the Zarqa, Ghazal, Baraka, and Tendi formations. The delta plain is composed of sandstone and green or red mudstone with a positive cyclic. The delta front is composed of a reverse cycle of sandstone and gray mudstone. The pre-delta and shallow lake deposits are mainly composed of gray mudstone mixed with sandstone and siltstone. (3) Shore-shallow lake sediments: mainly developed in Aradeiba formation, consisting of gray mudstone, gray-green mudstone, and purple-red mudstone with siltstone, forming positive and negative cycles on the section (Fig. 3).

By studying the sedimentary facies of the Upper Cretaceous in the NE-trending main section of the work area (Fig. 4), it is found that the Aradeiba formation developed floodplain deposits in the north and south edge parts and shallow lake deposits in the center of the basin. In plane, the Aradeiba formation developed delta front subfacies in the northern, western, and eastern margins of the study area, and the central part mainly developed shallow lake to pre-delta subfacies. The Zarqa, Ghazal, and Baraka formations developed delta front subfacies in the margin of the study area and

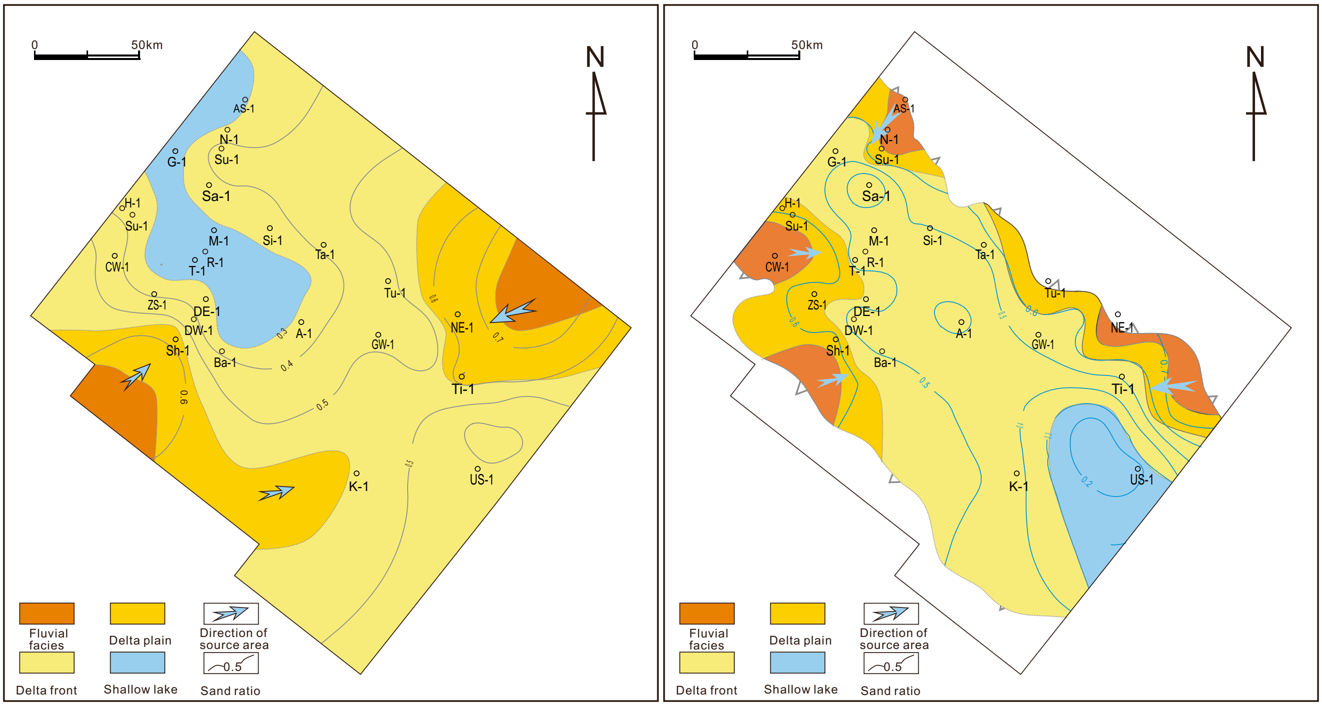


Fig. 3 Sedimentary faces map of Ghazal (left) and Tendi (right) formation

shallow lake to pre-delta subfacies deposits in the center of the lake basin. Overall, the delta progressed toward the center of the lake. The Amal formation is a fluvial facies deposit widely developed in the whole basin, which is thicker in the center of the basin and thinner on both sides. Nayil formation is a set of red flooding basin deposits, which are widely distributed in

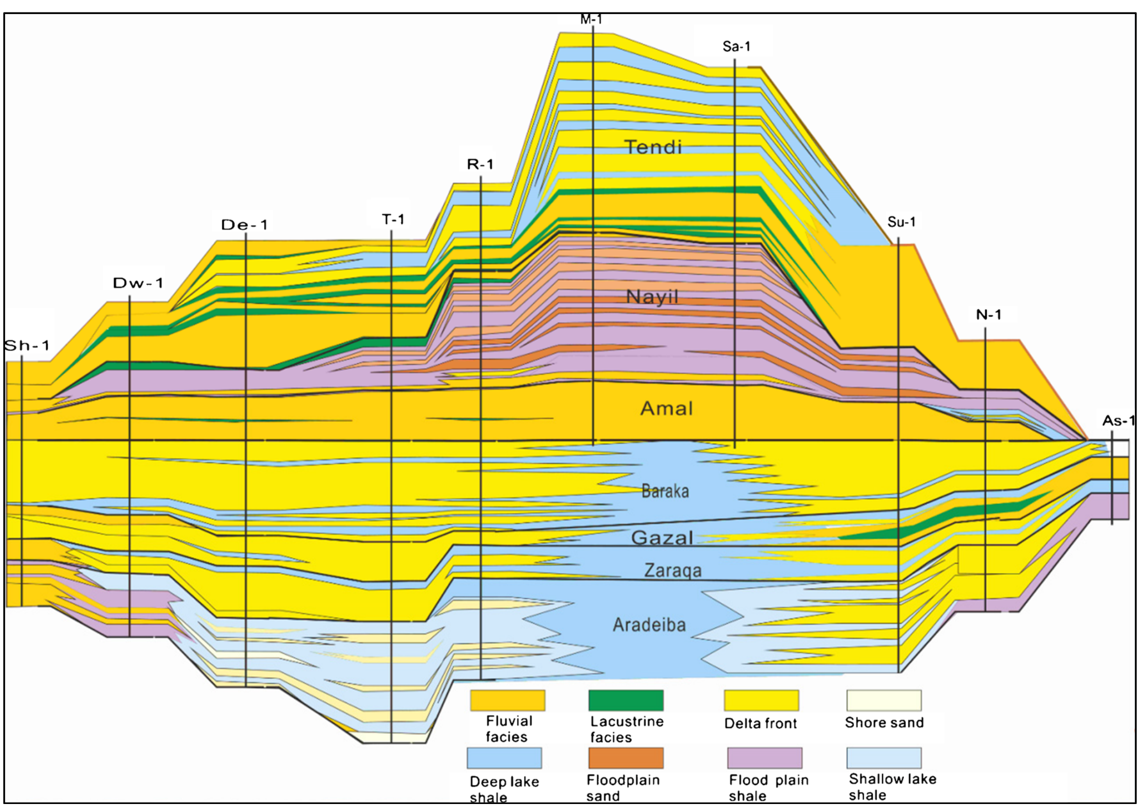


Fig. 4 NE-trending sedimentary facies section of Upper Cretaceous and Tertiary formation in Kaikang trough

the whole basin. The Amal and Nayil formations constitute a set of sedimentary assemblages of alluvial fan facies on the profile. The Nayil formation developed alluvial fan-flooding basin deposits, alluvial fan deposits in the eastern and western parts, and north-south flooding plain deposits in the center of the study area. The Tendi formation developed fluvial delta sedimentary system; alluvial fan-delta plain subfacies developed in the eastern, western, and northern provenance areas; and delta front developed in the main body of the study area, while the former delta developed in the southeastern part of the study area, with a smaller scope (Fig. 4).

Characteristics and distribution of reservoir-cap assemblages

According to the distribution characteristics of sedimentary facies and stratigraphic lithology, the Upper Cretaceous and Paleogene strata in this area can be divided into three sets of reservoir-cap assemblages, which are Bentiu-Aradeiba, Zarqa-Ghazal, and Nayil-Tendi assemblage from bottom to top (Fig. 3).

Bentiu-Aradeiba assemblage is the most important oil-bearing assemblage in the whole basin, and a large number of oilfields have been discovered. Bentiu formation is a set of high-quality reservoirs distributed in the whole area, while Aradeiba formation is a set of mudstone caprock with sandstone thickness ratio of 0.2–0.3. Because Bentiu formation is buried deep in Kaikang depression, generally over 5000 m, it is not the main target layer at present. In addition, the Aradeiba formation itself has developed thin sandstone reservoirs, especially in fault terrace and slope zone, which are dominated by delta front sand deposits with relatively shallow depth, and hydrocarbon has been discovered in this area, such as Diffra Oilfield.

Zarqa-Ghazal assemblage is also an important assemblage of Upper Cretaceous in fault terrace zone and slope zone on both sides of Kaikang trough. As a whole, Zarqa and Ghazal formations are mainly composed of delta front sand-mudstone interbedding deposits with a sand-to-ground ratio of 0.2–0.4(Fig. 2). Mudstone can be used as a regional stable caprock, and the sand layer developed inside can be the effective reservoir. This combination developed well in Kaikang trough-edge fault terrace zone and slope zone.

Nayil-Tendi assemblage belongs to Paleogene strata. The Nayil formation is dominated by purple-red mudstone deposits, with mudstone thickness of 200–600 m and mudstone thickness ratio of more than 0.7. However, there are 2–3 layers of sandstone with a thickness of 8–15 m in the lower part of Nayil formation, which has a stable lateral distribution and a porosity of 10–20%. It is a good reservoir and has a good reservoir-cap association with the upper mudstone. The oil discoveries in the Paleogene of Kaikang trough are mainly concentrated in this section. Sand-mudstone interbedded deposits are developed vertically in the Tendi formation. Tendi formation developed interbedded sand-mudstone deposits belonging to delta front facies, with the sandstone thickness ratio basically below 0.5, where the sand-mud interaction can form better reservoir-cap assemblages (Fig. 2).

Characteristics of source rocks

As mentioned above, the main proven source rock in Muglad Basin is the AG formation in Lower Cretaceous, which is distributed all over the region, and a large number of reservoirs from the AG source rock have been found. Whether there are hydrocarbon source rocks in the Upper Cretaceous and Paleogene in this area has not been confirmed, especially in areas with large thickness and widely distributed mudstone. The TOC data of some drilling wells indicate that the Paleogene in this area has a certain hydrocarbon generation potential, but most wells in the Upper Cretaceous and Paleogene have no measured data, which makes it difficult to confirm the hydrocarbon generation potential of these two formations in the whole area. According to the logging data of the work area and the mature TOC evaluation method at present (Zhang and Zhang 2000; Zhu et al. 2003a), the TOC calculation of 8 wells with good and representative data in the work area has been carried out. The resistivity-acoustic formula is used as follows:

$$\Delta LogR = Log10\left(\frac{RT}{RT_{Baseline}}\right) + 0.02*(DT - DT_{Baseline}) \quad (1)$$

$$TOC = \Delta LogR*10(2.297 - 0.1688*R_0) \quad (2)$$

In the formula, RT is the resistivity, unitΩ.m; DT is the acoustic time difference, unitμm/s; and R_o is the actual vitrinite reflectance. The TOC value of mudstone can be calculated by the above formula and then corrected by the measured value; the more accurate TOC value of the target stratum can be obtained (Zhu et al. 2003b; Chen et al. 2015).

The calculation results are shown in Figs. 5 and 6. Figure 6 shows that the effective source rocks of Paleogene are mainly distributed in the central and northern regions, which is close to the distribution of the sedimentary center of the Kaikang trough. The thickness of Paleogene source rock ranges from 50 to 200 m, and the TOC content can reach 1–4%, which is a high-quality source rock. The distribution of source rock in Upper Cretaceous is similar to the Paleogene, but the thickness is relatively thin, about 10–25 m. In addition, the TOC content of the Upper Cretaceous source rocks is only 0.5–0.8% (Fig. 5), which is a moderate-quality source rock with limited hydrocarbon generation potential. The history of thermal evolution in this area indicates that the burial depth of 1800 m corresponds to 0.6% of R_o, which is the threshold of affective source rock in this area. However, the burial depth of the Paleogene source rock with TOC 1–4% is mostly 1500 m

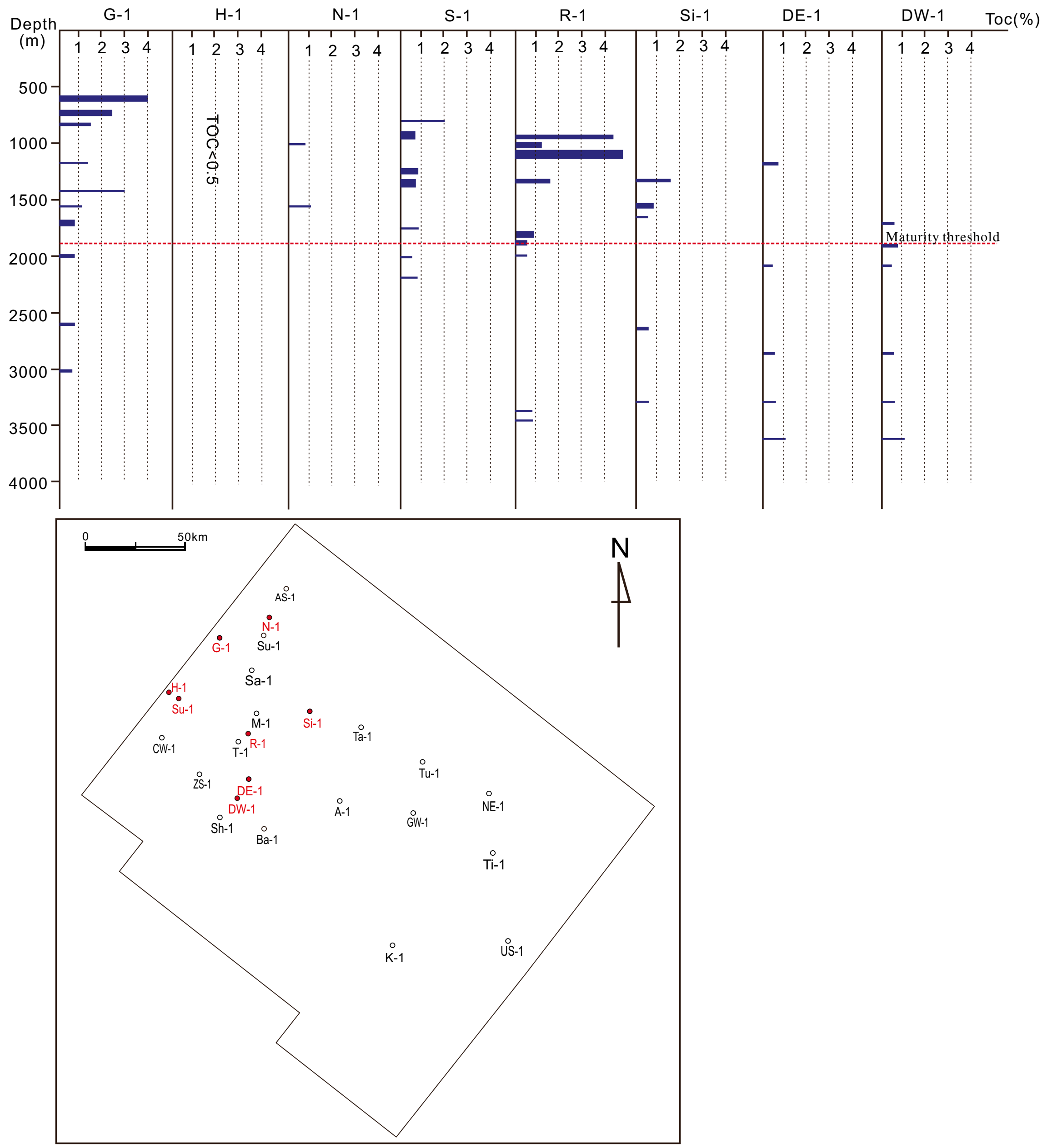


Fig. 5 The upper figure shows the distribution of TOC values of source rocks in 8 wells with depth. Those source rocks with high TOC (1–4%) value did not enter the hydrocarbon generation threshold. The lower map shows the location of these 8 wells (in red color)

or shallower (Fig. 5), and it is immature. Nevertheless, Upper Cretaceous source rocks mostly entered the maturity threshold, its TOC values and thickness are both small, so the hydrocarbon generation potential is limited (Fig. 5).

According to predecessors research outcome, AG source rock began to generating oil in Upper Cretaceous and generating gas in Paleogene, but over mature in Neogene time (Abdalla et al. 2002). Simulation of well T-1 burial history and hydrocarbon generation and expulsion history shows that AG source rock entered the peak of oil production ($R_o = 1.3\%$) during the deposition time of Aradeiba-Baraka formations and entered the gasification window in the period of Amal sedimentary time ($R_o = 1.6\%$), which has now reached a high state of maturation ($R_o > 2.0\%$) in the area of Kaikang trough (Fig. 7).

Characteristics and Main controlling factor of hydrocarbon accumulation

Since the wells in the central Kaikang trough were drilled before the 1990s, the data and information were incomplete. The reinterpretation of the reservoirs and hydrocarbons for 5 wells (such as M-1, G-1) showed that the reservoir of Paleogene and Upper Cretaceous is well developed with an

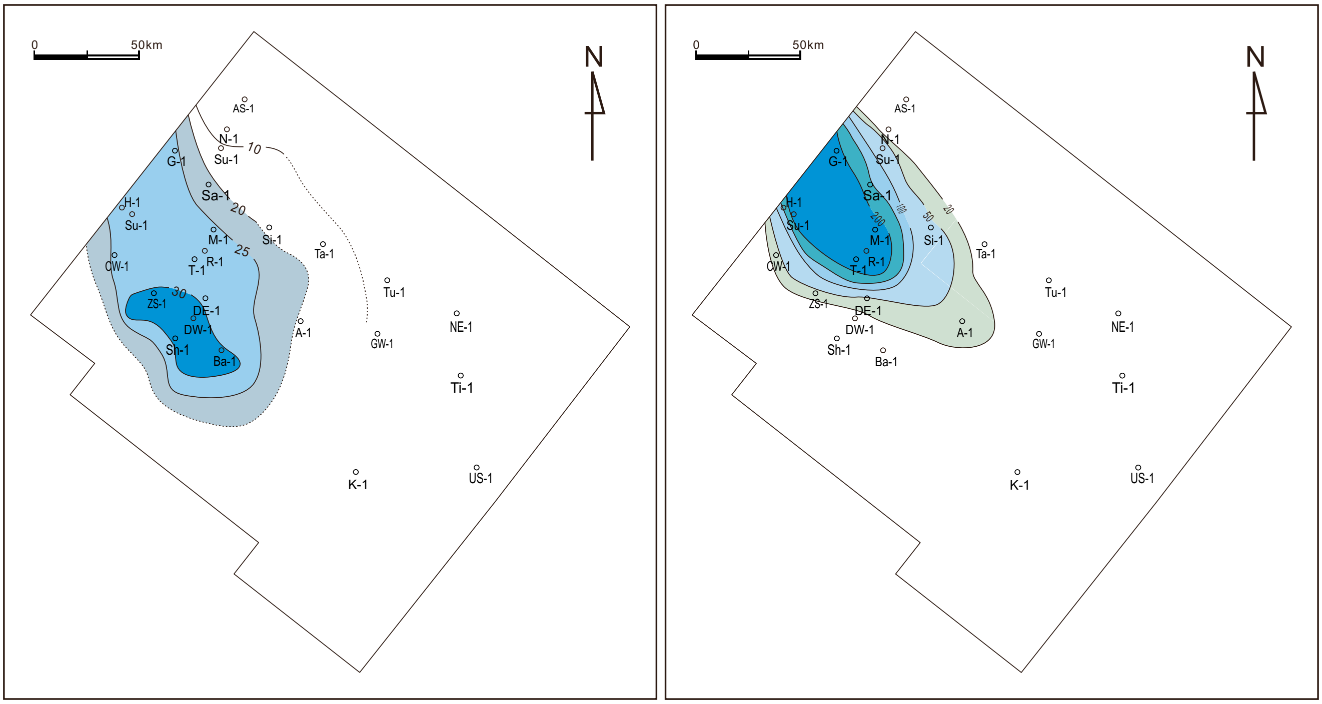


Fig. 6 Distribution of thickness of effective source rocks of K2 and Tertiary formation

average porosity of 10 to 18% and thickness of 50–200 m. However, there is no any hydrocarbon display during drilling and logging, so all these wells are interpreted as dry wells. The analysis of the evolutionary history of central Kaikang trough shows that most of structures in the central troughs were formed since the Paleogene (Maurin and Guiraud 1993; Mohamed et al. 2001; Guiraud et al. 2005; Pan et al. 2005), which are later than the main accumulation period of the AG hydrocarbon source, so they lacked of oil filling, and their hydrocarbon potential is limited (Fig. 8).

The reinterpretation of the four wells (Su-1, T-1, R-1, Ta-1) in the stepped zone on both sides of the Kaikang trough shows that the Cretaceous and Paleogene reservoirs were well developed, with average porosity of 7–12% and thickness of 10–

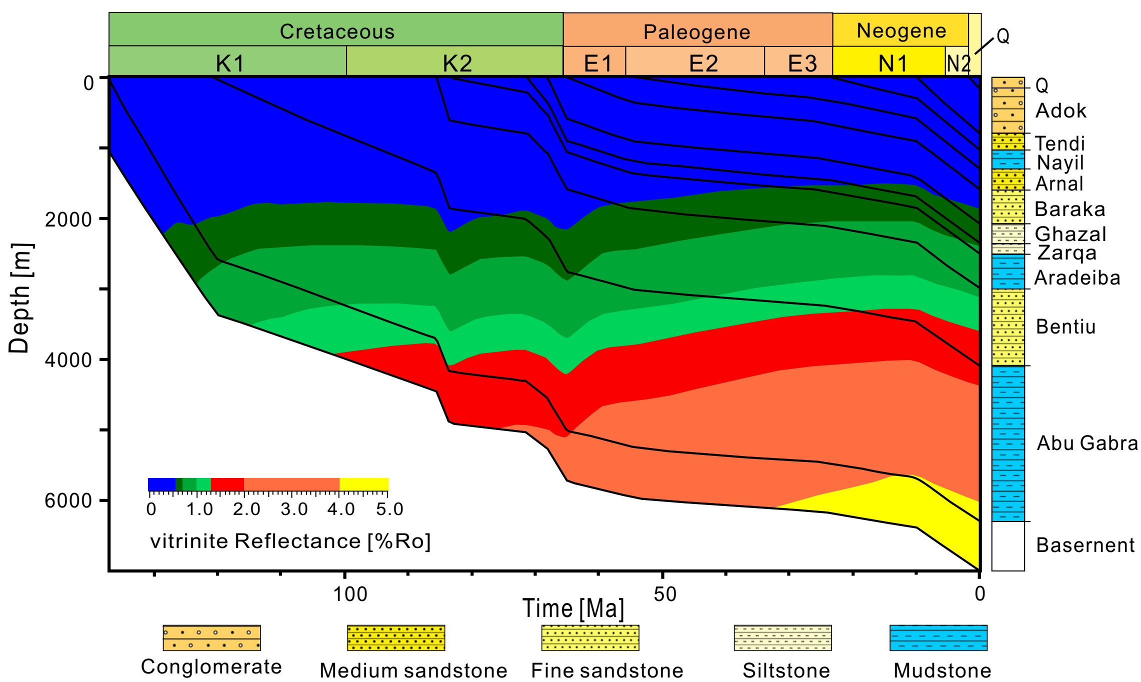


Fig. 7 Simulation outcome of well T-1 burial history and hydrocarbon generation and expulsion history

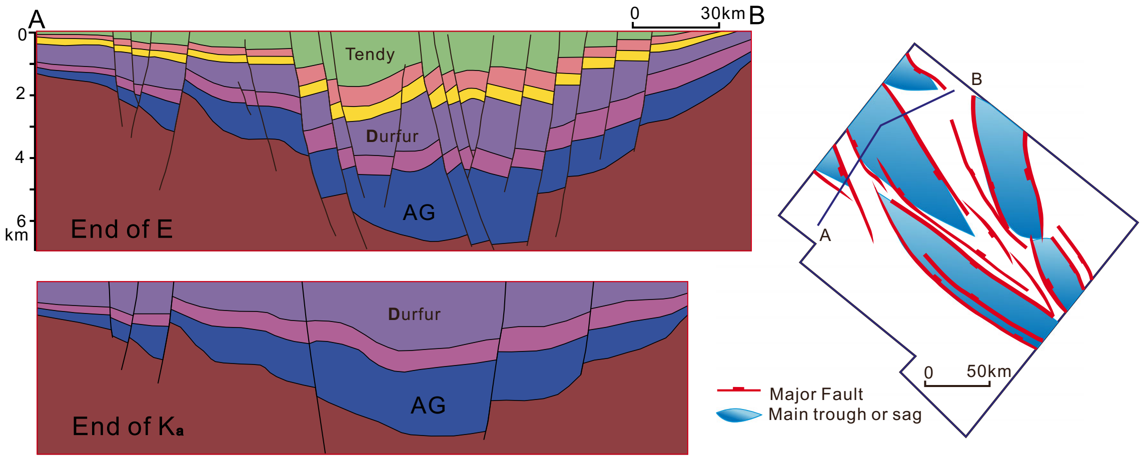
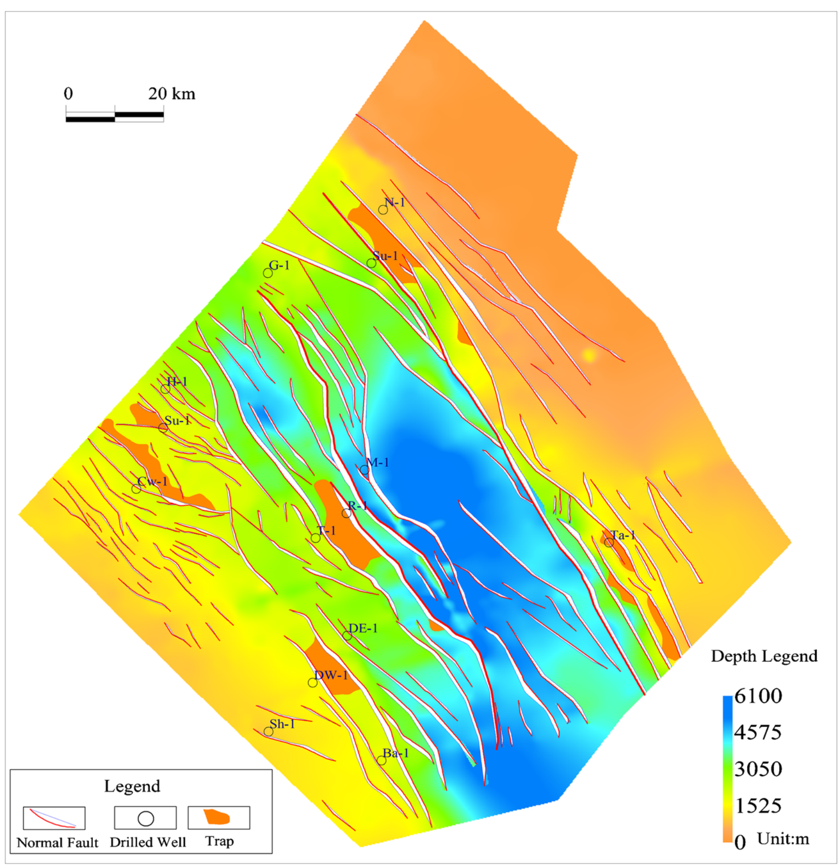


Fig. 8 The NE evolutionary history section of K2 and Tertiary formation in Kaikang trough

30 m and some wells can reach 150–200 m. Several oil layers were discovered in two wells (Su-1, T-1), and heavy oil was obtained from one tested wells, which indicates that the hydrocarbon potential of the fault terrace zones is better than those in the center of trough (Fig. 9). However, due to the complicated structures of the fault terrace zones and the fault contact relationship, the distribution of oil layers is much complicated (Zhang et al. 2019).

Based on the analysis of reservoirs characteristics found in Kaikang trough, the main controls on hydrocarbon accumulation are formation dips, fault activity intensity, and fault lateral docking characteristics. For reservoirs that have been discovered, except for individual with better anticline structures, the structural dip of faulted anticline or block is mostly less than 3°. Because the bigger the dip angle is, the worse the vertical sealing of faults is, which is unfavorable to hydrocarbon accumulation. The secondary controlling factor is the fault distance. Most of the reservoirs have the fault distance less than 200 m, and there are probably no good hydrocarbon accumulations in reservoirs which have fault

Fig. 9 The Top structure map and fault distribution of Upper Cretaceous in North Kaikang trough



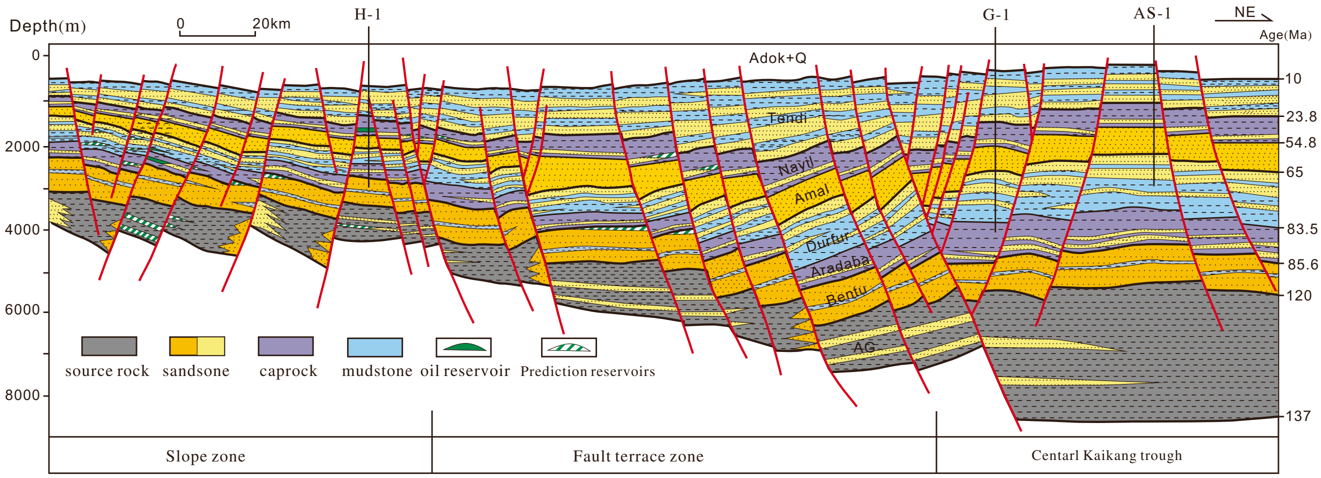


Fig. 10 NEE-trending strata, lithology, and reservoir-forming profile in North Kaikang trough

distance greater than 500 m. Because the larger the fault distance, the stronger the activity of the fault and the greater the frequency of the fault activity; it is easy to be loss of oil and gas. The third factor is the connection situation on both sides of the fault. For example, in the Bohai Bay Basin, east of China (Zhao and Chi 2000; Dou et al. 2006; Yang et al. 2008), the fault connection situation determines directly whether the trap can seal oil and gas or not. Sandstone and mudstone connection in the two sides of fault can seal the reservoir, but sandstone and sandstone docking can invalidate the trap. Therefore, the weaker active fault block in late time can develop the more effective trap, which is the key factor to hydrocarbon enrichment at the fault terrace zones in the faulted depression (Fig. 10).

The important role of the main controlling factors of reservoir formation can be more clearly defined by case study. For example, Diffra and Diffra East fault-nose structures are located in the Western fault terrace belt of Kaikang depression (Fig. 9), which belong to the inherited fault anticline structures, and many groups of NW faults are laterally developed. Diffra structure is located on the west side of the fault terrace zone, near the slope zone. The stratum of trap development is gentle, with less than 2° dip angle, and fault distance is small, only 50–100 m.

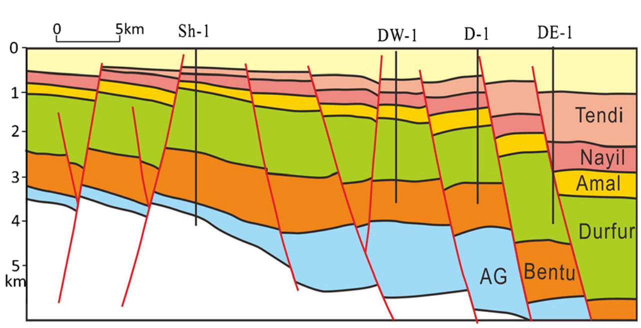


Fig. 11 The geological section with faults and well of Diffra structure in Kaikang trough

These conditions are conducive to trap closure, and D-1 well has found oil reservoirs. Diffra East structure is located in the eastern side of Diffra structure, close to the eastern depression-controlling faults, with a fault distance of 1100 m. The structural evolution history showed that the fault distance before the deposition of Tendi formation is small and the trap was well sealed laterally, just like Diffra structure. However, after Tendi period, the right trough next to Diffra East structure subsided rapidly, the fault distance increased even to 1100 m, which led to the docking of the lateral sandstone-rich formations from the Bentiu and Baraka formation, the lateral seal basically failed, and then a large number of oil and gas were lost. Therefore, the oil and gas shown in the vertical section appeared in the drilling process of DE-1 well, but there was no hydrocarbon accumulation (Fig. 11)

The pattern of hydrocarbon accumulation

As mentioned before, secondary oil and gas reservoirs are mainly developed in the target formation of this area, and the oil source mainly comes from the underlying AG source rock or paleo-reservoirs of Lower Cretaceous. In addition to meeting the above three factors, effective source fault is the important requirement for hydrocarbon accumulation. This requires that the distances of the lower part of the source faults connecting the source exceed 200 m, even to 500–1000 m, and the dip angle is usually greater than 3°, which destroys the regional caprock of Aradeiba formation, and hydrocarbon migrates upward. In addition, the enrichment of lower oil source or paleo-reservoir requires that paleo-structure usually exists in this area, which is the migration direction area of oil and gas, such as Haraz and Hilba areas in the north part of work area, and both have this feature (Fig. 12 left).

Furthermore, Kaikang trough also develops primary reservoirs in Bentiu formations, where the traps conform to the

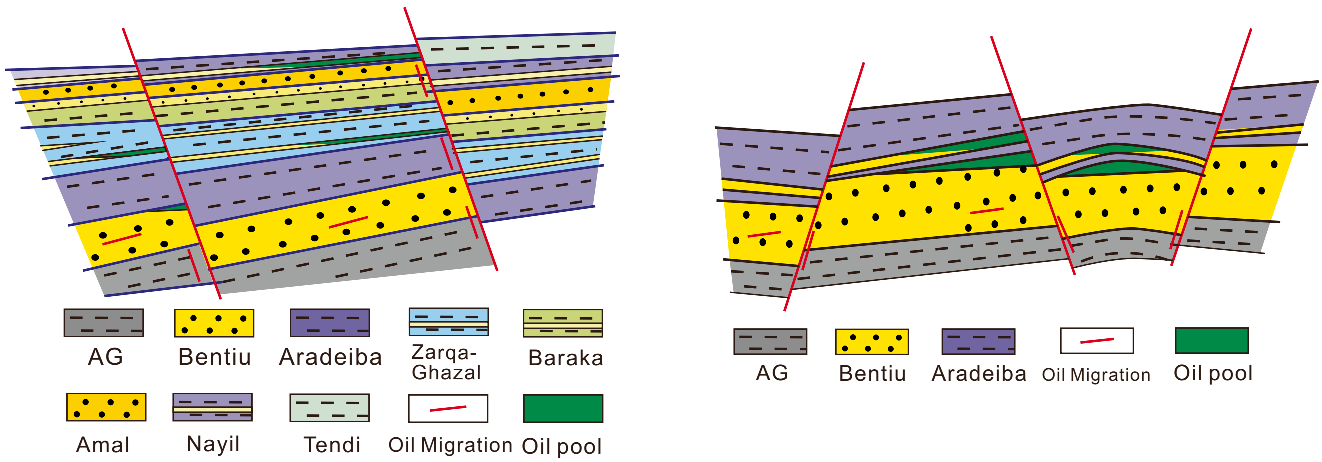


Fig. 12 The hydrocarbon accumulation section of two typical reservoir-forming modes

above three factors, so that the primary reservoir can be effectively preserved and not destroyed by the later tectonic movement. In addition, it should be located near the hydrocarbon-generating sag, with abundant oil sources. Therefore, the favorable reservoir-forming areas of the lower assemblage are mainly located in the slope zone of the development area of hydrocarbon-generating sub-sag on the east and west side of Kaikang trough, and the fault terrace zone is difficult to preserve because of the large fault distance (Fig. 12 right).

These two types of reservoirs belong to two typical hydrocarbon accumulating modes; one is the small fault distance reservoir-forming mode of the lower primary reservoir (Fig. 12 left), and the other is the secondary reservoir-forming mode of the upper and middle combination (lower large fault-spacing + upper small fault-spacing) (Fig. 12 right).

Discussion

Based on the analysis of reservoirs characteristics found in the Kaikang trough, the main controls on hydrocarbon accumulation are formation dips, fault distance, and fault lateral docking characteristics. Firstly, the reservoirs with good hydrocarbon accumulations often have a lower structural dip mostly less than 3°. Secondly, most of the oil reservoirs have the fault distance less than 200 m in the target formation and a big distance near source rocks, and there are hardly hydrocarbon accumulations in reservoirs which have fault distance greater than 200 m, especially greater than 500 m. The third factor is the formation lithology on both sides of the fault. Sandstone and mudstone connection can seal the reservoir, but sandstone and sandstone docking can invalidate the trap. Therefore, the weaker active fault block in late time and the more effective trap are the key to hydrocarbon enrichment at the fault terrace zones in the faulted depression.

Conclusion

This paper shows us that the source rocks in Upper Cretaceous and Paleogene have limited hydrocarbon generation potential, and the main effective source rock is the AG Group in the Lower Cretaceous. The hydrocarbon potential of Paleogene in the northern Kaikang trough is poor, because the structures in the central troughs were formed since the Paleogene, which are later than the main accumulation period of the AG hydrocarbon source. The main controls on hydrocarbon accumulation in the Kaikang trough are formation dips, fault distance, and fault lateral docking characteristics. The eastern stepped zone developed many fault blocks with small dip angle, which is beneficial to the large-scale lateral migration of hydrocarbon from the AG source rock. So those are the favorable exploration area for oil exploration.

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