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Study on fault-controlled hydrocarbon migration and accumulation process and models in Zhu I Depression

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Abstract
Through the analysis of the faults and their internal structure in Zhu I Depression, it is found that the internal structure of the late fault is obviously segmented vertically. It develops unitary structure (simple fault plane) in shallow layers, binary structure (induced fracture zone in hanging wall and sliding fracture zone in footwall) in middle, layers and ternary structure (induced fracture zone in hanging wall and sliding fracture zone in middle, and induced fracture zone in footwall) in deep layers. Because the induced fracture zone is a high porosity and permeability zone, and the sliding fracture zone is a low porosity and ultra-low permeability zone, the late fault in middle layers has the character of “transporting while sealing”. The late fault can transport hydrocarbon by its induced fracture zone in the side of the hanging wall and seal hydrocarbon by its sliding fracture zone in the side of the footwall. In deep layers, the late fault has the character of “dual-transportation”, induced fracture zones in both sides of hanging wall and footwall can transport hydrocarbon. The early fault that only developed in the deep layers is presumed to be unitary structure, which plays a completely sealing role in the process of hydrocarbon migration and accumulation due to inactivity during the hydrocarbon filling period. Controlled by hydrocarbon source, early/late faults, sand bodies and traps, two reservoir-forming models of “inverted L” and “stereo-spiral” can be proposed in middle layers, while two reservoir-forming models of “cross fault” and “lateral fault sealing” are developed in the deep layers of Zhu I Depression.

Key words: fault structure, transport/sealing, migration and accumulation process, reservoir-forming model, Zhu I Depression

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1 Introduction

Many theories and experiences have been formed in the study of hydrocarbon migration and accumulation in China, for example, source-control theory (Hu, 2005), multiple hydrocarbon accumulation belt (Hu et al., 1986), structural ridge accumulating oil (Zou et al., 1991), source-cap co-control theory (Zhou and Wang, 2000), compound transduction and meshwork-carpet reservoir (Zhang et al., 2003), full-concave oil-bearing (Zhao et al., 2004), multiple oil-control and phase potential-control accumulation (Li, 2003). Hydrocarbon migration and accumulation process is the key of hydrocarbon accumulation research, which mainly describe the migration period, migration path (Li, 1988; Zhou et al., 2008) and migration direction (Chen et al., 2003b) of hydrocarbon with the help of geochemical and basin model methods at present. Applying the theories and methods above, a lot of works have been carried out in the study of hydrocarbon reservoir formation in Zhu I Depression (Gong et al., 2012; He et al., 2012; Shi, 2013, 2015). However, through the analysis of the reasons for the failure of more than 140 exploratory wells in Zhu I Depression, there are 72 of them failed due to migration. Hence the unclear process of hydrocarbon migration and accumulation is still the biggest problem restricting petroleum exploration in Zhu I Depression.

Faults, especially late faults (Tian et al., 2008), are the keys to control hydrocarbon migration and accumulation in Zhu I Depression. Fault-sand transport system is the most important hydrocarbon transport combination in Zhu I Depression, especially when faults contact with source rocks (Wu et al., 2001). The fault activity, internal structure and spatial association of fault-sand all have a vital impact on the migration-accumulation process of hydrocarbon. This study classified the faults according to the differences of fault formation stages. On this basis, the internal structure of fault zone and its role in the process of hydrocarbon migration and accumulation are emphatically analyzed. The process of hydrocarbon migration and accumulation under the control of faults is basically clarified, and a variety of reservoir-forming modes is established. These models can be used for guiding the exploration of Zhu I Depression and even the whole Zhujiang River Mouth Basin.

2 Geological setting

The Zhu I Depression with an area of about 4×10^4 km^2 is located in the northern depression zone of Zhujiang River Mouth Basin in the north of South China Sea (Fig. 1). It is a Cenozoic faulted lake basin developed on the basement of Mesozoic continental shelf. The Enping (EP) Sag, Xijiang (XJ) Sag, Huizhou (HZ) Sag, Lufeng (LF) Sag and Hanjiang (HJ) Sag successively developed from west to east. From deep to shallow, the depositional environment is lacustrine in Wenchang (WC) formation, fluvial in Enping (EP) formation, marine delta in Zhuhai (ZH) forma-

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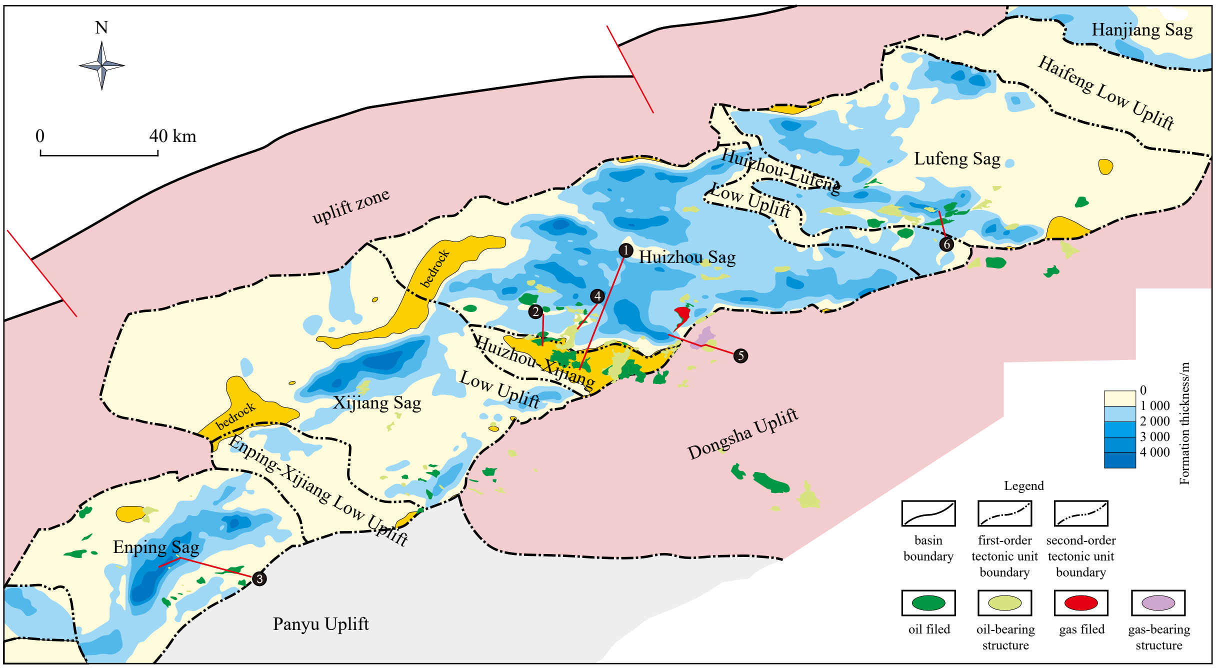

Fig. 1. Location of Zhu I Depression showing the tectonic unit division and reservoir distribution.

tion and shallow marine in Zhujiang-Quaternary formation (Chen et al., 2003a). The most important source rock in the Zhu I Depression is semi to deep lacustrine mudstone in WC formation, and the secondary source rock is the coal measures strata in EP formation. The major oil producing strata are sandstone reservoirs in upper and lower Zhujiang (ZJ) formation, followed by lower HJ formation and ZH formation. The marine mudstone in upper ZJ formation and HJ formation is the regional cap rock (Lü et al., 2011).

3 Fault active stages and classification

Since Cenozoic, the tectonic evolution of Zhu I Depression has undergone four stages: strong rifting (WC-EP formation), rifting-depression conversion (ZH formation), stable depression (ZJ-HJ formation) and fault reactivate stage (Yuehai-Wanshan formation) (Hu et al., 2016), which resulted in the formation of early and late faults (Fig. 2). Early faults formed in the stage of strong rifting, mainly developed in WC-EP formation, and disappeared upward in ZH formation. Generally, the major strike of early faults is NEE and near EW, while a few of them is NWW. The extension distance of early fault is usually from several kilometers to tens of kilometers. These faults have remarkable controlling effects on sag form and deposition, especially on the formation and distribution of semi to deep lacustrine source rocks in WC formation. Late faults (formed during the reactivate stage), especially the inherited late faults, cut off the whole sedimentary strata vertically. The strike of late faults is mainly NWW and near EW. The extension distance of inherited late fault is usually between several kilometers and tens of kilometers, while the extension distance of non-inherited late fault is relatively small, usually between several hundred meters and several kilometers.

4 Internal structure of late faults and their transporting/sealing property

A large number of studies have confirmed that the fault is not a simple plane, but a three-dimensional geological body with complex internal structure (Wu et al., 2010; Chester and Logan, 1986). It mainly consists of two types of structural units: sliding fracture zone (fault core) and induced fracture zone (damage zone) (Caine et al., 1996). Induced fracture zone is a high porosity and permeability zone due to the development of micro-fractures and the interconnection of fractures (Lockner et al., 1992). Its porosity (21%–27%) and permeability (100–3 000 mD) are higher than that of original rock (porosity:17%–25%; permeability: 5–400 mD) (Brogi, 2008). The sliding fracture zone is a low porosity and ultra-low permeability zone due to the development of fault rock and fault gouge. Its porosity (11%–23%) and transverse permeability (0.3–150 mD) are much smaller than that of original rock (Antonellini and Aydın, 1995; Gibson, 1998). Generally, the scale of the induced fracture zone (several meters to tens of meters) is far greater than that of the sliding fracture zone (several centimeters to several meters) (Ben-Zion and Sammis, 2003). Moreover, the stronger the fault activity (large fault distance, more activities and long activity duration) and the more brittle the formation lithology (such as crystalline rock, low porosity sandstone, etc.), the more developed the induced fracture zone (Xue, 2015).

Influenced by active stage, duration of activity, lithology on both sides of the fault plane and sectional occurrence, the internal structure of late faults in Zhu I Depression has obvious segmentation in vertical direction. Unitary structure, binary structure and ternary structure developed successively from shallow to deep, and show different characteristics of transporting/sealing (Fig. 3). Based on the burial depth of present, geological ages of formation and the difference of reservoir-forming, the WC to ZH formation is classified as the deep layer, the ZJ to HJ formation is classified as middle layer, and the Yuehai (YH) to Wanshan (WS) formation is classified as shallow layer.

4.1 *Late faults in shallow layers*

The shallow layers are plasticity to semi-brittle and mud rich stratum, in which, the late faults formed during the reactivate stage. These faults have short duration of activity (Pliocene),

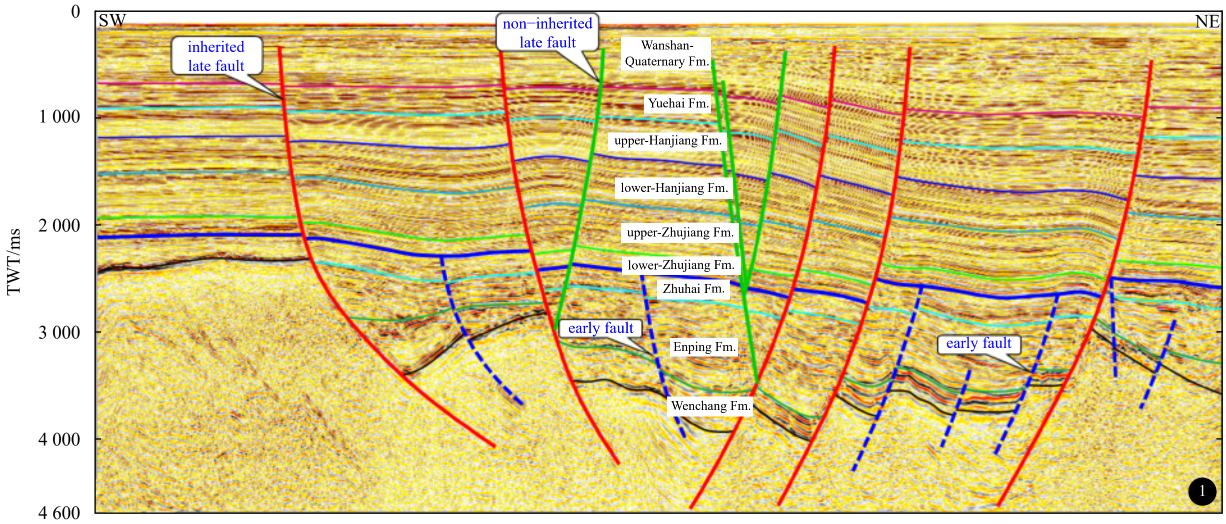

Fig. 2. Cross section showing the development characteristics of faults in SW–NE seismic profile of Huizhou Sag. Location is shown in Fig. 1. Fm.: formation.

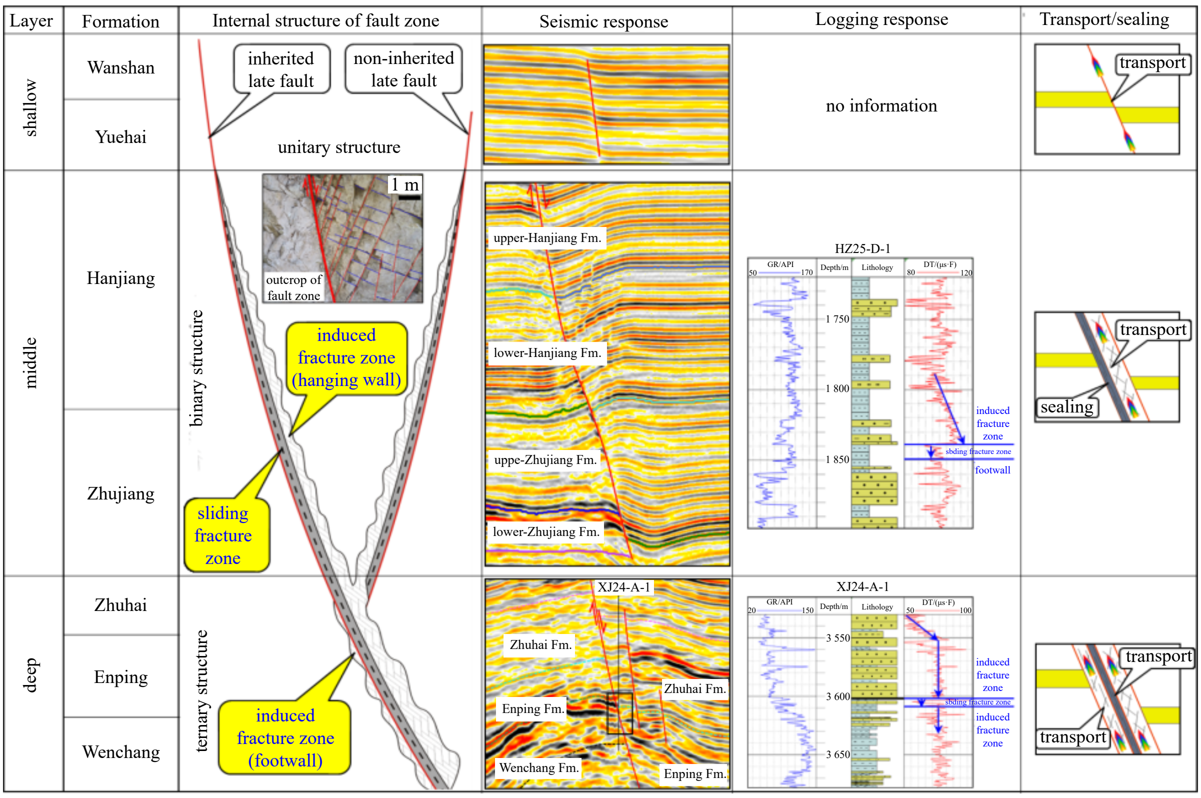

Fig. 3. Diagram of the internal structure of late active faults and its well-seismic-rock responses.

small fault distance of 0–50 m, smooth and upright fault plane, so the internal structure of fault zone is usually not developed. The strata on both sides of the fault plane keep the original rock state and do not break, so it is a one-dimensional structural fault (hanging wall rocks-fault plane-footwall rocks). Because of its activity in the hydrocarbon filling period, it mainly plays a role of transduction in hydrocarbon migration-accumulation process.

4.2 *Late faults in middle layers*

The middle layers are semi-brittle to brittle and sand mud interbedded stratum, in which, the late faults also formed during the reactivate stage. These faults have longer duration of activity (late Miocene–Pliocene), larger fault distance of 50–200 m, and smooth fault plane with a dip angle of 60°–80°, so the fault zones are very developed. However, the hanging wall (passive plate) stratum still maintains the original rock state, while the footwall (active plate) stratum often undergoes obvious fragmentation, thus it always forms binary structure (hanging wall rocks-sliding fracture zone-induced fracture zone-footwall rocks). When hydrocarbon enters such fault zone, it will show a remarkable dual character of “transporting while sealing”, that is, late fault can not only transport oil or gas efficiently in vertical direction by inducing fracture zones, but also seal oil or gas effectively in lateral direction by sliding fracture zones.

4.3 *Late faults in deep layers*

The deep layers are brittle sandstone/mudstone stratum, in which, the late faults are usually inherited faults which have undergone two tectonic activities of rifting and fault reactivate. These faults have the longest duration of activity (middle Eocene–early Oligocene, late Miocene–Pliocene), the largest fault distance of greater than 200 m, and uneven fault plane with a dip angle of less than 60°, so the fault zone is very developed. Because the rocks of hanging wall and footwall have been fractured to different extent, the ternary structure (hanging wall rocks-induced fracture zone-sliding fracture zone-induced fracture zone-footwall rocks) have formed. Generally, the ternary structure is asymmetric, and the width of the induced fracture zone on the hanging wall is wider than that of the footwall (Flodin and Aydin, 2004). In the process of hydrocarbon migration, the induced fracture zones on both sides of the sliding fracture zone can transport oil or gas in the vertical direction.

5 Fault-controlled hydrocarbon migration-accumulation process and reservoir-forming model

5.1 *Assemblage types of source and fault*

According to the relationship between faults and source rocks, the inherited late faults in Zhu I Depression can be divided into three types: source-faced faults, source-backed faults and source-in faults (Fig. 4). The source-faced fault means the source rock is only located in the side of the hanging wall. The source-backed faults means the source rock is only located in the side of the footwall. The source-in faults can be regarded as the combination of the above two. The early faults mainly developed in the interior of the depression, so most of them are source-in faults.

5.2 *Migration-accumulation process and reservoir-forming model in middle layers*

5.2.1 *Inverted L reservoir-forming model*

Inverted L model is the most common reservoir-forming model in the middle stratum of Zhu I Depression, which can form two types of reservoirs:

(1) Anticlinal reservoirs on hanging wall of source-faced faults. Taking the XJ30-B oilfield as an example (Fig. 5a), this structure is a rolling anticline located on the hanging wall of the boundary fault, the oil bearing strata is upper ZJ formation, with a proved geological reserves of 63.084 7 million cube. The reservoir-forming process of XJ30-B structure is as follows: hydrocarbons generated by the source rocks in WC formation in XJ30 sub-sag migrated directly along the induced fracture zone of hanging wall of F1 (source-faced fault) to upper ZJ formation, and accumulated in the rolling anticline of hanging wall finally.

(2) Opposite fault noses reservoirs on hanging wall of source-faced faults. Taking the EP18-A Oilfield as an example (Fig. 5b), this structure is a fault nose structure located on the southern uplift of the EP17 sub-sag, the oil bearing stratum are HJ-ZJ forma-

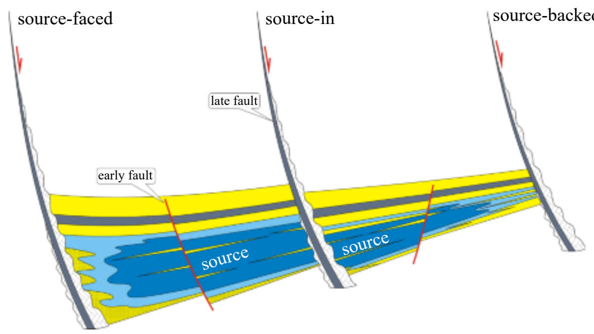

Fig. 4. Source-fault relationship in Zhu I Depression.

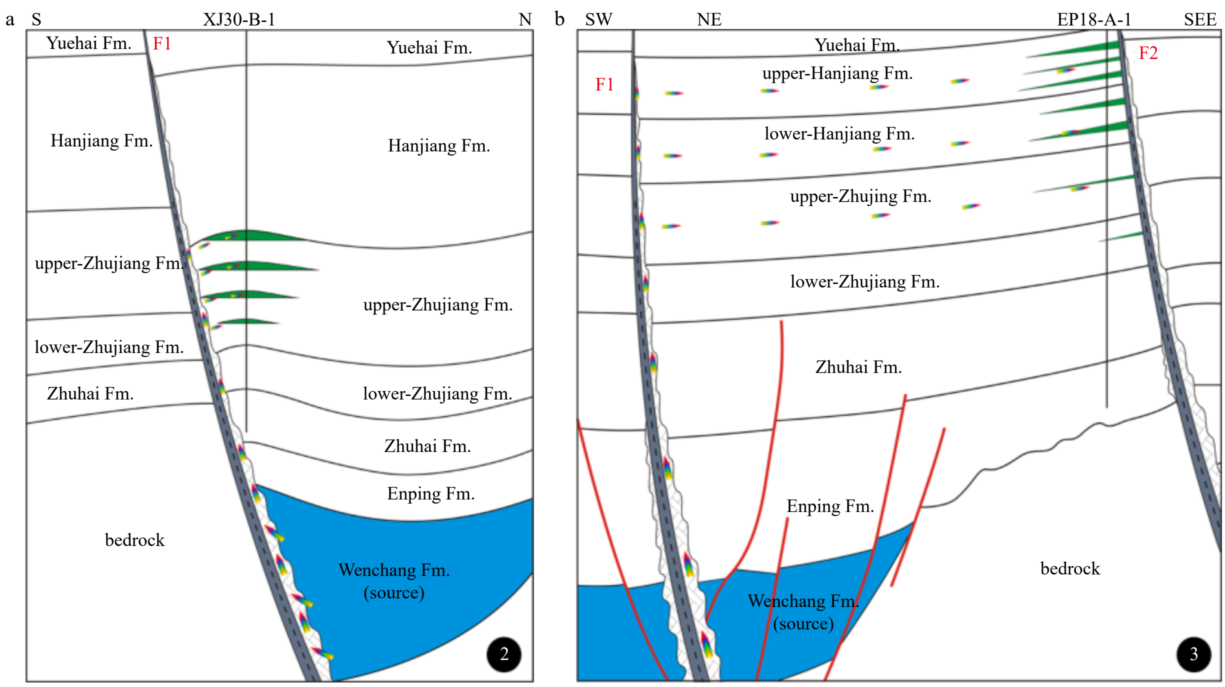

Fig. 5. Hydrocarbon migration-accumulation process of XJ30-B structure (a) and EP18-A structure (b). Locations are shown in Fig. 1. F1: source-faced fault, F2: source-backed fault.

tions, with a proved geological reserves of 4.550 8 million cube. The reservoir-forming process of the EP18-A structure is as follows: hydrocarbons generated from the source rocks in WC formation in the EP17 sub-sag migrated firstly along the induced fracture zone of hanging wall of the late source-in fault F1 to HJ-ZJ formations, then transported along the upward dipping formation to EP18-A structure, and accumulated in the opposite fault noses of footwall of the source-backed fault F2.

5.2.2 *"Stereoscopic-spiral" reservoir-forming model*

In this study, an interesting process is proposed, that hydrocarbon after generation always tends to migrate along the induced fracture zone of hanging wall of source-faced/in faults from deep to shallow (Fig. 6). The hydrocarbon can easily enter the strata on the hanging wall under the action of migration force component f_2 (Fig. 6) when the strata is back-dipping. If the conditions are met, the hydrocarbon could bypass the fault in the

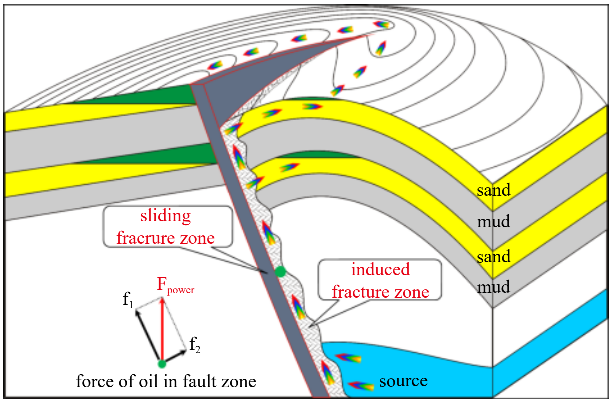

Fig. 6. Schematic diagram of "stereoscopic-spiral" hydrocarbon migration-accumulation process.

three-dimensional space and migrate to the side of the footwall and finally accumulate in the traps of opposite fault nose. Because the whole process of hydrocarbon migration is spiral in space, it can be named as the "stereoscopic-spiral" process.

The most typical reservoir-forming examples of "stereoscopic-spiral" in Zhu I Depression are HZ25-AA and HZ25-D reservoirs (Fig. 7). Both of them are opposite fault nose structures and located on the low uplifts which are surrounded by XJ30, XJ24 and HZ26 sags. HZ25-AA is located on the footwall of the source fault F3, and HZ25-D is located on the footwall of the source fault F1. There have not developed source faults which could provide hydrocarbon for HZ25-AA and HZ25-D in middle-shallow layers in XJ30 and XJ24 sags, the hydrocarbon could only be derived from XJ24 sag by "stereoscopic-spiral" way.

The reservoir-forming process is as follows: hydrocarbon generated from source rocks in EP and WC formations in XJ24 sag first migrated to the middle layers along the induced fracture zone of source fault F3 and its Y branch fault F4, then filled into the sand body on the confluence ridge of the hanging wall. After that, hydrocarbon migrated to the height of northwest and southeast respectively along the structural trend. Among them, hydrocarbon migrating southeastward might be migrated around the fault at the southern end of F3 to HZ25-D structure on the footwall to form reservoirs; hydrocarbon migrating northwestward was more likely to migrate along the structural ridge after filling HZ19-A, HZ19-B and HZ19-C structures, and eventually went around the F3 at the northern end to the HZ25-AA.

5.3 *Migration-accumulation process and reservoir-forming model in deep layers*

5.3.1 *Cross fault reservoir-forming model*

The ZH formation is the most important hydrocarbon transporting layers in deep Zhu I Depression, due to the development of high-quality delta front sand body during the stage of fault-de-

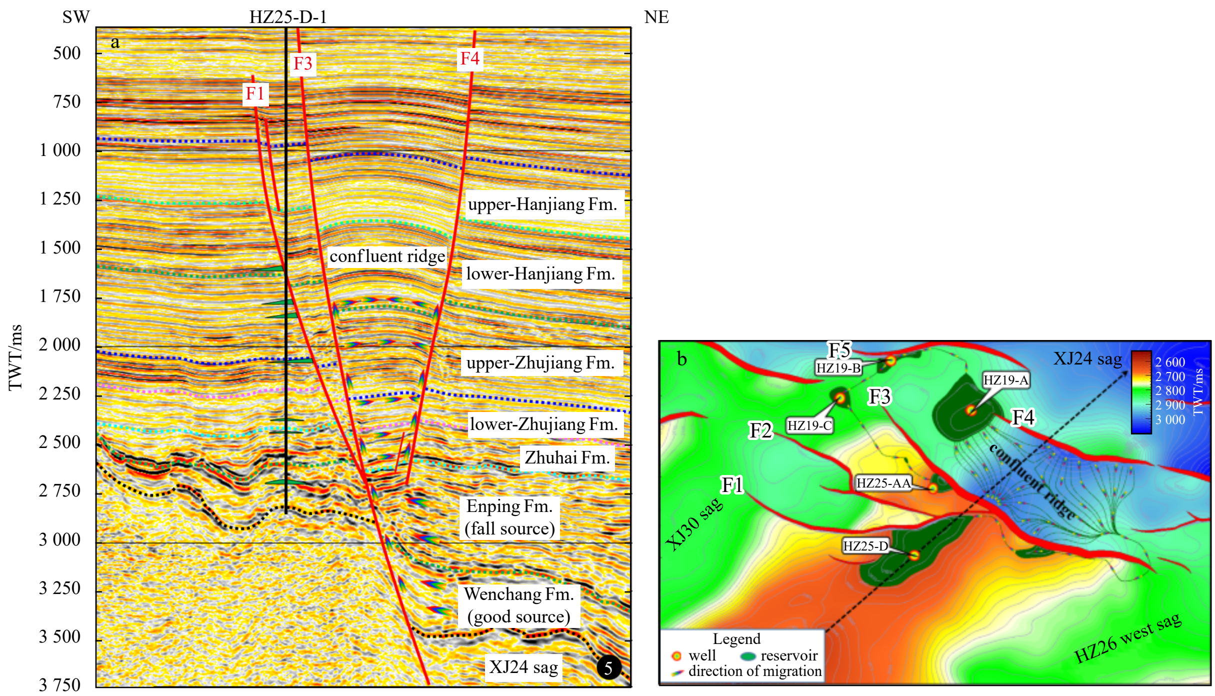

Fig. 7. Hydrocarbon migration-accumulation process of HZ25-AA and HZ25-D structure. a. Profile migration process, location is shown in Fig. 1. b. Trend of planar hydrocarbon migration and accumulation.

pression conversion. This set of sand has a thickness of 100–300 m and covering almost the whole Zhu I Depression. Because of the huge thickness of this sand, the late faults cannot completely disrupt it in part, thus forming a partial docking of the same set of sand bodies. When hydrocarbon migrates along the late faults, parts of hydrocarbon will migrate through the sand-sand docking section to the side of the footwall to accumulate and form reservoirs.

For example, the HZ27-C oil-bearing structure is located on the Dongsha Uplift, which is separated from HZ26 sag by an inherited late fault F1 with a strike of nearly E–W. Because the fault distance of F1 is only 10–30 m at the end of east, the huge thick sand body in ZH formation cannot be completely dislocated. As a result, when the hydrocarbon derived from the source rocks in HZ26 sag and migrated upward along F1, some can cross F1 through the sand-sand docking section to HZ27-C structure (Fig. 8).

5.3.2 *Lateral fault sealing reservoir-forming model*

Early faults developed in deep layers in Zhu I Depression are inactive in late stage, so they mainly play a role of sealing, and both sides of the fault can form faulted reservoirs.

LF14-D oilfield is a complex fault block structure which is located in the deep of the steep slope zone in the south of LF13E sag. The oil bearing strata mainly is WC formation, and with a proved geological reserves of 34.76 million cube, which make it become the largest deep oil field that have found in Zhu I Depression at present. The process of hydrocarbon accumulation is relatively simple. Because LF14-D trap developed in WC formation, which is adjacent to the source rocks of LF13E sag, hydrocarbon generated from the source rocks can filled into the trap only after a short lateral migration distance, and can be trapped laterally by several early faults (Fig. 9).

6 Conclusion and suggestions

(1) Twice tectonic activities led to the formation of two types of faults in Zhu I Depression. The internal structure of the late fault is obviously segmented in space. It develops the unitary structure in shallow layers, while the binary structure in middle layers and the ternary structure in deep layers. The early fault in deep is mainly presumed to be developed unitary structure.

(2) The late fault has the character of “transporting while sealing” in the middle layers, “dual-transportation” in deep layers. The early faults in the deep layers play a completely sealing role in the process of hydrocarbon migration and accumulation due to inactivity during the accumulation period. The fault noses developed on hanging wall of the late faults are not conducive to preserve oil or gas, and the drilling risks are generally high. But those developed on the footwall of the late faults could be beneficial to form reservoirs with exploration value due to the good sealing conditions.

(3) Controlled by hydrocarbon source, faults, sand bodies and traps, two reservoir-forming models of “inverted L” and “stereoscopic-spiral” are developed in the middle-shallow layers; also two reservoir-forming models of “cross fault” and “lateral fault sealing” developed in the deep layers of Zhu I Depression.

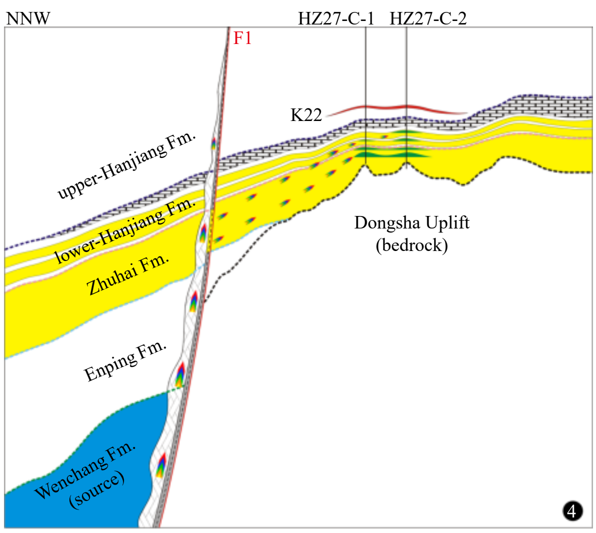

Fig. 8. Hydrocarbon migration-accumulation process of HZ27-C structure. Location is shown in Fig. 1.

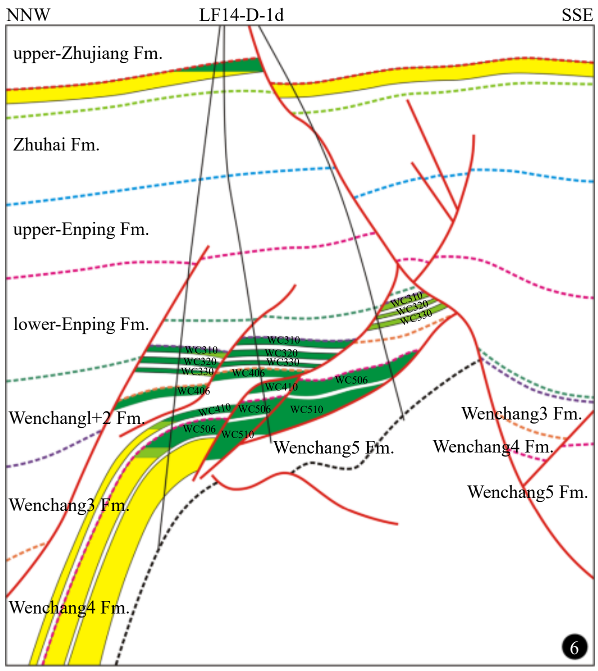

Fig. 9. Reservoir profile of LF14-D structure. Location is shown in Fig. 1.

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