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Quantitative evaluation and models of hydrocarbon accumulation controlled by faults in the Pearl River Mouth Basin

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Abstract:
The Pearl River Mouth Basin is the largest petroliferous basin in the northern South China Sea, where hydrocarbon accumulation is strongly controlled by fault activities. This study performed the quantitative evaluation of the effects of faults on hydrocarbon migration and accumulation in the basin. The results indicate that the critical values of vertical migration of middle-shallow hydrocarbon, including the active strength of faults and the ratio of fault throw to shale caprock thickness, were up to 10 m/Ma and 5, respectively. The lateral hydrocarbon migration efficiency of the unbreached relay zone was higher than that of the barely breached and strongly breached types. The lower critical value of shale gouge ratio for the clay sealing efficiency was 0.32. Additionally, the zones with the EW-trending transtensional faults were found to have unique dual functions of migration and stress sealing, suggesting that the linking fault positions play important roles in the lateral migration of hydrocarbons. Finally, seven hydrocarbon accumulation models controlled by faults in different tectonic settings were constructed to clarify the effects of faults on the vertical and lateral migrations of hydrocarbon. These models suggested that fine hydrocarbon exploration should be undertaken in the northeastern Baiyun Sag, and that middle-deep hydrocarbon exploration should be enhanced in the Enping, Huizhou, and southwestern Baiyun Sags.

1. Introduction

Faults are closely related to hydrocarbon accumulation, with the main manifestations of affecting the formation and evolution of basins, promoting the migration of oil and gas, controlling the generation of traps, and restricting the formation and distribution of oil and gas reservoirs (Hindle, 1997). For instance, it was confirmed that faults play dominant roles in hydrocarbon accumulation in many oil and gas fields, such as the Cantarell oil field in the Gulf of Mexico and the San Juan Basin (Mandujano et al., 2005). Notably, summarizing the typical oil and gas field systems in China revealed that more than 70% of oil and gas accumulations are controlled by faults (Zhang et al., 2011; Deng et al., 2022). This controlling effect in the various stages on oil and gas accumulation has always been a hot topic in petroleum geology (Sorkhabi and Tsuji, 2005), which can be commonly described by exploring the flow mechanism of oil and gas migration in faults, the heterogeneous hydrocarbon migration capacity in different parts of a fault, fault-sand body migration, sand and mud docking sealing, and shale smear (Smith, 1966, 1980; Gibson et al., 1994; Knipe, 1997).

The Pearl River Mouth Basin (PRMB) is the largest hydrocarbon-bearing basin in the northern continental margin of the South China Sea, with no hydrocarbon generation capacity in the middle and shallow strata (Shi et al., 2014). Fault systems connect the Paleogene source rocks with effective

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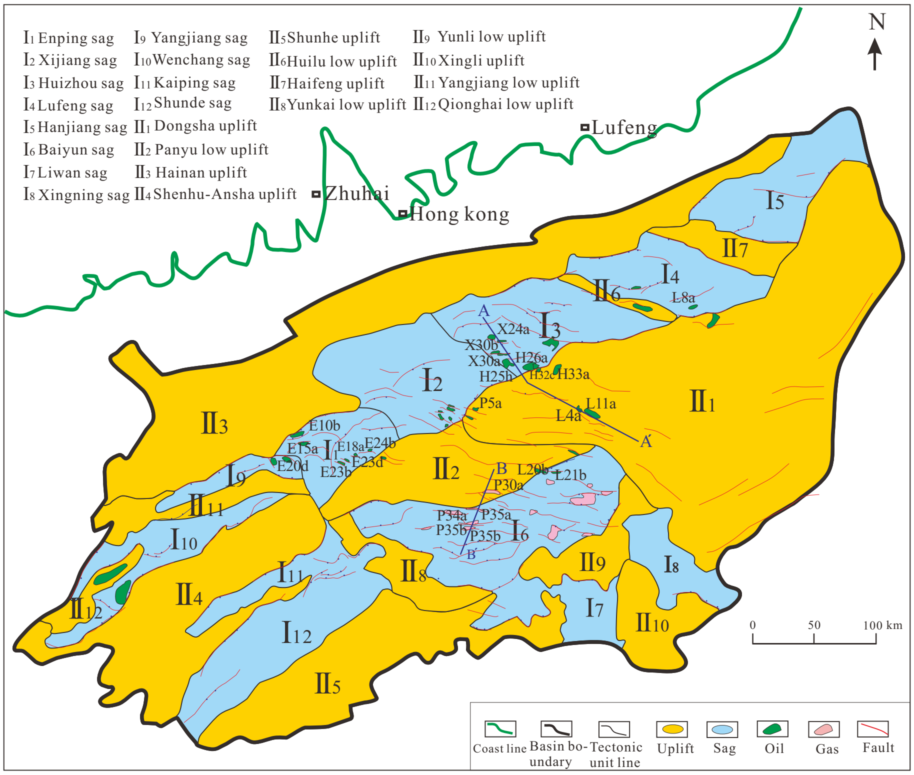

Fig. 1. Distribution of typical faults and discovered hydrocarbon fields in the Pearl River Mouth Basin (the terms "E10b" and "P30a" refer to the names of hydrocarbon fields).

traps in the middle and shallow strata. More than 80% of the drilled traps in the PRMB are fault traps, and the large-scale oil and gas reservoirs have been found to be strongly controlled by faults. Among them, the proven reserves of crude oil and natural gas directly controlled by fault sealing are 430 million tons and 180 billion cubic meters, respectively, and the prospective resources of undrilled fault traps reach an estimated 5.86 billion cubic meters (Jiang et al., 2022; Pang et al., 2022). Evaluating the effects of faults on hydrocarbon migration and the analyses of accumulation models are crucial and among the main research objects of fine hydrocarbon exploration in the PRMB.

Faults are key factors for differential hydrocarbon accumulation in the PRMB (Shi et al., 2014). Previous studies have paid attention to the relationship between the fault characteristics and hydrocarbon accumulation in the PRMB from the early stage of the fault formation mechanism (Li et al., 1994; Chen et al., 2003; Sun et al., 2008), to fault sealing efficiency (Lv et al., 2011; Yu et al., 2012), and to hydrocarbon charging and migration efficiency (Sun et al., 2014; Jiang et al., 2015; Huang et al., 2018). Each achievement in the theoretical understanding of fault controlling hydrocarbon accumulation in the PRMB has promoted new discoveries. The exploration practice in the PRMB shows that the fault types, fault activities and fault sealing are the three key factors affecting hydrocarbon accumulation (Peng et al., 2013; Shi et al., 2014; Xu et al., 2014; Bai et al., 2022). However, with the increasing complexity of exploration objects, the current knowledge of the effects of faults on hydrocarbon accumulation in the PRMB has been severely limited. Previous studies paid attention to qualitative analysis, but the roles played by faults in the different stages of hydrocarbon accumulation in the PRMB have received less attention. In addition, existing research on faults has been limited to the Huizhou and Enping Sags of the Zhu I Depression in the PRMB (Yu et al., 2012; Xu et al., 2014; Jiang et al., 2016), and a whole-basin perspective on the models and quantitative evaluation of faults controlling hydrocarbon accumulation is lacking.

Based on the statistical data of geological, geophysical and hydrocarbon accumulation, this study aims to summarize the characteristics of fault activities in the PRMB, and establish an evaluation method and charts regarding the process of hydrocarbon migration, sealing, and lateral migration through faults. Moreover, we describe the characteristics of the discovered hydrocarbon accumulation, discuss the fault controlling models under different tectonic settings in the PRMB, and point out the exploration directions for different sags.

2. Geological setting

The PRMB is a Cenozoic extensional basin with a double-layer structure of early faulting and late depression. Since the late Cretaceous, it has experienced rifting, post-rifting and tectonic reactivation (Hall, 2002; Ren et al., 2002; Yang et al., 2012), including the Shenhu, Zhuqiong, South China Sea, Baiyun, and Dongsha movements. Fault activity is widespread in this basin. Petroleum discoveries have proven that the hydrocarbons are obviously controlled by faults (Shi et al., 2014) (Fig. 1). According to orientation, four groups of

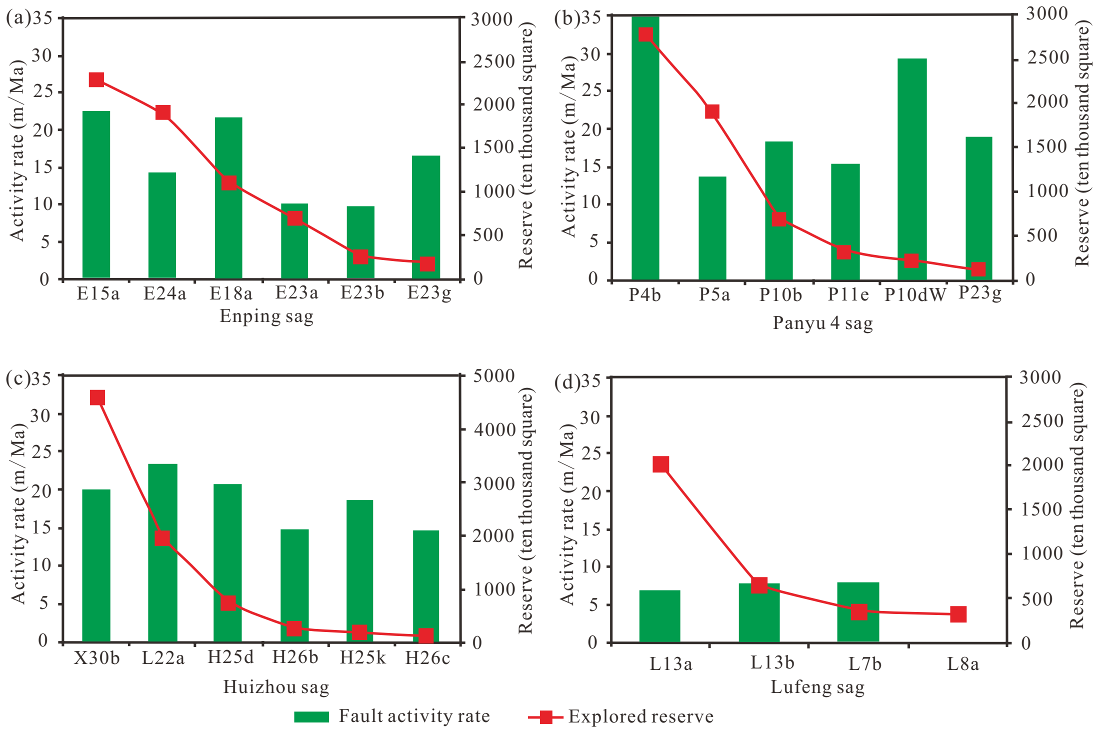

Fig. 2. The critical values of fault vertical migration efficiency in different sags of Zhu I Depression (E15a, P4b, X30b, L13a et al., refer to the names of Wells).

faults developed in the PRMB, namely NEE, EW, NWW, and NNW, which rotate clockwise from deep to shallow, indicating the change in regional stress field. Paleogene faults are generally featured by strong activity intensity and long extension distance, which control the sag structure of the basin during the rifting period. In the PRMB, there are more than 2,000 Neogene faults with different scales. These often appear in groups on the plane, forming a variety of plane fault combination styles of echelon, broom or parallel, and showing an obvious oblique slip or torsion characteristic.

3. Hydrocarbon accumulation controlled by faults

3.1 Hydrocarbon migration

3.1.1 Vertical migration

During the active faulting period, hydrocarbon migrated rapidly upward in the "seismic pump" (Sibson et al., 1975; Sorkhabi and Tsuji, 2005), with the vertical migration efficiency controlled by the active fault intensity and the relationship between fault throw and caprocks. Based on typical hydrocarbon reservoir analyses in the Zhu I Depression, the maximum active intensity of faults controlling hydrocarbon migration and accumulation was calculated in the key hydrocarbon generation and expulsion period (10-5 Ma), and the minimum active intensity of faults in case of commercial hydrocarbon accumulation was taken as the critical value of vertical migration efficiency. It was found that the fault activity rate during 10-5 Ma in the middle and shallow hydrocarbon reservoirs reaches 10 m/Ma, and the critical values of vertical migration efficiency of faults are 10 m/Ma in the Enping Sag, 13.3 m/Ma in Panyu-4 Sag and 12.5 m/Ma in the Huizhou Sag (Fig. 2), indicating that differences in the critical value of vertical migration efficiency exist among various sags. In the Lufeng Sag, however, the vertical migration of hydrocarbon in deep Paleogene reservoirs is related to the fracture opening (Li et al., 2022). In fact, the scale of hydrocarbon accumulation is not only controlled by the vertical migration of faults but also affected by hydrocarbon supply intensity, caprock characteristics, trap size, etc.

Next, the relationship between the degree of caprock broken by fault and the vertical distribution of hydrocarbon reservoirs was further analyzed. Statistically, hydrocarbon partially passes through mudstone and migrates to the shallow strata when the fault-caprock ratio (fault throw/thickness of mudstone caprock) is larger than 5, and reserves can be found in both deep and shallow strata. However, when the fault-caprock ratio is less than 5, the upward migration of hydrocarbon may be blocked, and hydrocarbon is mostly accumulates in the deep strata (more than 3,500 m). With a decreasing fault-caprock ratio, the vertical sealing efficiency of the caprock may be enhanced.

3.1.2 Migration along the fault-ridge

There are three types of migration through the fault-ridge, including two structural ridges on the fault surface and along the fault strike, and one sand ridge with complicated faults. This study focuses on the migration efficiency of the former two types of fault-ridges. Taking the X30 oilfield as an example (Jiang et al., 2019), the X30 major fault possesses several

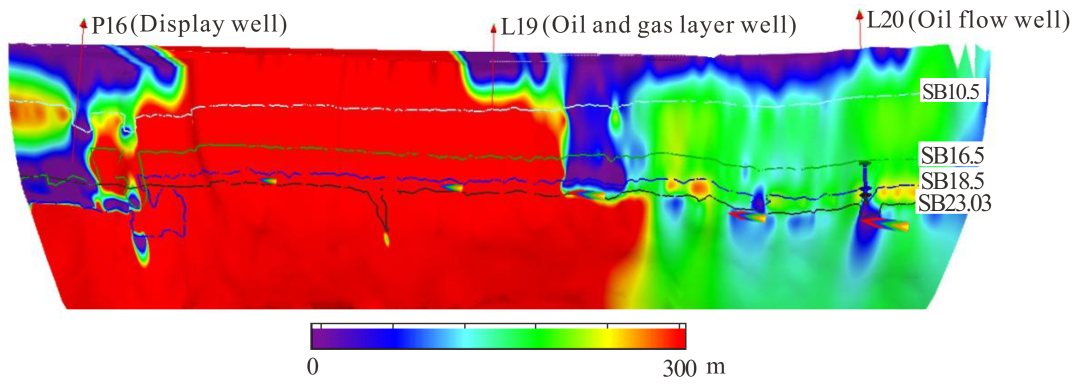

Fig. 3. Sketch map of hydrocarbon migration along the fault strike.

structural ridges and controls the hydrocarbon migration and accumulation. The structural ridge in the middle part of the fault surface is the largest, with a length of 8.5 km and a width of around 2.3 km. It also has the best vertical migration efficiency, which is beneficial for hydrocarbon enrichment near the structural ridge. The hydrocarbon migration efficiency along the fault strike was analyzed by using seismic data and drilling data. Studies have established that the migration efficiency along the footwall is obviously higher than that of the hanging wall. This is because the fractures induced by the hanging wall are relatively developed, which easily leads to the upward dispersion of hydrocarbon. However, the fractures induced by the footwall are less developed, hence they block hydrocarbon migration and ensure it along the fault plane. This phenomenon also occurs in the northeastern Baiyun, Panyu-4 and northern Enping Sags. For example, on the step-fault zone in the northern Enping Sag, hydrocarbons migrated along the arc-shaped fault strike and were enriched in the high part of the footwall; nonetheless, the drilling of the hanging wall failed. It was further found that, when hydrocarbon migrates along the fault strike, hydrocarbon leakage easily occurs in the junction of the fault system. Taking the Panyu-24 fault system as an example, the fault throw distribution map shows the characteristics of fault connection (Fig. 3). When hydrocarbon migrates along the strike of the fault system in Baiyun Sag, the migration efficiency gradually decreases owing to leakage, which was also confirmed by the drilling results. That is, oil flow wells are distributed in the proximal end of fault system, oil layer wells are distributed in the middle, and show wells are distributed at the distal end.

3.1.3 Lateral migration in the relay zone

The structural area where the two faults interact is the relay zone (Morley, et al., 1990; Gawthorpe and Hurst, 1993; Wang et al., 2013), which is widely developed in the PRMB and closely related to hydrocarbon accumulation. The migration efficiency of the faults can be characterized quantitatively by its length, separation, density, and dip (Wang et al., 2021). Lateral hydrocarbon migration efficiency in the relay zone is related to the dip of the transition sand body, which commonly affects the development scale and density of fractures and faults (Fossen and Rotevatn, 2016; Li et al., 2018). Based on the displacement-distance method (Fossen and Rotevatn, 2016), we calculated the dip angle of the relayed sand body to classify the relay zone types (Fig. 4), and then characterized the lateral migration efficiency. The unconnected relay zone has a gentle dip angle (about 3°-10°), moderate developed fractures, and the best lateral migration efficiency. The dip angle of sand body in the weakly connected relay zone is moderate (about 10°-16°), with relatively developed fractures, and modest lateral migration efficiency. The sand body in the strongly connected relay zone has a large dip angle (about 16°-26°), with highly developed fractures. The relayed sand body is easy to form a steep slope, with the poorest lateral migration efficiency. Several relay zones developed in Southwestern Huizhou Sag. Based on the evaluation chart (Fig. 4), the H25 relayed sand body is an unconnected type, with a dip angle of 8.9°. Meanwhile, the H27 relayed sand body is a weak connection type, with a dip angle of 11.1°. The H26 relayed sand body is a strong connection type, with a dip angle of 16°.

Abundant oil and gas resources have been found on the path of the H25 relay zone, while the shallow and middle strata on the path of H26 and H27 relay zones are not the dominant oil and gas accumulation positions. In both the weak and the strong connection relay zones, the deep strata are the key directions for hydrocarbon accumulation.

3.2 Lateral sealing of faults

The evaluation of lateral sealing efficiency of faults includes lithology joint, clay smearing and stress sealing (Smith, 1966, 1980; Bouvier, et al., 1989; Yielding, et al., 1997), which should be considered jointly in evaluation practice. The lithology joint can be effectively evaluated based on the Allen diagram (Allan, 1989). This study focuses on the clay smear and stress sealing evaluation.

3.2.1 Clay smearing

Two indicators are commonly utilized to characterize the sealing efficiency of fault clay, including the shale smearing

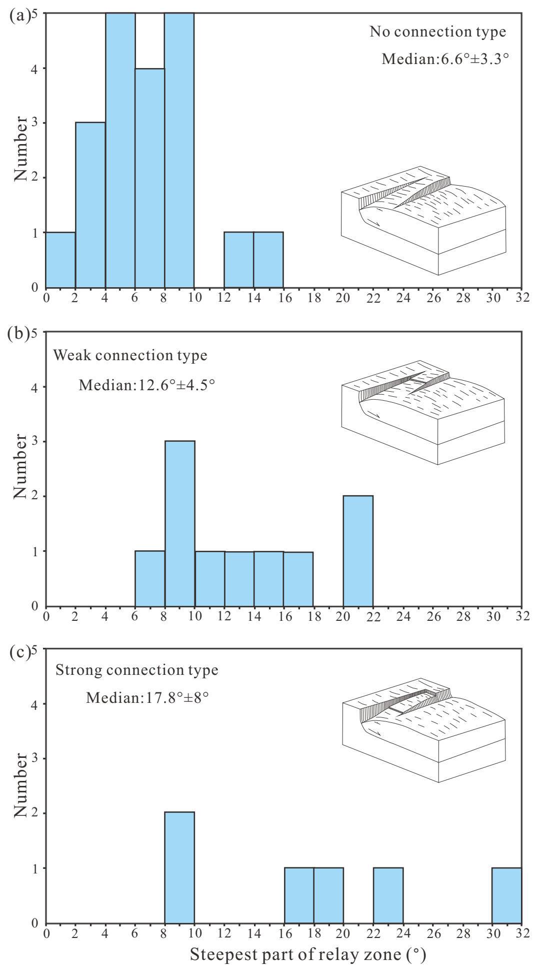

Fig. 4. Statistics of the dip angle of relayed sand bodies for different relay zones (modified from Fossen and Rotevatn, 2016; Li et al., 2018).

factor (SSF, the accumulation of the ratio of shale thickness square to smearing distance), and the shale gouge ratio (SGR = ∑accumulated shale thickness/fault throw) (Lindsay, 1992; Yielding, 1997). By analyzing the SGR of more than 300 oil-bearing layers of 40 faulted traps in the Zhu I Depression, the shale content of the fault zone was characterized and the difference of sealing efficiency of fault clay smearing in different sags was obtained (Fig. 5). The critical value of SGR is not fixed but changes with the burial depth. Taking the burial depth of 3,000 m as the boundary between deep and shallow strata, the fault sealing efficiency shows obvious differences between deep and shallow parts. For the shallow strata in the Enping, Panyu 4 and Huizhou Sags, the critical value of SGR decreases firstly and then increases (Figs. 5(a), 5(b) and 5(c)), with the turning point at roughly 1,700-1,800 m and a critical SGR value of 0.32. Hydrocarbons mainly accumulated in deep Paleogene reservoir of Lufeng Sag, thus there is no obvious change in clay smear sealing efficiency (Fig. 5(d)). The diagenesis of the shallow fault zone in the Zhu I Depression was strengthened, and the sealing efficiency was affected by cementation and the fracture development degree. Therefore, the lateral sealing efficiency of faults in the middle-deep strata cannot be characterized simply by clay smearing.

3.2.2 Stress sealing

Neogene fault activity is affected by extensional and strike-slip stress (He et al., 2019). The NWW normal faults and the near EW left lateral echelon fault were mainly developed in the PRMB. Moreover, extensional action was dominant and supplemented by strike-slip, which is different from the Bohai area that is featured by obvious strike-slip. Strike, dip and features of faults are important parameters affecting stress sealing. It can be simply considered that the stress sealing efficiency of transtensional faults in this area is higher than that of tension faults. Based on the imaging logging data, it is shown that the maximum horizontal principal stress direction of the present tectonic stress field in the PRMB is NWW (295°). For the fault stress sealing capacity in different directions, NE faults have obvious advantages over EW and NWW faults. Because of its unique dual functions of migration and stress sealing, the near EW transtensional fault zone is generally favorable for hydrocarbon accumulation. Transtensional faults control the trap formation and hydrocarbon accumulation of large-medium oil and gas fields, including echelon fault zones in the Enping Sag, broom shaped fault zones in the Huizhou Sag and several rows of echelon fault zones in the northeast of Baiyun Sag, such as Enping 24b, Panyu 5a, Xijiang 30b and Panyu 35a, with a proved reserve of over 200 million cubic meters.

3.3 Hydrocarbon lateral migration across faults

Recently, several oil and gas fields that developed after lateral hydrocarbon migration across fault planes were discovered in the PRMB, which were controlled by the conditions, strata and locations of hydrocarbon migration across faults (Wu et al., 2020). Taking the E18 fault system in the Enping Sag as an example, we used evaluation methods for hydrocarbon migration across faults such as lithology joint, clay smearing, fault gouge development, and oil column height. The value of clay smearing in the E18 fault zone was found to be generally lower than the critical value of Enping Sag at 0.32, indicating that there are many sand-sand joints, among which the sealing efficiency of fault zones in the Zhuhai Formation (SGR: 0.22-0.35) and the lower Hanjiang Formation (SGR: 0.22-0.32) is low. Light oil can easily penetrate through the above two sets of strata in the E18 fault zone and migrate laterally. At the distal ends of the fault, due to the small fault throw, the fault gouge is often less developed, which is conducive to hydrocarbon migration across the fault plane. Moreover, the fracture degree at the fault connecting points is much better developed, which is also conducive to hydrocarbon migration across the fault plane. Combined with the growth-connection process of the E18 fault zone, there are two pathways for hydrocarbon migration across the fault plane: pathway A and pathway B (Fig. 6). Considering the influence of oil column height, path A with the largest oil column height is the most suitable for hydrocarbon penetrating the E18 fault zone. The stratum is in an upward dip, which is conducive to continued southward migration. Therefore, hydrocarbon can easily penetrate the E18 fault zone in the Zhuhai Formation and the lower Hanjiang Formation, and then migrate laterally.

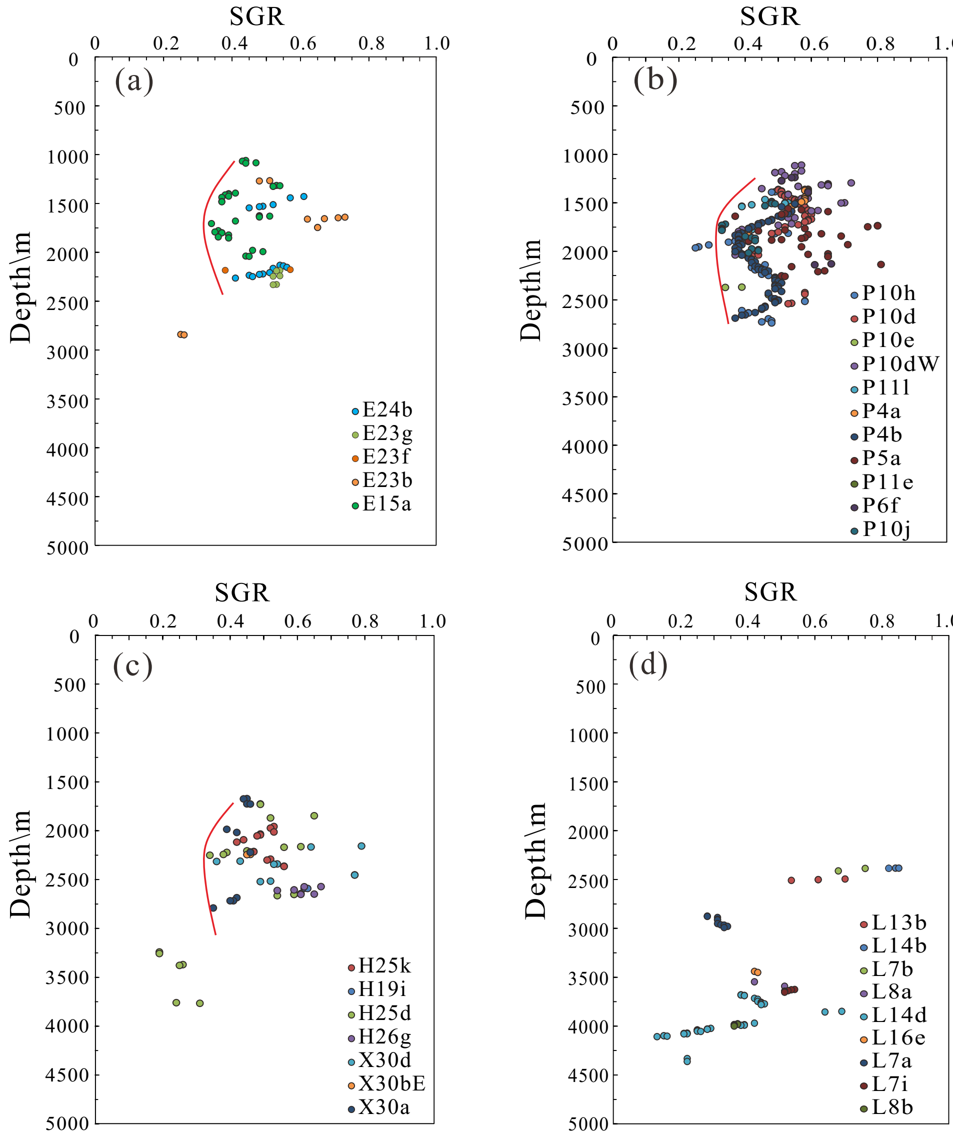

Fig. 5. Trends of the critical values of SGR with buried depth in the (a) Enping Sag, (b) Panyu4 Sag, (c) Huizhou Sag and (d) Lufeng Sag (E24b, P10h, H25k et al., refer to the names of Wells).

The connecting point with the highest height of hydrocarbon column is the most favorable area for lateral migration. Further analyses of migration across faults in Xijiang 30a and Enping 15b indicated that strong hydrocarbon charging intensity is necessary for migration across the fault. The fault connecting points or fault ends are the locations of migration across the fault, and low SGR strata are often favorable in this regard.

4. Hydrocarbon accumulation and exploration potential

4.1 Hydrocarbon accumulation models

Compared to the accumulation patterns in other basins (Walker and Anderson, 2016; Huang et al., 2016; Fu et al., 2021; Wang et al., 2021), we identified the relationship between the discovered large-scale hydrocarbon in the PRMB and the fault development characteristics, and established seven accumulation models controlled by faults in the steep slope, gentle slope, depression and uplift areas (Fig. 7).

At present, there is only one type of uplift inside the depression area found in the Lufeng Sag (L8a), which is controlled by active faults in the early stage. The oil charging is strong from the LF13 sag, resulting in fracture opening in the hanging wall of migration faults and migration to the near Paleogene strata.

Three models developed for the steep slope area include rollover anticline, accumulation along the fault strike and relay zone controlling accumulation. The rollover anticline model was developed for the X30 oilfield in the Huizhou Sag and E20d oilfield in Yangjiang Sag. As shown in Fig. 8, hydrocarbon in the X30b oilfield not only migrated vertically through sag-controlled and source-connecting faults to the

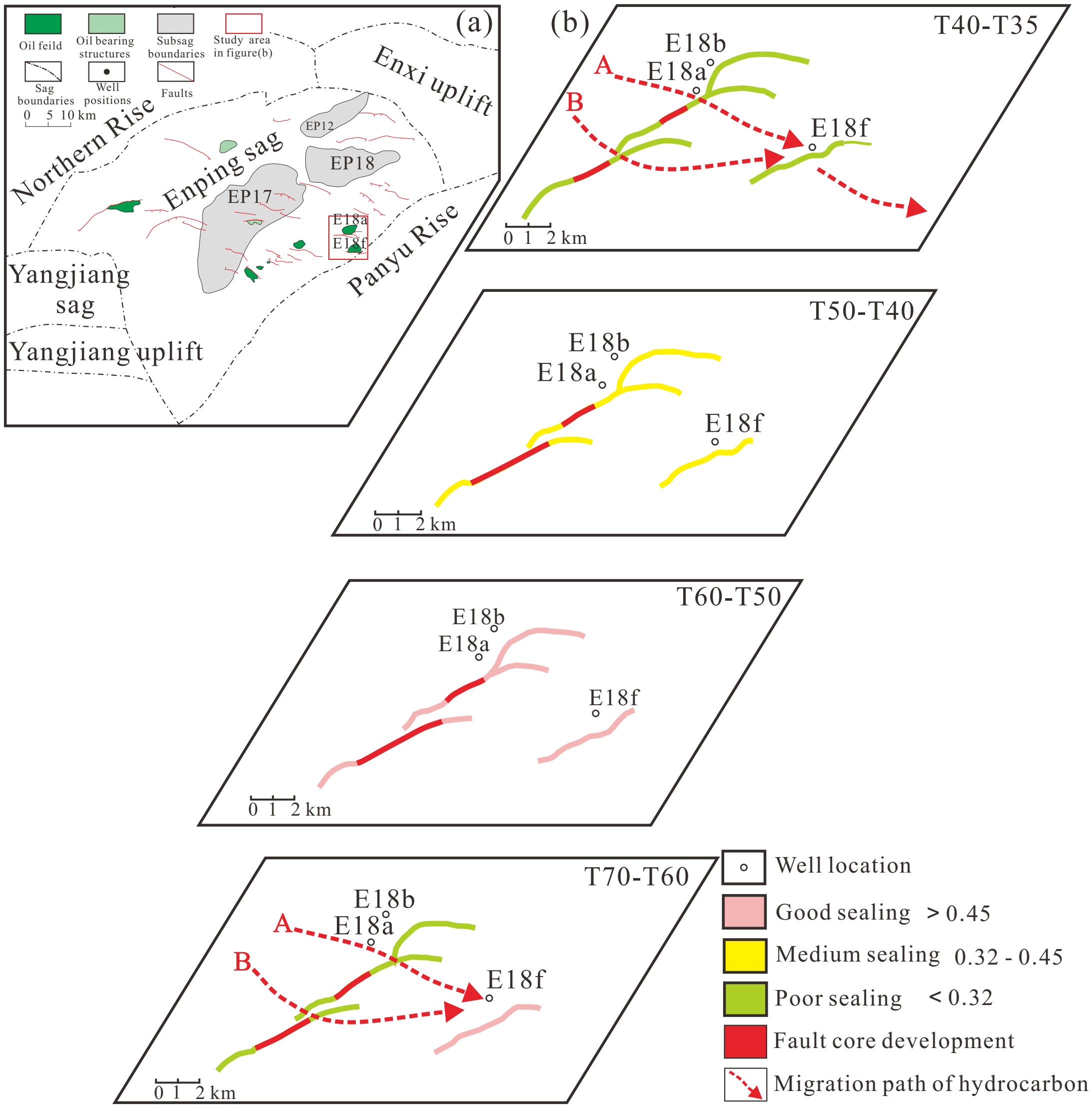

Fig. 6. Evaluation of hydrocarbon lateral migration across faults based on the characteristics of clay smearing and internal structure.

hanging wall and accumulated in the anticlinal traps, but also migrated to the footwall by relayed sand bodies and accumulated in the fault traps, forming the X30a oilfield, which is characterized by hanging wall migration and footwall trapping. The accumulation types along the fault strike are featured in the step-fault of the northern Enping Sag and the steep slope area of Panyu 4 Sag. Hydrocarbons migrate and accumulate along the footwall of arc-shape fault or echelon fault system, forming E15a, E10b, P5a, and other oil fields. The accumulation type of relay zones is the most typical in the southwest Huizhou Sag (Li et al., 2018). The oil generated in Huizhou Sag migrated to the uplift area through the H26 unconnected relayed sand body, forming H25h, H26a, H32c, and other draped anticline oil fields (Fig. 8). Currently, the deep strata of H26 weakly connected relay zone and H27 strongly connected relay zone are the key exploration targets.

We developed two models for the gentle slope area, including the source-fault-ridge-trap type and fault-controlled differential accumulation type. The former type can be commonly observed in the northeastern Baiyun Sag (Mi et al., 2018). The bitumen, fluid inclusions and quantitative grain fluorescence images indicate hydrocarbon accumulation process. Oil and gas from the main or eastern Baiyun Sag migrated firstly vertically through faults and diapirs, and then laterally along the fault-ridge sand bodies to favorable structural belts. The large-scale fields discovered in the northeastern Baiyun Sag are all controlled by faults. For example, the Panyu-Liuhua gas fields (P35a, P35b, P30a, L19d, L19e, etc.) were trapped by the EW-trending echelon fault system (Fig. 9), while Liuhua 20b and Liuhua 21b oil fields were trapped by NE-trending boundary faults. The latter model is most typical in the southern Enping Sag. The oil generated in the Enping 17 sub-sag migrated to the gentle slope zone in the southern Enping Sag along the complex migration system composed

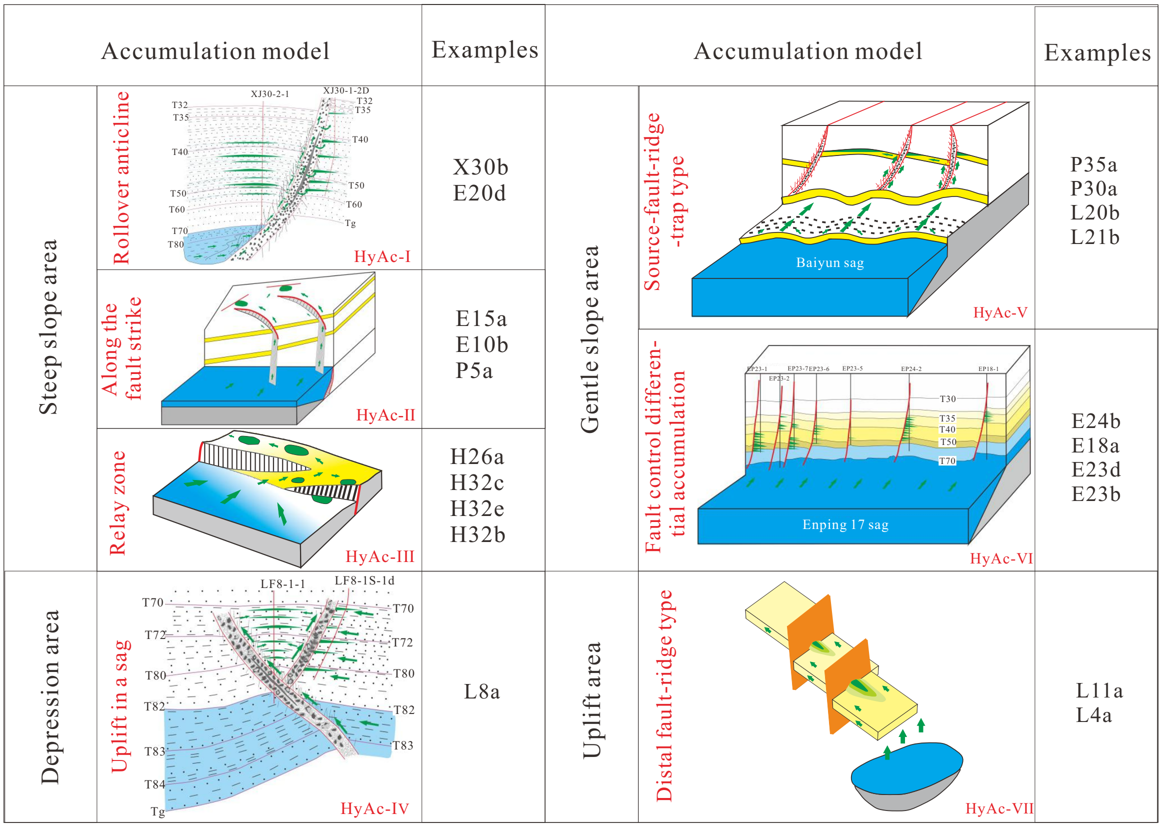

Fig. 7. Seven hydrocarbon accumulation models controlled by faults in the different tectonic settings of the Pearl River Mouth Basin.

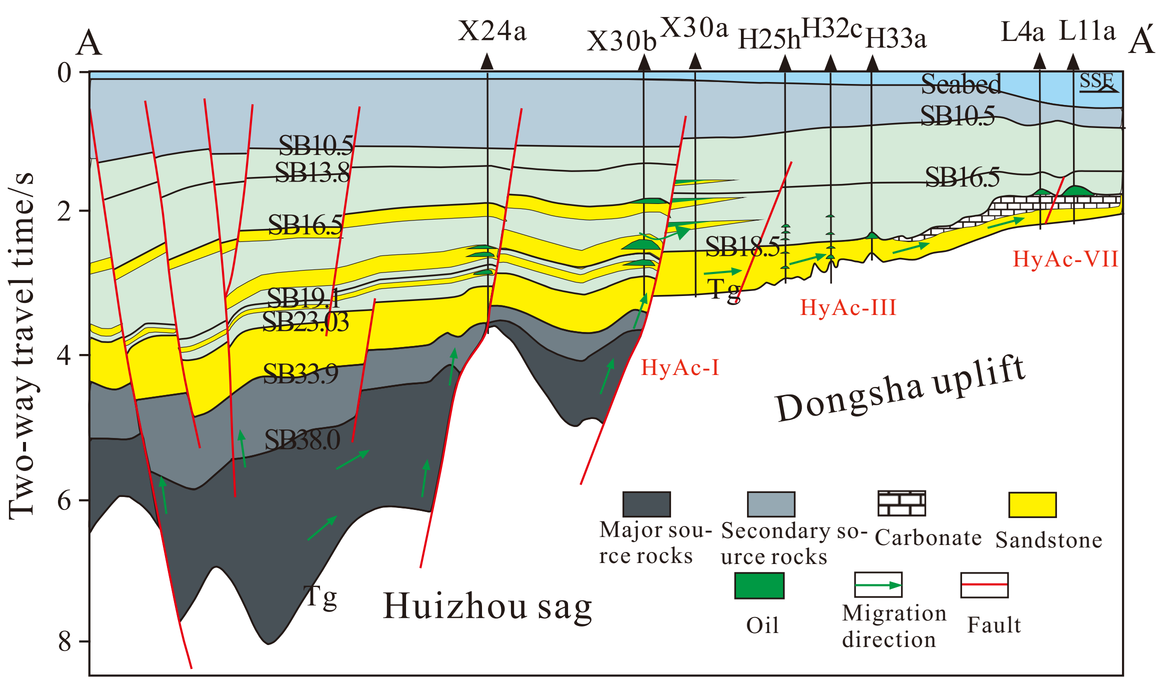

Fig. 8. Hydrocarbon accumulation model controlled by faults and ridge-fault in the Huizou Sag-Dongsha Rise (profile line shown by A-A’ in Fig. 1).

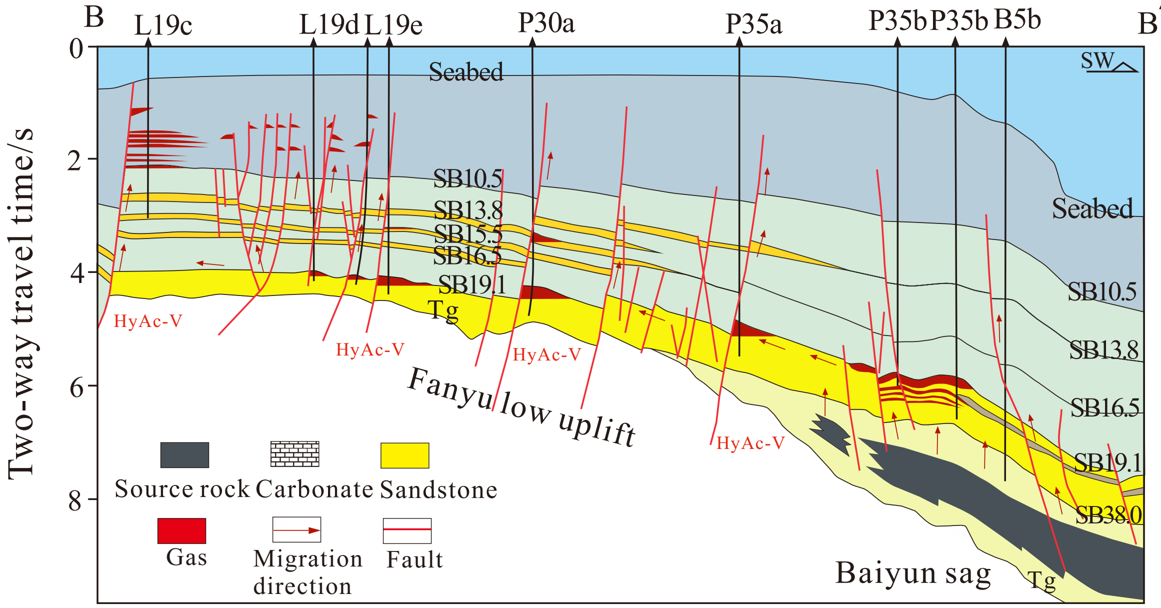

Fig. 9. Hydrocarbon accumulation model of Panyu–Liuhua gas fields controlled by Faults in the northern Baiyun Sag (profile line indicated by B-B' in Fig. 1).

of basement unconformity, sand bodies in the Wenchang Formation and structural ridge, and then accumulated through the vertical migration of faults. Fault intensity seems the key to the accumulation in the southern Enping Sag. The middle and shallow strata with greater than 10 m/Ma fault intensity is favorable for hydrocarbon accumulation.

The uplift area is an accumulation model controlled by the long fault-ridge system, such as the L11a and L4a oilfields. The oil-source correlation analyses indicate that the oil of L11a came from the middle-deep lacustrine source rocks in the Huizhou Sag. The effect of long migration distance on the geochemical indicators of reservoirs in the migration path is obvious. The oil from Huizhou Sag migrated to Dongsha Uplift through the relay zone first, and then to the carbonate reservoir 60 km away through the inherited structural ridge (Fig. 8), forming a 100-million-ton carbonate oil field offshore.

4.2 Exploration potential and direction

Based on the development characteristics of different types of faults in the Zhu I Depression and Baiyun Sag, combined with our understanding of the controlling effect of fault on reservoirs, the petroleum exploration potential and direction of different sags were analyzed. The deep-shallow connecting fault is a proven high-quality hydrocarbon migration fault type. The exploration practice in the Lufeng Sag proves that deep/middle-deep fault is favorable for Paleogene deep accumulation. At present, discoveries in the Zhu I Depression are mainly in the shallow and middle strata, which are obviously controlled by the deep-shallow connecting faults. However, the middle/middle-deep faults developed in the Enping and Huizhou Sags are in majority, with promising exploration potential in the deep Paleogene strata. The deep-water area in the Baiyun Sag is featured by differential fault activity, that is, the late extensional faults developed in the northeastern area are favorable for petroleum accumulation in the shallow and middle strata, whereas the middle and deep transtensional faults developed in the southwest and south areas are favorable for petroleum accumulation in the deep Paleogene strata.

5. Conclusions

Hydrocarbon accumulation in the PRMB is closely related to fault activities. This study established characterization methods and evaluation charts of the different processes of faults in the various stages of hydrocarbon accumulation, including migration, sealing, and lateral migration through the fault surface. Studies have shown that the intensity of fault activity and the ratio of fault-cap affect the vertical migration efficiency. The EW-trending transtensional fault zones have unique dual functions of migration and stress sealing. Seven accumulation models for the controlling effect of faults under different tectonic settings were established in the PRMB. Our findings contribute to the recent breakthroughs of hydrocarbon exploration in the Enping and Yangjiang Sags in the PRMB.

This study enhances our knowledge of fine hydrocarbon exploration in the PRMB, such as in the northeast Baiyun Sag, Enping Sag, Huizhou Sag, and Dongsha rise. With the increasing exploration maturity in this area, the controlling effects of faults on hydrocarbon accumulation in the Paleogene strata will be the next research focus. In addition, we suggest the Enping, Huizhou, and southwestern Baiyun Sags as the further exploration objects of the Paleogene strata.

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Conflict of interest

The authors declare no competing interest.

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