# Structural Characteristics and its Significances on Hydrocarbon Accumulation in the Yunkai Low Uplift, Pearl River Mouth Basin

YU Yixin[1, 2], ZHANG Tianlong[3], ZHANG Zhongtao[4], ZHANG Gongcheng[5, *], ZENG Jianhui[1, 2], YANG Haizhang[5], ZHAO Zhao[5] and LIANG Weiwei[3]

[1] *State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China*
[2] *College of Geosciences, China University of Petroleum, Beijing 102249, China*
[3] *Research Institute, Shaanxi Yanchang Petroleum (Group) Co., Ltd., Xi'an 710075, China*
[4] *CNOOC China Limited, Shenzhen Branch, Shenzhen 518054, China*
[5] *CNOOC Research Institute Co., Ltd., Beijing 100028, China*

**Abstract:** The Yunkai low uplift with low exploration degree is close to the Baiyun sag, and has hydrocarbon exploration potential in the deepwater area of the Pearl River Mouth Basin. Based on seismic and drilling data, balanced profiles and growth strata, this paper mainly discusses geological structures and formation processes of the Yunkai low uplift, and also analyzes the characteristics of fault system and their influence on hydrocarbon migration and accumulation. The EW-trending basement faults divide the Yunkai low uplift into two parts, i.e. the southern sector and the northern sector. The northern sector is a relatively wide and gentle uplift, while the southern sector is composed of two secondary half-grabens with faulting in the south and overlapping in the north. The Yunkai low uplift experienced three major formation stages, including the rapid uplifting stage during the deposition period of the Eocene Wenchang Formation, the slow uplifting stage during the deposition period of the Late Eocene-Middle Miocene Enping-Hanjiang formations, and the whole burial stage from the Middle Miocene to present. The extensional faults in the Yunkai low uplift and its adjacent areas strike mainly along the NW, NWW and near-EW directions. Also, the strikes of faults present a clockwise rotation from the deep to the shallow strata. According to effects of faults on hydrocarbon accumulation, the faults in the Yunkai low uplift and its adjacent areas can be divided into trap-controlled faults and source-controlled faults. The trap-controlled faults control trap development and can effectively seal oil and gas. The source-controlled faults connect directly source rocks and reservoirs, which are highly active during the rifting stage and weakly active since the Miocene. This activity features of the source-controlled faults is beneficial to migration of the early crude oil from the Baiyun sag to the high part of the Yunkai low uplift, but is not good for migration of the late natural gas. In the Yunkai low uplift and its adjacent areas, the traps in the deep Zhuhai and Enping formations that are close to source rocks in the Baiyun sag should be the favorable exploration objectives.

**Key words:** fault activity, hydrocarbon accumulation, Yunkai low, Pearl River Mouth Basin

Citation: Yu et al., 2021. Structural Characteristics and its Significances on Hydrocarbon Accumulation in the Yunkai Low Uplift, Pearl River Mouth Basin. Acta Geologica Sinica (English Edition), 95(1): 21–29. DOI: 10.1111/1755-6724.14622

## 1 Introduction

Extensional faults with various scales and trends, and multi-stage activities are one of the most significant structural features of faulted basins and are of significance for the basin formation, sedimentary systems and trap development, hydrocarbon migration and accumulation (Yielding et al., 1997; Luo, 2002; Gawthorpe and Leeder, 2010; Childs et al., 2017; Serck and Braathen, 2019; Wang et al., 2019). Consequently, the research on fault is the key content of structural analysis, hydrocarbon accumulation and exploration potential evaluation in faulted basin. The Pearl River Mouth Basin is an important petroliferous basin located on the continental margin of southeast China, and also a Cenozoic rift basin developed from the quasi-passive continental margin (He et al., 2008). In recent years, several important exploration breakthroughs have been achieved in the Pearl River Mouth Basin (Shi et al., 2014; Mi et al., 2018; Xie and Gao, 2020). Previous studies were mainly carried on the basin formation, dynamic mechanisms, hydrocarbon accumulation characteristics and their controlling factors of the Pearl River Mouth Basin. The results show that the hyper-extended continental crust and a series of large-scale detachment fault systems exerted important influence on basin formation, and the different zones within the basin has differential evolution characteristics. Also, the neotectonic movement had controlled the accumulation and distribution of oil and gas. The above understanding have effectively led to the oil and gas discoveries in the basin (Ren et al., 2002, 2018; Hutchison, 2004; Zhu et al., 2008, 2012; Zhu, 2009; Lv et al., 2012; Zhang et al.,

* Corresponding author. E-mail: zhanggch@cnooc.com.cn

2013, 2015a, b; Shi et al., 2014, 2020; Liu et al., 2017; Pang et al., 2018; Mi et al., 2018). Because of the important role of faults in hydrocarbon accumulation, the deformation and activity characteristics and activity-migration mechanisms of faults have been analyzed. Furthermore, the sealing capacity of faults was qualitatively evaluated, and then the formation models of composite migration transportation systems dominated by faults were also established (Nie et al., 2001; Yu et al., 2007; Hou et al., 2008; Shi et al., 2009; Zhang et al., 2010; Shao et al., 2013; Li et al., 2014; Sun et al., 2014; Xu et al., 2016; Zhang et al., 2016; Feng et al., 2017; Ye et al., 2017; Xie et al., 2017). The Yunkai low uplift is located in the southwestern part of the Baiyun sag in the Pearl River Mouth Basin. At present, there are only some oil and gas shows in several drilling wells in the Yunkai low uplift and its adjacent areas, which is sharp contrast to the exploration results in the Panyu low massif in the northern basin and the Dongsha massif in the eastern basin. In addition, the geological study of the Yunkai low uplift is in relatively low degree because only the petroleum geological conditions and fault development characteristics have been simply addressed (Zhong et al., 2008; Lv et al., 2017), which also limits the further understand on the main controlling factors of hydrocarbon enrichment and favorable exploration zones. In this paper, the geological structural characteristics and formation processes of the Yunkai low uplift are analyzed based on interpretation of the newest seismic and drilling data. The development characteristics of faults and their significances on hydrocarbon migration and accumulation are also discussed in detail. The research can afford scientific basis and theoretical guidance for oil and gas exploration in this area.

## 2 Geological Settings

The Pearl River Mouth Basin is located on the continental margin of the northern South China Sea, which is also in the interaction zone of the Pacific plate, the Eurasian plate and the India-Australian plate. Influenced by the subduction and collision among the three plates, Pearl River Mouth Basin has complex continental dynamics background. As a result, the basin is a very good natural laboratory for study on plates interaction and basin structures. The Pearl River Mouth Basin, with an area of about $26 \times 10^4$ km$^2$, strikes in the NE-SW direction and is a Cenozoic rift basin from a quasi-passive continental margin (Fig. 1a) (He et al., 2008). Since the Late Cretaceous, due to changes in the subduction rate and angle of the Pacific plate to the Eurasian plate (Northrup et al., 1995), the tectonic stress field on the continental margin of the eastern China has changed from compression to extension (Guo et al., 2001). At the same time, rifting was also happened on the continental margin of South China with the retreat of the subduction zone of the Pacific plate. On this basis, the Pearl River Mouth Basin began to develop on the complex Mesozoic folded basement. During the Cenozoic, the evolution of the Pearl River Mouth Basin mainly experienced three stages, including the Paleocene-Oligocene rifting stage, the late Oligocene-Middle Miocene sagging stage, and the neotectonic stage since the Middle Miocene (Fig. 2) (Mi et al., 2019; Shi et al., 2020). The basement of the Pearl River Mouth Basin comprises of the pre-Paleogene metamorphic and volcanic rocks, and the Cenozoic sedimentary strata with a thickness of more than 10,000 meters have a double-layer structure, i.e., the lower faulted layer and the upper sagging layer. From the oldest to the youngest, the Cenozoic strata consist of the Paleogene Shenhu Formation, Wenchang Formation, Enping Formation, Zhuhai Formation, and the Neogene Zhujiang Formation, Hanjiang Formation, Yuehai Formation, Wanshan Formation, and the Quaternary, of which the Shenhu Formation has a very limited distribution area (Liu et al., 2017; Mi et al., 2019).

The structural framework of the Pearl River Mouth Basin is characterized by the north-south zoning and east-west blocking. According to the difference of basement structures and sedimentary filling, the Pearl River Mouth Basin can be divided into several subordinate structural units, including the Northern massif belt, the Northern depression belt, the Central massif belt, the Central depression belt, the Southern massif belt, and the Southern depression belt, respectively (Fig. 1a). The Yunkai low uplift is located in the Central depression belt, and is

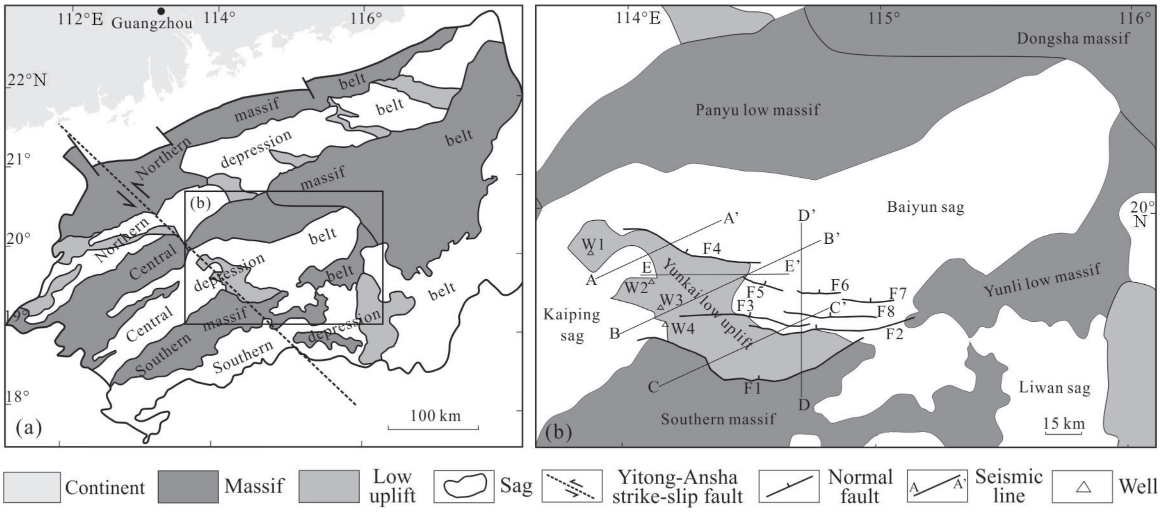


Fig. 1. Regional geological setting of the Yunkai low uplift and its adjacent areas in Pearl River Mouth Basin.

| Stratum | | | | Age (Ma) | Horizon number | Tectonic movement | Basin evolution |
|---|---|---|---|---|---|---|---|
| System | Series | | Formation | | | | |
| Quarternary | | | | 2.6 | T2 | | Neotectonic movement |
| Neogene | Pliocene | | Wanshan | 5.3 | T3 | | |
| | Miocene | U | Yuehai | 10.0 | T32 | Dongsha | |
| | | M | Hanjiang | 16.0 | T4 | | Sagging |
| | | L | Zhujiang | 23.0 | T6 | Baiyun | |
| Paleogene | Oligocene | U | Zhuhai | 33.9 | T7 | Nanhai | |
| | | L | Enping | | | | Rifting |
| | Eocene | U | | 38.0 | T8 | Zhuqiong II | |
| | | M | Wenchang | | | | |
| | | L | | 56.0 | Tg | Zhuqiong I | |

Fig. 2. Generalized tectonostratigraphic column of the Baiyun sag.

bounded by the Baiyun sag to the east, Kaiping sag to the west, Panyu low massif to the north, and the Southern massif to the south (Fig. 1b). The Yunkai low uplift is also an uplift transitioning from the Baiyun sag to the Southern massif (Zhong et al., 2008). The Baiyun sag is a wide and deep faulted sag controlled by the detachment and thinning of the crust (Pang et al., 2018), and has been proven to be a hydrocarbon-rich sag in the deep water area of the Pearl River Mouth Basin (Zhang et al., 2014). There are several secondary hydrocarbon-generating sags such as the main sag, the east sag and the west sag within the Baiyun sag, a key area for deep-water hydrocarbon exploration in China. Different from the surrounding NE-trending massifs and sags, the Yunkai low uplift is mainly distributed along the NW–SE direction. The low uplift has a relatively irregular shape in plane, with a length of about 160 km and a width of 15–35 km, and an area of approximately 2900 $km^2$ (Fig. 1b). The Shenhu Formation is absent in the Yunkai low uplift. Both the Wenchang and Enping formations have suffered relatively strong denudation and therefore, their distribution is limited. However, the Zhuhai Formation, Zhujiang Formation, Hanjiang Formation and their overlying strata are well developed (Fig. 2). Among them, the Zhuhai and Zhujiang formations are composed of sandstones of delta facies, littoral facies and fluvial facies, which are the main reservoirs. In some areas, the Enping Formation also contains sandstone layers with relatively good properties.

## 3 Structural and Evolution Characteristics of the Yunkai Low Uplift

### 3.1 Structural characteristics

The MW-trending Yunkai low uplift separates the Baiyun sag and the Kaiping sag (Fig. 1b). The seismic profiles show that the Yunkai low uplift is connected to the Kaiping sag to the west by a slope, and to the Baiyun sag by a faulted step zone. The low uplift gradually plunges into the Baiyun sag to the east. Affected by the division of the EW-trending basement fault (F3 in Fig. 1b), there are some differences of the structural shapes and stratigraphic distribution between the north and south sectors of the Yunkai low uplift (Fig. 3).

In the north sector, the Yunkai low uplift has irregular shape, which is separated from the Baiyun sag to the northeast by an NWW-trending fault (F4 in Fig. 1b), and by the Kaiping sag to the west by a slope (Figs. 3a, b). On the whole, the Yunkai low uplift has a relatively wide and gentle uplift shape. The depth of the bottom Cenozoic varies from 2500 m to 6500 m, and the thickness of the Paleogene Wenchang and Enping formations (Tg–T7) remaining on the top of the Yunkai low uplift change significantly (Fig. 3a, b). In the southern section, the Yunkai low uplift is divided into two half-grabens with faulting in the south and overlapping in the north by a nearly EW-trending basement fault (F2 in Fig. 1b) (Fig. 3c). The southern half-graben is smaller, with thicker and more inclined Wenchang and Enping formations. In addition, there are some drag folds developed in the Neogene (T6-T32) on the hanging wall of the main boundary fault F1 (Fig. 3c). In the northern half-graben, there are some secondary north-dipping faults with small throws. The Wenchang and Enping formations gradually thin to the highest point northward, while the thickness of the strata above T7 is relatively stable, and gradually descends toward the Baiyun sag (Fig. 3c).

### 3.2 Formation processes

According to restoration of balanced cross-section and characteristics of growth strata, the formation processes of the Yunkai low uplift during the Cenozoic can be divided into three main stages, including the rapid uplifting stage during the deposition period of the Wenchang Formation, the slow uplifting stage during the deposition period of the Enping-Hanjiang formations, and the whole burial stage since the Middle Miocene (Fig. 4).

During the depositional period of the Eocene Wenchang Formation, several north-dipping basement-involved normal faults developed between the Southern massif and the Baiyun sag. The faults was highly active, and the strata on the hanging walls tilted strongly. As a result, some half-grabens formed, and the Yunkai low uplift began to develop (Fig. 4a). During this stage, the basement uplifting rate of the Yunkai low uplift was significantly greater than the deposition rate of the Wenchang Formation. Consequently, the Wenchang Formation gradually thins from the Baiyun sag to the Yunkai low uplift, and overlies on the basement top (Tg), which is characterized by growth strata (Fig. 5). During the deposition of the Late Eocene-Middle Miocene Enping-Hanjiang formations, the basement in the study area continued to uplift, and the Yunkai low uplift continued to develop (Figs. 4b–e). However, the basement uplifting and strata tilting during this stage were relatively weaker than those during the Wenchang Formation deposition period. The deposition rate was greater than the basement uplifting rate, and the strata was characterized by draping (Fig. 5). At the end of the deposition of the Hanjiang Formation, the structural configuration of the Yunkai low uplift was gradually finalized (Fig. 4e). Since the Miocene, the Yunkai low uplift entered the whole deposition and burial stage, due to the weak activity of the boundary faults (Fig. 4f). The basement uplifting and strata tilting were very weak, and some wide and gentle folds developed in the shallow layer (Fig. 3c).

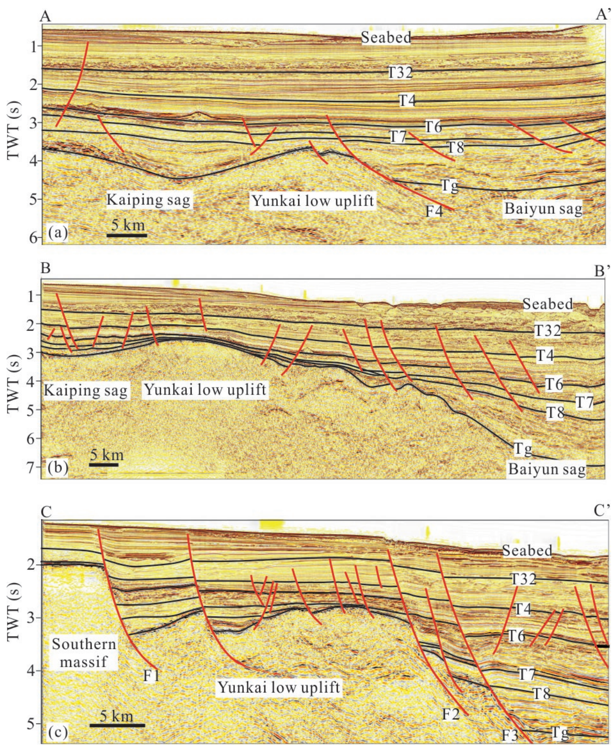


Fig. 3. Seismic sections through the Yunkai low uplift and its adjacent areas. See Fig. 1b for line locations and Fig. 2 for seismic reflections and their corresponding stratigraphy.

## 4 Characteristics of Faults System

There are numerous normal faults with various scales and trends in the Yunkai low uplift and its adjacent areas. In cross sections, normal faults are mostly inclined to north and northeast, and have listric and planar shapes. Several normal faults often constitute to form domino and "Y" patterns (Fig. 3). The main faults that separate the Yunkai low uplift and the Baiyun sag, and the northern and southern secondary half-grabens within the low uplift are mostly listric faults which are characterized by multiple faulted horizons, large throws in deep and long active duration. The maximum throw of the main faults can exceed 5000 m. On the contrary, the internal faults of the Yunkai low uplift are mainly planar faults with small throws.

Previous studies show that the Yitong-Ansha strike-slip fault zone passes through the Yunkai low uplift and its adjacent areas (Fig. 1a). The Yunkai low uplift is just located in the tectonic transition region between the east and west of the Pearl River Mouth Basin (Lv et al., 2017; He et al., 2019). Consequently, the distribution shapes and fault characteristics of the Yunkai low uplift have certain particularity. In this study, the fault system map on different horizons in the Yunkai low uplift and its adjacent area have been drawn by comprehensively interpretation of seismic data, combined with previous studies (Fig. 6). The maps show that the dominant trends of faults in the study area mainly include NWW, NW and near EW directions. From the bottom Cenozoic (Tg) to the bottom Zhujiang Formation (T6), the dominant trend of the faults has a clockwise rotation from NEE to near EW and then to

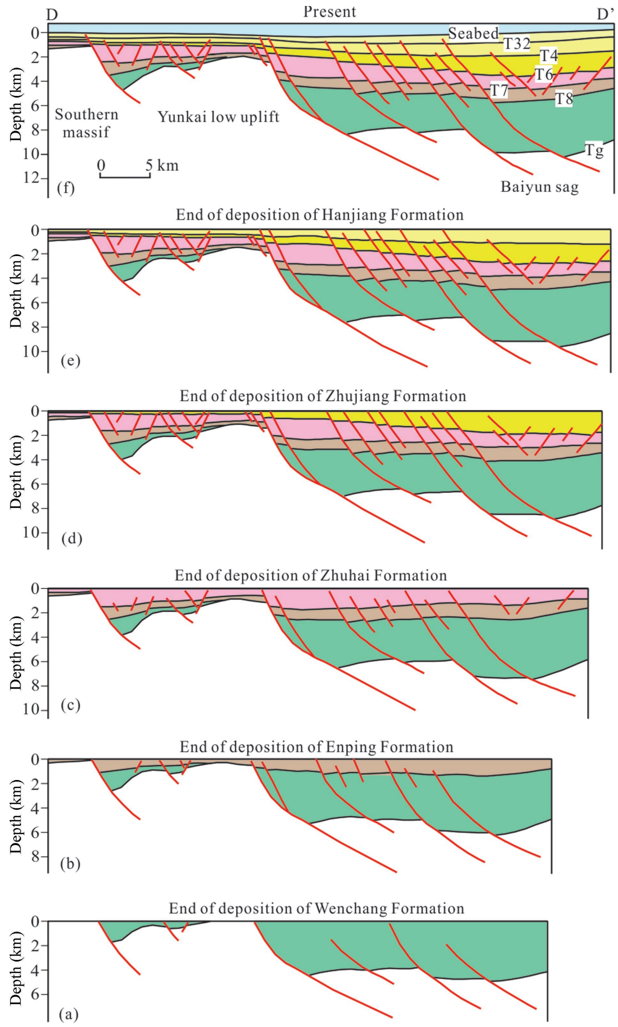


Fig. 4. Balanced cross section through the Yunkai low uplift. See Fig. 1b for line location.

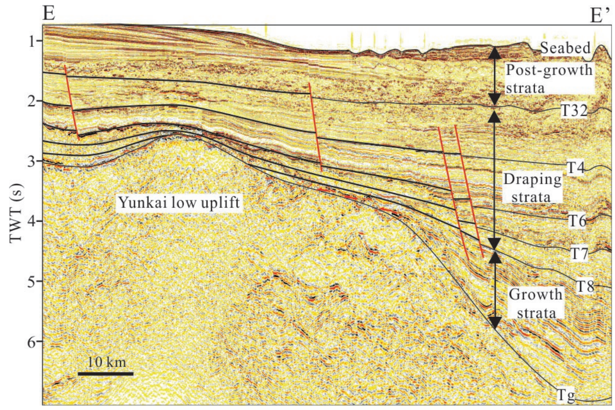


Fig. 5. Seismic section showing the characteristics of growth and drape strata in the Yunkai low uplift and its adjacent areas. See Fig. 1b for line location.

NWW (Figs. 6, 7). In addition, the faults length in planes gradually decreases from the deep to the shallow strata. Except for the basement-involved faults at the interface Tg, the fault lengths are generally less than 5 km. From the interface Tg up to T6, the number of faults gradually increases and the fault densities increase from 0.012 to

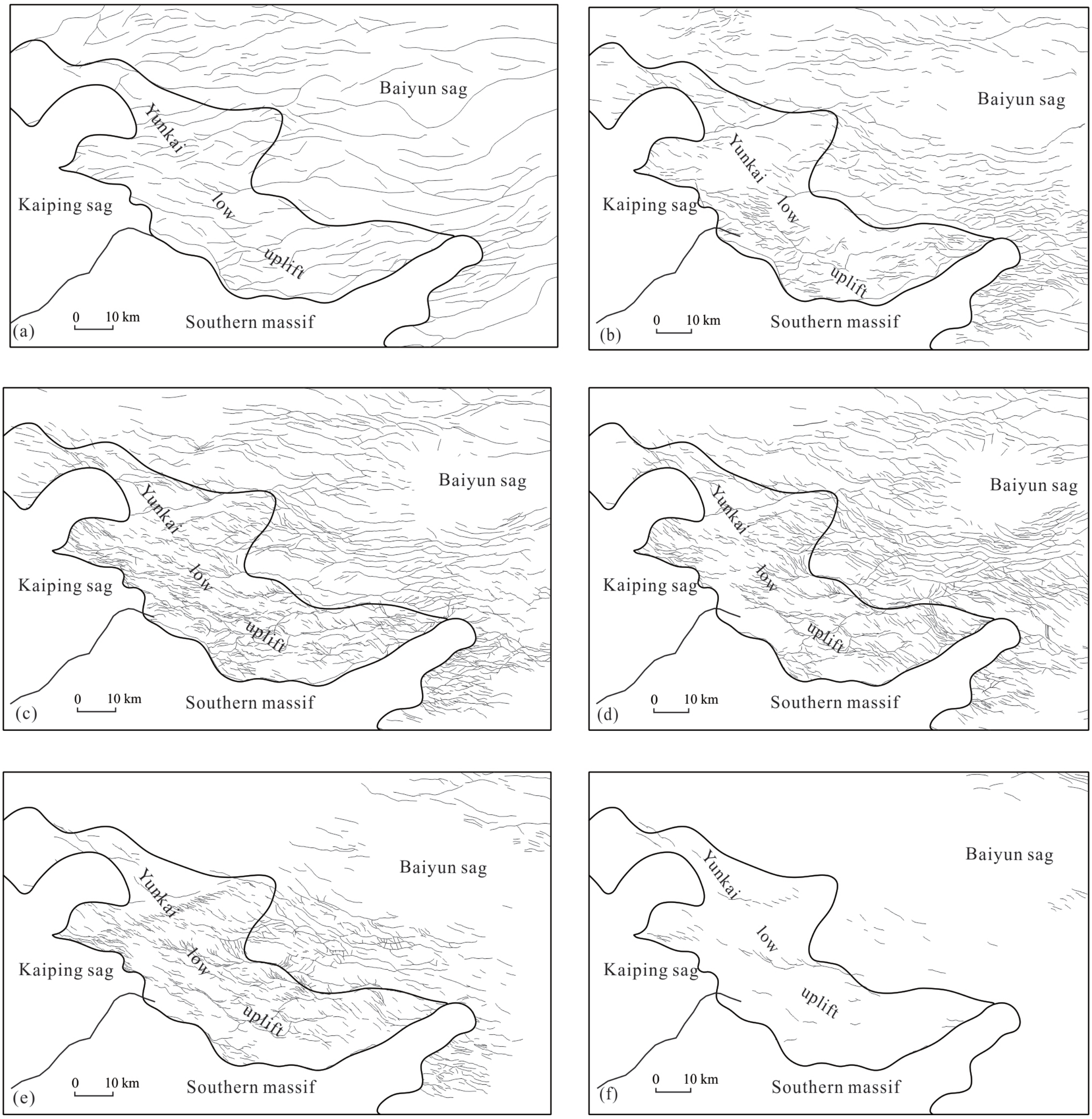


Fig. 6. Fault systems on different horizons in the Yunkai low uplift and its adjacent areas.
(a)–Tg, (b)–T8, (c)–T7, (d)–T6, (e)–T4, (f)–T3.

0.122 per square kilometre. However, from the interface T6 upwards, the number of faults gradually decreases, and the fault density at the interface T3 has decreased to 0.007 per square kilometre (Fig. 7).

This paper analyzes activity characteristics of the main faults in the study area by fault growth index and activity rate. The results show that the main faults are characterized by early highly active and late weak active (Fig. 8). During the rifting period, the growth index of the main boundary faults can reach five, and their activity rate exceeds 120 m/Ma, even up to 170 m/Ma. Since the Middle Miocene, the fault activity has significantly weakened, and the growth index is generally less than two, and the average rate is about 7 m/Ma (Fig. 8).

The fault activity characteristics of the Yunkai low uplift and its adjacent areas are in contrast to those of the northeastern Baiyun sag. The main faults in the northeastern Baiyun sag were strongly active during the early rifting stage and the late stages when the average activity rate reaches 15 m/Ma (He et al., 2019). The different activity of faults in different areas is may related to the neotectonic movement of the Pearl River Mouth Basin since 13.8 Ma. Previous studies show that the neotectonic movement in the Pearl River Mouth Basin is mainly characterized by re-uplifting of the Dongsha massif and fault activity of the surrounding regions.

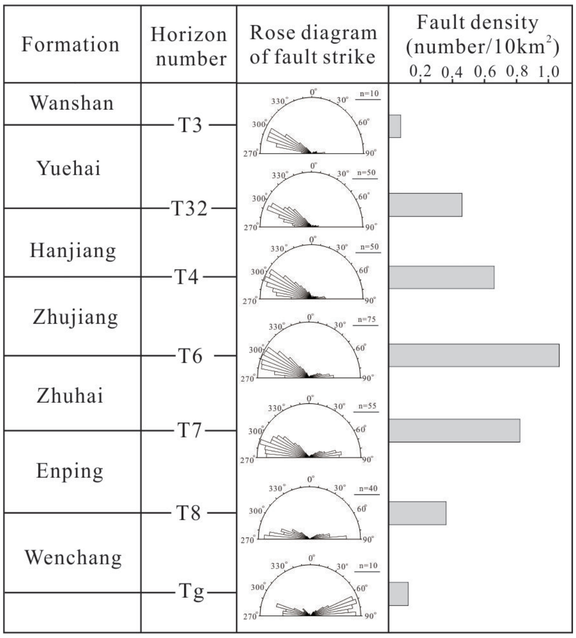

Fig. 7. Rose diagrams of fault strikes and fault densities on different horizons in the Yunkai low uplift and its adjacent areas.

Therefore, the fault activity during the neotectonic period in the adjacent areas of the Dongsha massif is relatively strong, while the activity intensity of faults in the Baiyun sag gradually weakens from NE to SW (He et al., 2019).

## 5 Relationships between Fault and Hydrocarbon Accumulation

Although there is still no commercial oil and gas fields discovered in the Yunkai low uplift and its adjacent areas, several wells have relatively rich oil and gas shows, which indicates that hydrocarbon activities in these areas were once active (Fig. 9). The lacustrine mudstones of the Wenchang and Enping formations in the Baiyun sag have high hydrocarbon generation and expulsion strength, which can provide sufficient oil and gas sources for the Yunkai low uplift (Fu et al., 2019). In addition, the Kaiping sag may also be a potential hydrocarbon source. At present, a large number of oil and gas fields have been discovered in the Panyu low massif, the Dongsha massif and its adjacent areas, while the Yunkai low uplift has a low exploration degree, which makes it an important potential area for future hydrocarbon exploration in the deep-water Pearl River Mouth Basin.

We believe that the faults play very important roles in hydrocarbon accumulation in the Yunkai low uplift and its adjacent areas. According to their roles in hydrocarbon migration and accumulation, the faults in the study area can be divided into trap-controlled faults and source-controlled faults.

### 5.1 Trap-controlled faults and trap formation

The trap-controlled faults mainly control formation of traps and can effectively seal oil and gas. Due to the widely faulting, many fault-related structural traps develop well in the Yunkai low uplift and the adjacent faulted step zone towards the Baiyun sag. The fault-related structural traps involve faulted anticlines, faulted blocks, faulted noses, and drape anticlines (Fig. 10). Those traps have a large closed area and the good reservoir-seal combination. The activity of the trap-controlled faults is generally weak. The drilling data also confirm that the trap-controlled faults can effectively seal hydrocarbon. Therefore, these structural traps are the ideal exploration targets in the study area.

### 5.2 Source-controlled fault and hydrocarbon migration

As stated above, the Yunkai low uplift is close to the hydrocarbon-generation center in the Baiyun sag, and the combination of traps, reservoirs and seal rocks is good. Therefore, the key factor affecting hydrocarbon accumulation of the Yunkai low uplift is whether an effective transport system developed to migrates oil and gas from the Baiyun sag to the low uplift. This study identifies a series of source-controlled faults in the Yunkai low uplift and its adjacent area, and part of them is shown in Fig. 1b. These source-controlled faults are mainly the boundary faults in the faulted step zone between the Yunkai low uplift and the Baiyun sag, which act as oil and gas migration pathways by directly connecting source

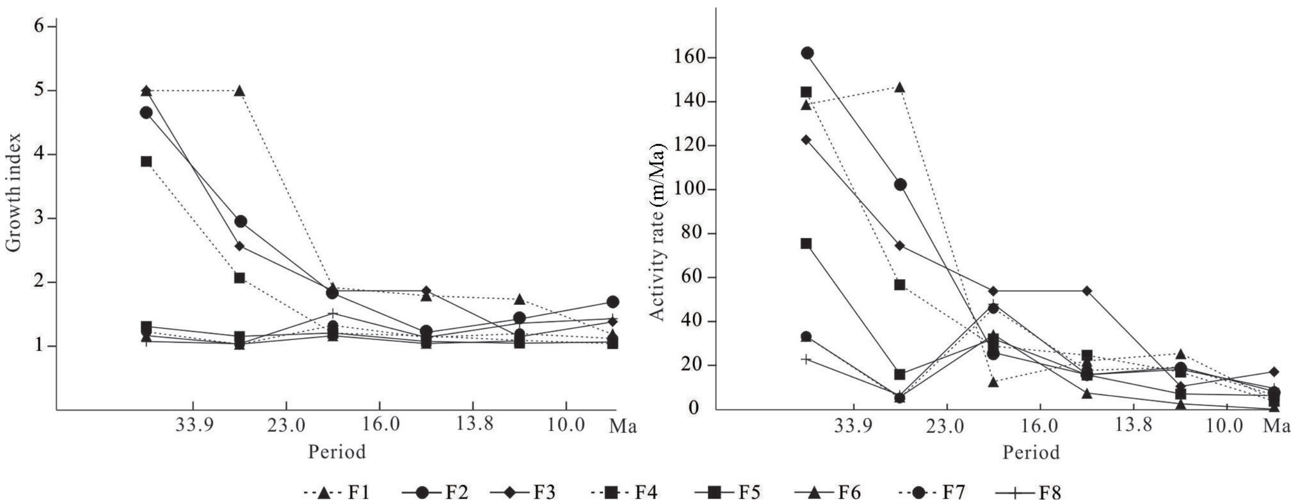

Fig. 8. Growth index and activity rate of the master faults in the Yunkai low uplift and its adjacent areas. See Fig. 1b for fault locations.

| Formation | Depth (m) | Oil/gas shows | | |
|---|---|---|---|---|
| | | W2 | W3 | W4 |
| Zhujiang | 1974–1980 | | Gas layer (5.6 m) | |
| | 2003–2006 | | Oil inclusions | |
| | 2109–2114 | Gas layer (4.7 m) | | |
| | 2112–2115 | Oil spot Fluorescence | | |
| | 2468–2482 | Residual oil | | |
| Zhuhai | 2274–2460 | | | Oil inclusions |
| | 2438–2439 | | Oil inclusions | |
| Enping | 3429–3432 | Fluorescence residual oil | | |

Fig. 9. Oil and gas shows of several wells in the Yunkai low uplift.

rocks of the Wenchang and Enping formations in the Baiyun sag and reservoirs of the Zhuhai and Zhujiang formations in the Yunkai low uplift. Generally, the activity characteristics of the source-controlled faults has an important influence on their ability transporting oil and gas. The activity of the source-controlled faults in the Yunkai low uplift and its adjacent areas is characterized by early highly active and late weak active (Fig. 8). When the source-controlled faults happened strongly active during the early stage, they could migrate the early crude oil from the Baiyun sag to the Yunkai low uplift (Fig. 11a). As the activity of the source-controlled fault gradually weakened, their ability transporting oil and gas was also decreased. Consequently, the migration of the late natural gas from the Baiyun sag to the Yunkai low uplift was not very smooth. The above oil and gas migration features have also been confirmed by drilling data (Fig. 9). In the well W2, which is located on the top structural ridge of the Zhujiang Formation and is close to the Baiyun sag, several oil spots, residual oils and fluorescent shows were found in the Zhujiang, Zhuhai and Enping formations. In addition, a gas layer with a thickness of 4.7 m was drilled in the shallow layer of the Zhujiang Formation. In the well W3, oil inclusions and gas layers were discovered in the Zhuhai Formation and the Zhujiang Formation, respectively. However, there are only oil inclusions with relatively high abundance (GOI is about 5%) in the Zhuhai Formation in the well W4 which is far from the Baiyun sag. The phenomena indicate that the early crude oil has been transported to the southern Yunkai low uplift from the Baiyun sag by the source-controlled faults with strong activity and transporting ability (Fig. 11a). As the activity of the source-controlled faults significantly weakened during the late stage, however, only a small amount of crude oil and natural gas could migrate vertically into the near-source reservoirs by the source-controlled faults, and then could not migrate to the high parts of the Yunkai low uplift in a wide range. As a result, there are fluorescence shows only in the near-source reservoirs of the Zhujiang Formation (Fig. 9). It is necessary to note, however, that the Zhuhai and Zhujiang formations in the Yunkai low uplift contain rich sand bodies, and the boundary faults have small throws in the shallow layers which is helpful for juxtaposition of sand bodies on both walls of the faults. Therefore, some oil and gas may still migrate vertically by the source-controlled faults and then move laterally along the shallow sandstone structural ridges into the Yunkai low uplift. During the migration processes, if there are suitable traps along this path, some oil and gas fields may be formed (Fig. 11b).

On the basis of comprehensive analysis of the activity features of the source-controlled faults and other geological conditions in the Yunkai low uplift and its adjacent areas, this paper points that the structural traps in the Zhuhai and Enping formations in the low faulted step zone adjacent to the Baiyun sag should be main exploration targets. In addition, some attention should also be paid to the traps on the favorable lateral migration paths in the Yunkai low uplift.

## 6 Conclusions

(1) Divided by the EW-trending basement faults, the Yunkai low uplift can be divided into two parts. The northern sector is a relatively wide and gentle uplift, while the southern sector is composed of two secondary half-grabens with faulting in the south and overlapping in the north.

(2) The Yunkai low uplift experienced three major formation stages, including the rapid uplifting stage during the deposition period of the Eocene Wenchang Formation, the slow uplifting stage during the deposition period of the Late Eocene-Middle Miocene Enping-Hanjiang formations, and the whole burial stage from the Middle Miocene to present.

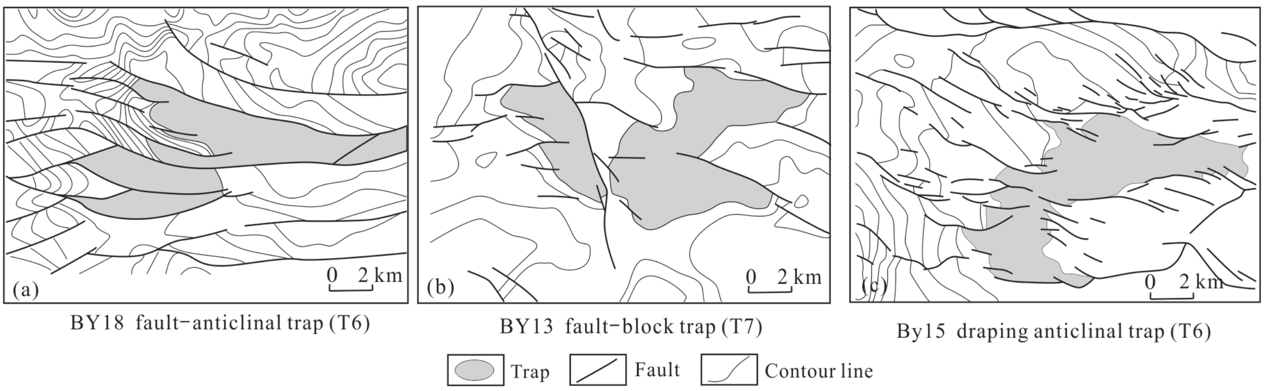


Fig. 10. Structural maps showing the typical fault-related traps in the Yunkai low uplift and its adjacent areas.

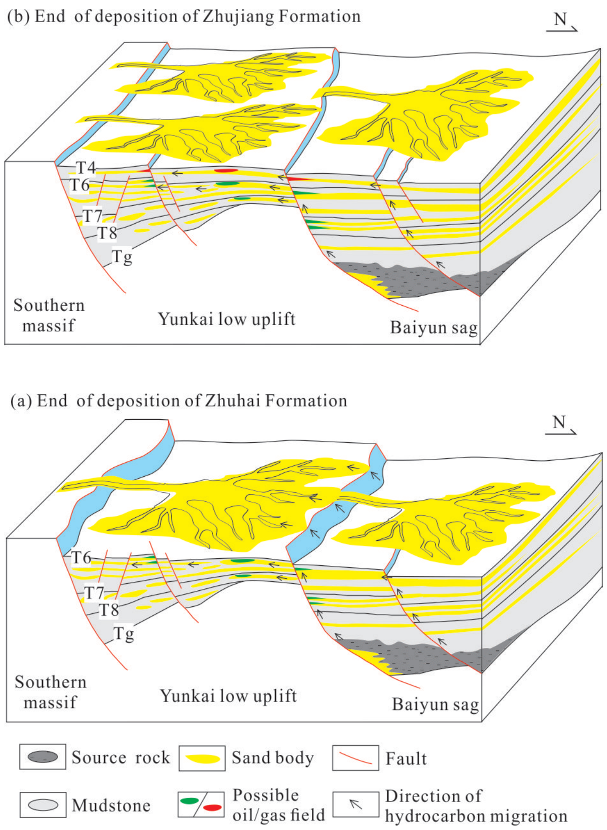


Fig. 11. Schematic maps showing hydrocarbon migration and accumulation models during the early and late stages in the Yunkai low uplift and its adjacent areas.

(3) The extensional faults in the Yunkai low uplift and its adjacent areas strike mainly along the NW, NWW and near-EW directions. The fault strikes present a clockwise rotation from the deep to the shallow strata, and faults are highly active during the rifting stage and weakly active since the Miocene.

(4) In the Yunkai low uplift and its adjacent zone, the trap-controlled faults mainly control trap formation and can effectively seal oil and gas. The activity features of the source-controlled faults are beneficial to migration of the early crude oil from the Baiyun sag to the high part of the Yunkai low uplift, and are unfavorable for migration of the late natural gas. Some oil and gas can still migrate laterally to the low uplift through the juxtaposition of sand bodies on both walls of the faults.

(5) The structural traps in the Zhuhai and Enping formations that are in the low faulted step zone and closed to the Baiyun sag should be main exploration targets, and some attention should also be paid to the traps on the favorable lateral migration paths in the Yunkai low uplift.

## Acknowledgements

This work is jointly funded by the National Science and Technology Major Project of China (2016ZX05026-007) and the National Natural Science Foundation of China (42072149). We are grateful to Gong Chenglin for his technical support and fruitful discussion.

Manuscript received May 22, 2020
accepted Nov. 7, 2020
associate EIC: ZHANG Gongcheng
edited by FANG Xiang

## References

Childs, C., Holdsworth, R.E., Jackson, C. A.L., Manzocchi, T., Walsh, J.J., and Yielding, G., 2017. The geometry and growth of normal faults. Geological Society, Special Publications: 439.

Feng, Y.W., Qu, H.J., Zhang, G.C., and Pu, R.H., 2017. Seismic interpretation and exploration direction of Miocene Meishan formation reef in Southern Qiongdongnan Basin, Northern South China Sea. Journal of Palaeogeography, 6(3): 206–218.

Fu, J., Zhang, Z.T., Chen, C., Wang, T.G., Li, M.J., Alia, S., Lu, X.L., and Dai, J.H., 2019. Geochemistry and origins of petroleum in the Neogene reservoirs of the Baiyun Sag, Pearl River Mouth Basin. Marine and Petroleum Geology, 107: 127–141.

Gawthorpe, R.L., and Leeder, M.R., 2010. Tectono-sedimentary evolution of active extensional basins. Basin Research, 12 (3/4): 195–218.

Guo, L.Z., Zhong, Z.H., Wang, L.S., Shi, Y.S., Li, H., and Liu, S.W., 2001. Regional tectonic evolution around Yinggehai basin of South China Sea. Geological Journal of China Universities, 7(1): 1–12 (in Chinese with English abstract).

He, J.X., Chen, S.H., Liu, H.L., and Wang, Z.F., 2008. Geological characteristics and the low of formation of hydrocarbon migration on accumulation, northern South China Sea. Journal of Southwest Petroleum University (Science and Technology Edition), 30(5): 46–52 (in Chinese with English abstract).

He, M., Zhu, W.L., Wu, Z., Zhong, G.F., Ren, J.Y., Liu, L.H., and Wang, W.Y., 2019. Neotectonic movement characteristics and hydrocarbon accumulation of the Pearl River Mouth basin. China Offshore Oil and Gas, 31(5): 9–20 (in Chinese with English abstract).

Hou, D.J., Pang, X., Xiao, J.X., Wang, J.R., Shu, Y., and Shi, H.S., 2008. The geological and geochemical evidence on the identification of natural gas migration through fault system, Baiyun Sag, Pearl River Mouth Basin, China. Earth Science Frontiers, 15(4): 81–87 (in Chinese with English abstract).

Hutchison, C.S., 2004. Marginal basin evolution: The southern South China Sea. Marine and Petroleum Geology, 21(9): 1129–1148.

Li, H., Chen, S.H., Zhang, Y.Z., Niu, C.Y., Zhang, K.K., Ye, Q., and Hu, G.W., 2014. Faults in the Zhu-3 depression of Pearl River Mouth Basin and their control over hydrocarbon accumulation. Marine Geology & Quaternary Geology, 34(3): 115–124 (in Chinese with English abstract).

Liu, Z.F., Wu, K.Q., Ke, L., Wang, S.L., Yu, K.P., and Zhu, W.Q., 2017. Main factors controlling hydrocarbon accumulation in northern subsag belt of the Zhu-1 depression, Pearl River Mouth Basin. Oil and Gas Geology, 38(3): 561–569 (in Chinese with English abstract).

Luo, Q., 2002. Fault controlling hydrocarbon theory and petroleum exploration practice. Earth Science-Journal of China University of Geosciences, 27(6): 751–756 (in Chinese with English abstract).

Lv, B.F., Yin, Z.X., Cai, Z.R., and Wang, Z.F., 2012. Cenozoic tectonic evolution sequence in northern South China Sea and its oil/gas significance. Acta Geologica Sinica, 86(8): 1249–1261 (in Chinese with English abstract).

Lv, C.L., Zhang, G.C., and Yang, D.S., 2017. Differential structure and dynamic mechanism of Wenchang Formation in the Zhu II Depression of the Pearl River Mouth Basin. Earth Science Frontiers, 24(6): 333–341 (in Chinese with English abstract).

Mi, L.J., Zhang, X.T., Pang, X., Zheng, J.Y., and Zhang, L.L., 2019. Formation mechanism and petroleum geology of Pearl River Mouth Basin. Acta Petrolei Sinica, 40(S1): 1–10 (in Chinese with English abstract).

Mi, L.J., Zhang, Z.T., Pang, X., Liu, J., Zhang, B., Zhao, Q., and Feng, X., 2018. Main controlling factors of hydrocarbon accumulation in Baiyun Sag at northern continental margin of

South China Sea. Petroleum Exploration and Development, 45 (5): 902–913 (in Chinese with English abstract).

Nie, F.J., Li, S.T., Wang, H., Xie, X.N., Wu, K.Q., and Jiang, M.Z., 2001. Lateral migration pathways of petroleum in the Zhu III subbasin, Peral River Mouth basin, South China Sea. Marine and Petroleum Geology, 18: 561–575.

Northrup, C.J., Royden, L.H., and Burchfiel, B.C., 1995. Motion of the Pacific plate relative to Eurasia and its potential relation to Cenozoic extension along the eastern margin of Eurasia. Geology, 23(8): 719–722.

Pang, X., Ren, J.Y., Zheng, J.Y., Liu, J., Yu, P., and Liu, B.J. 2018. Petroleum geology controlled by extensive detachment thinning of continental margin crust: A case study of Baiyun sag in the deep-water area of northern South China Sea. Petroleum Exploration and Development, 45(1): 27–39 (in Chinese with English abstract).

Ren, J.Y., Pang, X., Yu, P., Lei, C., and Luo, P., 2018. Characteristics and formation mechanism of deepwater and ultra-deepwater basins in the northern continental margin of the South China Sea. Chinese Journal of Geophysics, 61(12): 4901–4920 (in Chinese with English abstract).

Ren, J.Y., Tamaki, K., Li, S.T., and Zhang, J.X., 2002. Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas. Tectonophysics, 344: 175–205.

Serck, C.S., and Braathen, A., 2019. Extensional fault and fold growth: Impact on accommodation evolution and sedimentary infill. Basin Research, 31: 967–990.

Shao, L., Meng, X.J., Zhang, G.C., and Liang, J.S., 2013. Feature of faults systems and its influence on tectonic and sedimentary history of Baiyun sag. Journal of Tongji University (Natural Science), 41(9): 1435–1441 (in Chinese with English abstract).

Shi, H.S., Du, J.Y., Mei, L.F., Zhang, X.T., Hao, S.H., Liu, P., Deng, P., and Zhang, Q., 2020. Huizhou movement and its significance in Pearl River Mouth Basin, China. Petroleum Exploration and Development, 47(3): 447–461 (in Chinese with English abstract).

Shi, H.S., He, M., Zhang, L.L., Yu, Q.H., Pang, X., Zhong, Z.H., and Liu, L.H., 2014. Hydrocarbon geology, accumulation pattern and the next exploration strategy in the eastern Pearl River Mouth basin. China Offshore Oil and Gas, 26(3): 11–22 (in Chinese with English abstract).

Shi, H.S., Qin, C.G., Zhang, Z.T., and Xuan Y.H., 2009. A discussion on the complex hydrocarbon transport system in the north slope of Baiyun Sag-Panyu low uplift, Pearl River Mouth Basin. China Offshore Oil and Gas, 21(6): 361–366 (in Chinese with English abstract).

Sun, Z., Xu, Z.Y, Sun, L.T., Pang, X., Yan, C.Z., Li, Y.P., Zhao, Z.X., Wang, Z.W., and Zhang C.M., 2014. The mechanism of post-rift fault activities in Baiyun sag, Pearl River Mouth basin. Journal of Asian Earth Sciences, 89(3): 76–87.

Wang, H.Y., Li, R.L., Zhu J.F., and Xu, W., 2019. Tectonic sedimentology characteristics of continental rift basin: Case Study from Fulongquan fault depression of Songliao basin. Geoscience, 33(6): 1151–1162 (in Chinese with English abstract).

Xie, Y.H., and Gao, Y.D., 2020. Recent domestic exploration progress and direction of CNOOC. China Petroleum Exploration, 25(1): 20–30 (in Chinese with English abstract).

Xie, Z.Y., Yang, J.M., Sun, L.T., Zheng, J.Y., Sun, Z., and Qiu, N., 2017. The characteristics of post-rift fault activities and sedimentary response on the northern slope of the Baiyun Sag in the northern margin of the South China Sea. Journal of Tropical Oceanography, 36(5): 59–71 (in Chinese with English abstract).

Xu, X.M., Jiang, J., Chen, S.H., Liu, L.H., and Liu, X.L., 2016. Study on the evaluation method of fault sealing and its application: An example of Neogene layer in Enping sag, Pearl River Mouth Basin. Geoscience, 30(1): 122–129 (in Chinese with English abstract).

Ye, Q., Shi, H.S., Mei, L.F., Shu, Y., Liu, H.L., Tian, W., and Yan, H., 2017. Post-rift faulting migration, transition and dynamics in Zhu I depression, Pearl River Mouth Basin. Earth Science, 42(1): 105–118 (in Chinese with English abstract).

Yielding, G., Freeman, B., and Needham, D.T., 1997. Quantitative fault seal prediction. AAPG Bulletin, 81(6): 897–917.

Yu, S.M., Mei, L.F., Shi, H.S., Qin, C.G., and Tang, J.G., 2007. Relationship between faults and hydrocarbon accumulation in Panyu low massif and north slope of Baiyun Sag, Pearl River Mouth Basin. Petroleum Exploration and Development, 34(5): 562–565 (in Chinese with English abstract).

Zhang, G.C., Qu, H.J., Liu, S.X., Xie, X.J., Zhao, Z., and Shen, H.L., 2015b. Tectonic cycle of marginal sea controlled the hydrocarbon accumulation in deep-water areas of South China Sea. Acta Petrolei Sinica, 36(5): 533–545 (in Chinese with English abstract).

Zhang, G.C., Wang, P.J., Wu, J.F., Liu, S.X., and Xie, X.J., 2015a. Tectonic cycle of marginal oceanic basin: A new evolution model of the South China Sea. Earth Science Frontiers, 22(3): 27–37 (in Chinese with English abstract).

Zhang, G.C., Xie, X.J., Wang, W.Y., Liu, S.X., Wang, Y.B. Dong, W., and Shen, H.L., 2013. Tectonic types of petroliferous basins and its exploration in the South China Sea. Acta Petrolei Sinica, 34(4): 611–627 (in Chinese with English abstract).

Zhang, G.C., Yang, H.Z., Chen, Y., Ji, M., Wang, K., Yang, D.S., Han, Y.X., and Sun, Y.H., 2014. The Baiyun sag: A giant rich gas-generation sag in the deepwater area of the Pearl River Mouth Basin. Natural Gas Industry, 34(11): 11–25 (in Chinese with English abstract).

Zhang, J.Y., Sun Z., and Zheng, J.Y., 2016. The structure and evolving history of faults during rifting stage in Baiyun Sag, Pearl River Mouth Basin. Journal of Tropical Oceanography, 35(4): 82–94 (in Chinese with English abstract).

Zhang, Z.T., Shi, H.S., Qin, C.G., Gao, P., and Qu, L., 2010. Study on fault sealability of Panyu Low Massif and north slope of Baiyun Sag. Fault-block Oil and Gas Field, 17(1): 24–27 (in Chinese with English abstract).

Zhong, K., Zhang, G.C., Hou, G.W., He, H.Z., Sheng, H.L., and Guo, R., 2008. Yunkai Low Uplift-a frontier of hydrocarbon exploration in the deepwater area, the northern South China sea. China Offshore Oil and Gas, 20(1): 15–17 (in Chinese with English abstract).

Zhu, W.L., 2009. Some key geological issues on oil and gas exploration in the northern deepwater area of the South China Sea. Acta Geologica Sinica, 83(8): 1059–1064 (in Chinese with English abstract).

Zhu, W.L., Zhang, G.C., and Gao, L., 2008. Geological characteristics and exploration objectives of hydrocarbons in the northern continental margin basin of South China Sea. Acta Petrolei Sinica, 29(1): 1–9 (in Chinese with English abstract).

Zhu, W.L., Zhong, K., Li, Y.C., Xu, Q., and Fang, D.Y., 2012. Characteristics of hydrocarbon accumulation and exploration potential of the northern South China Sea Deepwater Basins. Chinese Science Bulletin, 57(20): 1833–1841 (in Chinese).

## About the first author

YU Yixin, male, born in 1977 in Jiangxi Province; doctor; graduated from China University of Petroleum (Beijing); associate professor. He is now interested in the study on structural analysis of petroleum-bearing basins. Email: yuxin0707@163.com; phone: 010-89734161, 18911226082.

## About the corresponding author

ZHANG Gongcheng, male, born in 1966 in Shaanxi Province; doctor; graduated from China University of Geosciences (Beijing); professor. He is now interested in the study on marine petroleum geology. Email: zhanggch@cnooc.com.cn; phone: 13910984265.