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Vertical migration through faults and hydrocarbon accumulation patterns in deepwater areas of the Qiongdongnan Basin

WANG Zhenfeng[1], LIU Zhen[2], CAO Shang[2]*, SUN Zhipeng[1], ZUO Qianmei[1], WANG Yahui[1], HE Weijun[1]

[1] Zhanjiang Branch of China National Offshore Oil Corporation (CNOOC) Limited, Zhanjiang 524057, China
[2] Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing 102249, China

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Abstract

In the Qiongdongnan Basin, faults are well developed. Based on the drilling results, the traps controlled two or more faults are oil-rich. However, when only one fault cut through the sand body, there is no sign for hydrocarbon accumulation in the sandstone. In terms of this phenomenon, the principle of reservoir-forming controlled by fault terrace is proposed, i.e., when the single fault activates, because of the incompressibility of pore water, the resistance of pore and the direction of buoyancy, it is impossible for hydrocarbon to accumulate in sandstone. But when there are two or more faults, one of the faults acts as the spillway so the hydrocarbon could fill in the pore of sandstone through other faults. In total five gas bearing structures and four failure traps are considered, as examples to demonstrate our findings. According to this theory, it is well-advised that south steep slope zone of Baodao-Changchang Depression, south gentle slope zone of Lingshui Depression, north steep slope zone of Lingshui Depression, and north steep slope zone of Baodao Depression are the most favorable step-fault zones, which are the main exploration direction in next stage.

Key words: principle of reservoir-forming controlled by fault terrace, gas bearing structures, step-fault zone, Qiongdongnan Basin

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1 Introduction

Faulting is one of the most important factors that controls the formation and distribution of reservoir. It can not only be used as a shelter of hydrocarbon accumulation, but also as “a bridge and link” which connects source rock and trap.

Currently, in terms of fault controlled hydrocarbon accumulation, many studies have been carried out on migration, accumulation and preservation of hydrocarbon. According to the theory of fault controlled hydrocarbon, faults represent a basic reason for the controlling of hydrocarbon generation, migration, accumulation, scattering and distribution (Luo, 2002). Based on the study of the main controlling factors for the formation of 46 large and medium size gas fields in China, Fu et al. (2008) proposed that the transport pathway through faults is the main mechanism for gas migration in these gas fields, and this may also be the case for other large and medium size gas fields in China. On the base of Hippler’s (1993) research on deformation microstructures and diagenesis in sandstone adjacent to an extensional fault, fault activities which are broadly coincident with maturation and expulsion of hydrocarbons in a basin can directly influence the location of migration pathways. In a study of dominant migration pathway, Jiang et al. (2005) pointed out that at geological temporal scales, hydrocarbon tends to migrate in the direction with a large gradient of liquid potential and least resistance of fault section. This thought is referred to as “fault section predominance”.

In the Qiongdongnan Basin, based on an analysis of the fault system, Li (2005) proposed that during the Neogene the basin came into the peak stage of hydrocarbon generation and expulsion, and the fault activity had significant controls on fluid migration and hydrocarbon accumulation. In particular, during the thermal subsidence in the early-middle Miocene, the fault activity could play an important role as vertical carriers. By establishing a three-dimensional isochronous stratigraphic pattern in the Paleogene Lingshui Formation in deepwater areas, Chen et al. (2010) divided the pathway systems into reservoir, unconformity surface and fault. The faults in this area can be divided into the north-east, east-west and north-west trending categories, with the NE-trending faults being the dominant migration system. Using the summation of failure factors for 27 traps in this basin, Zhu et al. (2007) believed that there are four failure situations for the drilled traps, i.e., invalid migration, invalid trap, insufficient reservoir and carbon dioxide first-standing, in which invalid migration accounts for the largest proportion. Therefore, the study of the hydrocarbon migration systems, especially the migration through faults, has a great significance for the prospect exploration in deepwater areas of the Qiongdongnan Basin.

As suggested above, when source rocks join reservoirs by faults, hydrocarbon can fill the sand body successfully. How-

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*Corresponding author, E-mail: caoshang1990@163.com

ever, in the past the difference between migration through faults and injection has been largely neglected. In addition, the incompressibility of water and the problem of buoyancy were not considered sufficiently. Moreover, the phenomenon that there is little oil or gas in the traps controlled by a single fault (i.e., large scale accumulation is associated with multi-faulting settings), and the role played by faults in hydrocarbon distribution, were not fully explained.

Hence, based on the theory of reservoir-forming controlled by fault terrace, we intend to explain the result of drilling. In total five gas bearing structures and four failure traps are considered, as examples to demonstrate our findings. On such a basis, we discuss about the location of most favorable step-fault zones, which may provide guidelines for future explorations.

2 Geological background

The Qiongdongnan Basin is a Cenozoic northeastward extensional Basin which is located in southeast of the Hainan Island, northwest continental margin of the South China Sea. The basin has an area of around 3.4×10^4 km^2. It is located between 108°50′E and 111°50′E, 16°50′N and 19°00′N. Its western part is adjacent to the Yinggehai Basin, divided by Fault 1. The northern basin is adjacent to Hainan Uplift, divided by Fault 5. The southeastern basin is adjacent to Xisha-Zhongsha Uplift, divided by Fault 11 (Fig. 1). The northeastern basin is adjacent to depression Zhu Ⅱ in the Zhujiang River (Pearl River) Mouth Basin (Zhong, 2000; Xie et al., 2007). The Qiongdongnan Basin is an untypical passive continental margin basin characterized by a double-layer structure, fracture downward and depressing upward. The lower structural layer consists of the Eocene, Yacheng Formation, Lingshui Formation. The upper structure layer was formed in the depression period, including the Sanya Formation, Meishan Formation, Huangliu Formation, Yinggehai Formation and Ledong Formation.

In the Qiongdongnan Basin, the faults are developed in rifting layers of the Paleogene. Rifting in the Paleogene led to the formation of three groups of basement faults, i.e., NE-trending, nearly EW-trend and NW-trending faults. Among them, the NE-trending faults, accounting for about 65%, have the greatest proportion; the nearly EW-trending faults account for 20%. These two groups control the boundary orientation and tectonic zonation of the basin, forming the framework of the basin. The basin is limited by three NE-trending faults, i.e., Faults 5, 2 and 11, with the appearance of tectonic framework of three depressions and two uplifts, i.e., the north depression zone, the central uplifted zone of Yacheng-Songtao, the central depression zone, south uplifted zone and south depression zone. In general, the Qiongdongnan Basin is a large, asymmetrical basin with a compound graben, which centers in the central depression zone and is characterized by zonal arrangement from the south towards the north, with its blocky distribution from the east to the west (Fig. 1).

3 The principle of reservoir-forming controlled by fault terrace

There exists a big difference between hydrocarbon migration through faults and injection, which should be seen as two different functions. Hydrocarbon migration through faults is associated with the transport capability of oil or gas in the vertical direction of faults, while the injection is concerned with filling the sand body through faults. The injection is a process changing migration pathway.

A suitable reservoir condition is necessary for the injection of hydrocarbon, but not all reservoirs near a fault zone can

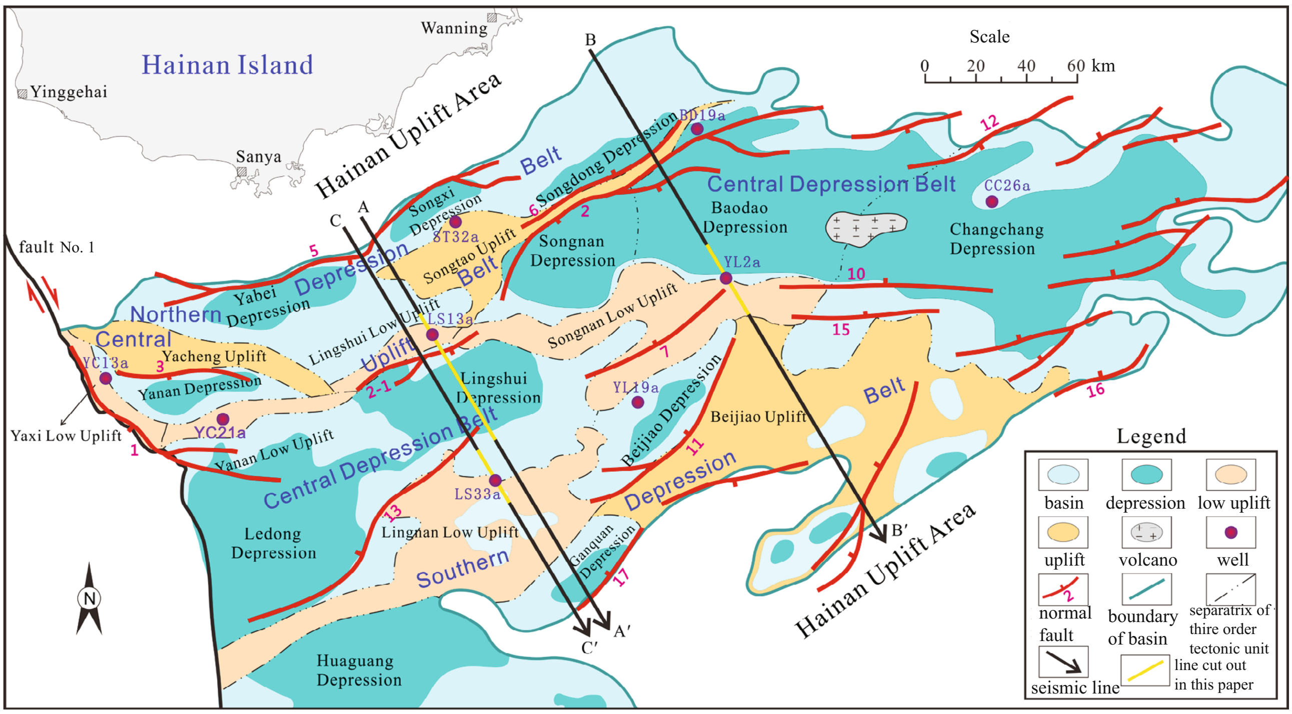

Fig.1. Structural location of the Qiongdongnan Basin.

be filled. There are three reasons. First, the sand body cutting through by faults has no spare space because the pore water in the reservoir cannot be compressed. Second, the height of the continuous liquid column in the section is limited so that buoyancy is difficult to break through the resistance of pore, and hydrocarbon cannot fill the sand body in the hanging wall of faults. Third, the direction of buoyancy is upward, so hydrocarbon cannot fill the sand body in the footwall of faults. Therefore, if the sand body is cut through by a single fault, there is no enough space for hydrocarbon to fill. However, if there are two faults or more, then one of the faults can act as the spillway so that the hydrocarbon successfully fill the sand body through other faults.

In the case of a single fault system, with an overpressure drive, hydrocarbon would move up quickly along the fault. Under the action of the pump-fault, pore water in the sandstone thinning out around the fault is discharged into the fault. Oil and gas would begin to migrate upward in the coalition of buoyancy and pressure. However, because pore water in the reservoir cannot be compressed, the sand body has little spare space; the height of continuous liquid column in the section is limited so that buoyancy would be unable to break through the resistance of pore. In addition, the direction of buoyancy is upward, which leads to the failure of injection in the fault footwall. In such a situation, a large amount of oil and gas would continue to move up along fault (Fig. 2a).

Under the circumstance of double faults, the source rock with overpressure is cut by double faults; with an overpressure drive, hydrocarbon moves up quickly along the faults. Sandstone thinning out around faults represents a similar condition to the single fault system. Hydrocarbon can fill into the sandstone between double faults from downdip direction of one of the faults. At the same time, pore water in the sand body can be discharged in an updip direction of the other fault. If there are sufficient oil and gas supply, then a reservoir can be formed in the sand body between the double faults. Likewise, some oil and gas may continue to migrate upward along faults (Fig. 2b).

The condition of multi-fault has resemblance to double faults. Although sandstone thinning out on both sides of the faults is difficult to be filled, hydrocarbon accumulation is relatively easy in the sandstone between the faults (Fig. 2c).

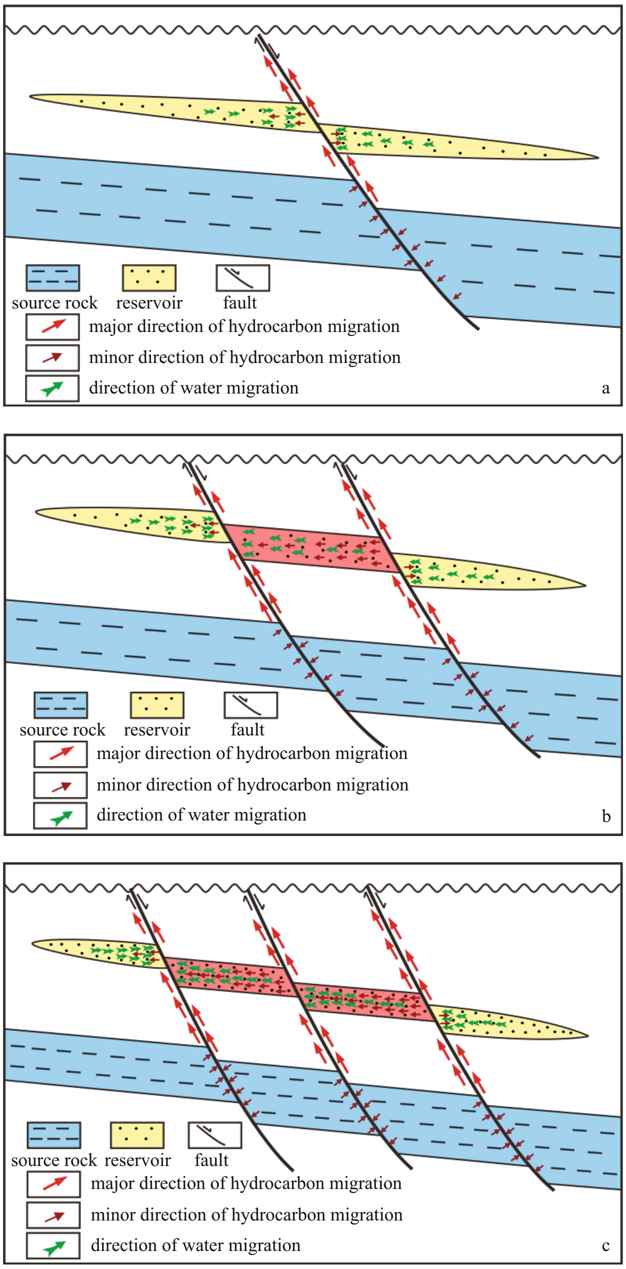

Fig.2. Flow patterns of fluid in a flash with overpressure and faults. a. Single fault, b. double faults and c. multi faults.

4 Reservoir-forming controlled by fault terrace

In the Qiongdongnan Basin, the results of drilling show that there is little oil or gas in the traps controlled by single fault, but where reservoirs have been confirmed, two or more faults exist, which represents a distinct feature of the reservoir-forming controlled by fault terrace. Here, the exploration results associated with BD19-2, YC13-1, LS13-2, YC21-1, ST32-2 will be analyzed to evaluate the theory of reservoir-forming controlled by fault terrace.

4.1 *Reservoir-forming controlled by fault terrace about Gas Reservoir BD19-2*

The structure BD19-2 is located in the northern steep slope zone of Baodao-Changchang Depression, at the end of the northeast area of Songtao Uplift (Fig. 1). It is a faulted anticline structure, consisting of numerous reverse faults and compression anticlines which have experienced multi-period activities of faults. Meishan Formation and 3rd member of Lingshui Formation are the main gas bearing formations; the gas originates from the highly mature coal-bearing source rocks of Yacheng Formation in Baodao Depression.

As can be seen from the gas reservoir section of BD19-2, the fan-deltas around the structure of BD19-2 are well developed, extending southward to the downthrown side of fault. At the same time, the sand body is cut through by Fault 2, Fault 2-1 and other small faults, forming a step-fault zone. In this setting, natural gas from Yacheng Formation migrates laterally along unconformity or sand stone, followed by vertical migration through Fault 2-1. Eventually, the natural gas turns into the top position of sandstone between the multi-faulta to form a

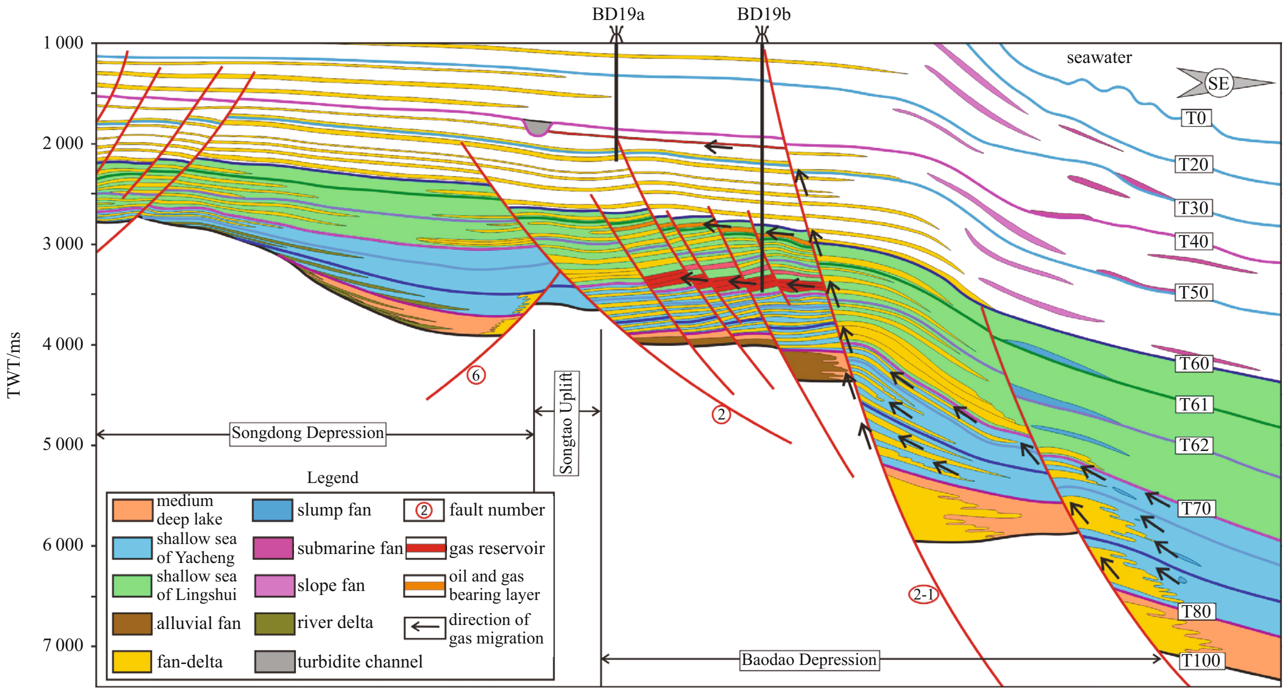

Fig.3. Section of Gas Reservoir BD19-2.

gas pool (Fig. 3). Thus, Reservoir BD19-2 is a typical example of reservoir-forming controlled by fault terrace.

4.2 *Reservoir-forming controlled by fault terrace about Gas Reservoir YC13-1*

The structure YC13-1, a half-anticline characterized by long-term inherited development on the pre-Paleogene basement, is located in north of Yanan Depression, west of Qiongdongnan Basin (Fig. 1). It is adjacent to Yinggehai Basin, divided by Fault 1. At present, five wells have been drilled, including YC13a, b, c, d, e. According to the analysis of drilling data, 3rd of Lingshui Formation is a gas congregation area which has many gas-bearing strata. The deep layers in Yanan Depression develop Yacheng coal measure source rock, with a high mature, which are the main horizons of gas generation. Faults make a connection between source rocks of Yacheng and reservoirs of Lingshui, becoming the main pathway of oil or gas migrating in the vertical direction.

As can be seen from the gas reservoir section of YC13-1, the faults of oil source cutting in source rock connect Gas Reservoir YC13-1 and Yanan Depression with a NWW trend. Driven by the overpressure, natural gas of Yacheng Formation migrates vertically through faults to overlying fan-delta sandstone in 3rd of Lingshui Formation. Then with a lateral migration of reservoir, gas turns into the top position named the structure of YC13-1 between multi faults to form gas pool. The relationship between YC13-1 gas field and distribution of faults is a typical model of reservoir-forming controlled by fault terrace (Fig. 4).

4.3 *Reservoir-forming controlled by fault terrace about condensate Gas Reservoir LS13-2*

Condensate Gas Reservoir LS13-2 is located on Lingshui Low Uplift, in the north steep slope zone of Lingshui Depression. The drilling data shows that Meishan Formation is the main layer forming gas. Natural gas is oil-type gas, which comes from source rock of Eocene.

As we can see from the seismic profiles crossing Well LS13a, there are many faults developing around condensate gas reservoir LS13-2. With the overpressure, gas migrates vertically along faults to sand body of Meishan between multi faults to form gas filling and pouring. It presents an obvious characteristic of reservoir-forming controlled by fault terrace (Fig. 5).

4.4 *Reservoir-forming controlled by fault terrace: Gas Reservoir YC21-1*

The structure YC21-1 is located in south gentle slope zone of Yanan Depression, in the western Qiongdongnan Basin. In terms of the location within the system, YC21-1 lies on the Yanan Low Uplift; it is close to Ledong Depression, separated by Fault 2. At the same time, it is an anticline-lithology trap controlled by the faults near the gentle slope zone of Yanan Depression. So far, four wells have been drilled, i.e., YC21a, b, c, and d, which reveal the presence of many gas-bearing strata. Among these wells, YC21c and YC21d have been drilled in gas dissolved in water with high pressure, in both Yacheng Formation and 3rd member of Lingshui Formation, but no commercial gas reservoirs were found. The source rocks of Yacheng Formation are the main source rocks of the area. The fan-delta and shore sandstone of Lingshui and Yacheng Formations, which have a direct contact with source rocks, are well developed to become good reservoirs. In addition, a lot of small faults are developed in the gentle slope zone between YC21-1 and Yanan Depression.

According to the gas reservoir section of YC21-1, between YC21-1 and Yanan Depression, a large number of small faults are developed to form a step-fault zone, and make the transition to the deep of depression across a gentle slope. Hydrocar-

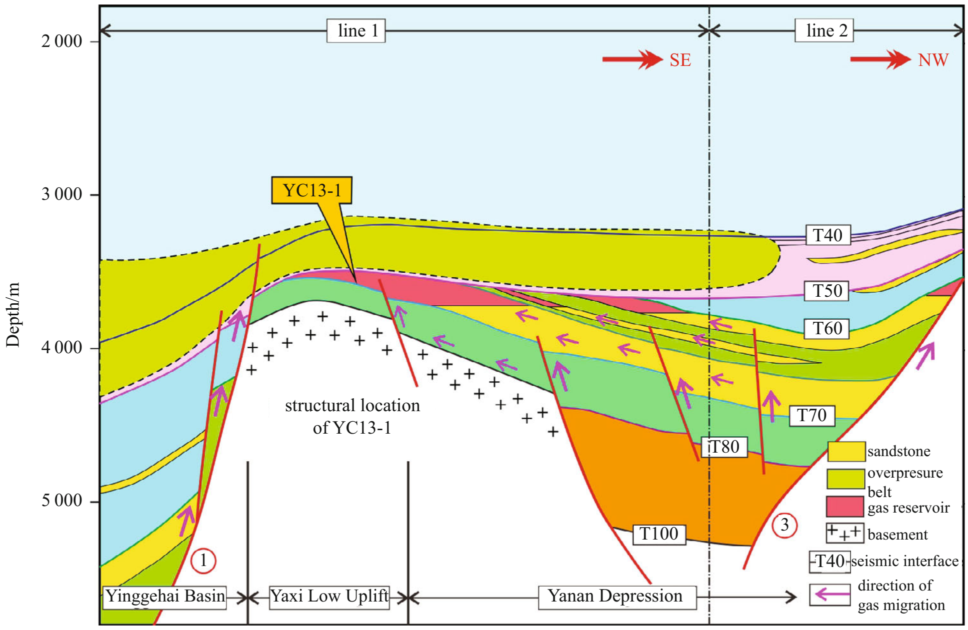

Fig.4. Section of Gas Reservoir YC13-1.

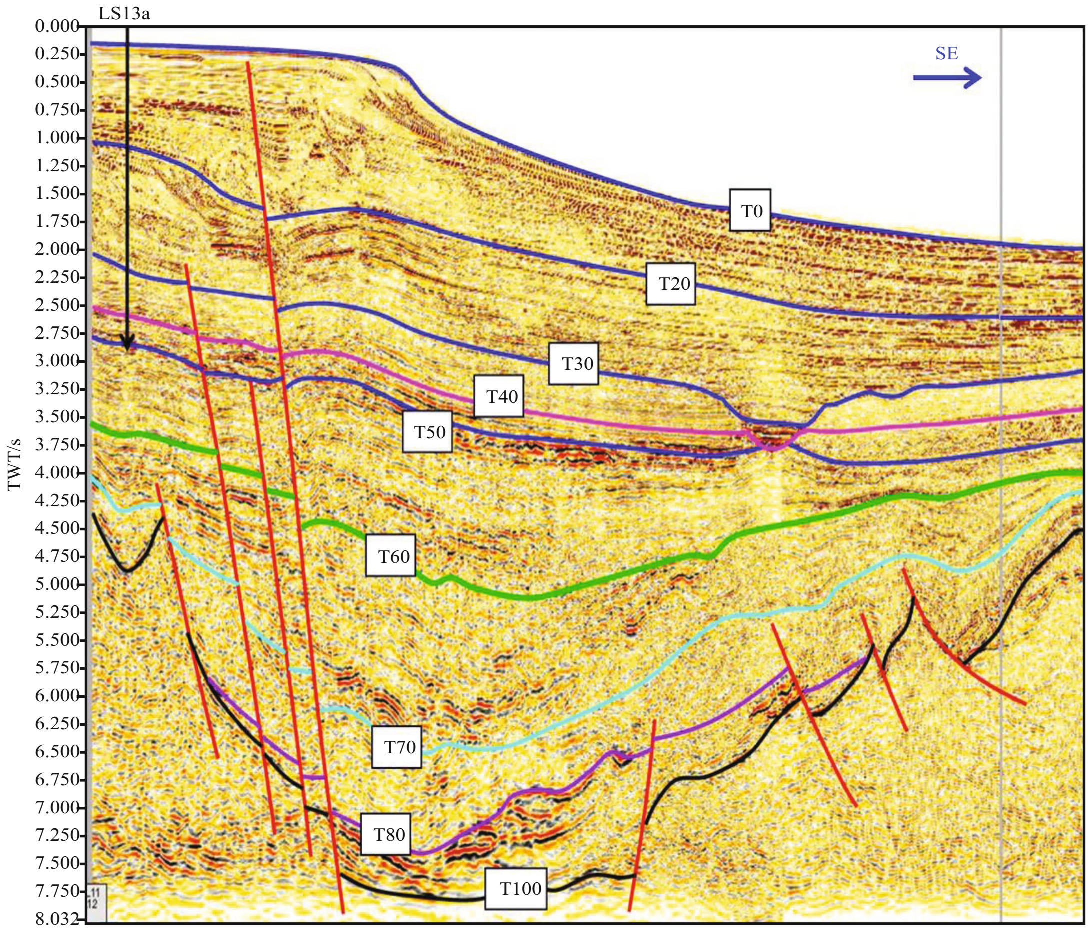

Fig.5. Seismic section crossing Well LS13a.

bon from Yanan Depression migrates to the tectonic position along the step-fault zone and has accumulated in the top position of the sandstone between the multi-faults. Gas Reservoir YC21-1 has a typical pattern of reservoir-forming controlled by fault terrace (Fig. 6).

4.5 *Reservoir-forming controlled by fault terrace: Oil Reservoir ST32-2*

The structure ST32-2, an anticline trap controlled by faults, is located in the south gentle slope zone of Songxi Depression, above the Songtao Uplift (Fig. 1). In Well ST32a, an oil reservoir was found in the target layer of 3rd member of Lingshui Formation. The main source rock belongs to the Eocene in age; coastal sandstone is present in 3rd member of Lingshui Formation, favorable for the formation of the reservoir.

As can be seen from the oil reservoir section of ST32-2, many faults are developed on the Songtao Uplift, and provide a connection between the source rocks in Songxi Depression and ST32-2 traps. With the overpressure, oil migrates vertically along the faults to the sand body between the multi-faults to form gas filling and pouring. In Fig. 7, the green part is the proven Oil Reservoir ST32-2, with an apparent characteristic of reservoir-forming controlled by fault terrace.

5 The analysis of effect for traps of non-fault terrace

The non-fault terrace traps CC26-1, YL19-1, YL2-1and LS33-1 are examples to support the theory of reservoir-forming controlled by fault terrace from the reverse side.

5.1 *The drilling results of non-fault terrace Trap CC26-1*

Structure CC26-1 is located in the mid-north part of Changchang Depression, and distributes in the nose-shaped structure zone formed by the Shenhu Uplift in the north, extending southward to Changchang Depression (Fig. 1). It is close to the active belt of faults in the northeast. Some deep faults have cut through above T60. So far, Well CC26a has been drilled. The data of drilling show that the turbidity channel fine sandstone is developed in 2rd member of Lingshui Formation. Source rock of Yacheng is drilled, and gas layers containing water are found, indicating that a small amount of hydrocarbon has been migrated over here, without accumulation.

The structure of CC26-1 has favorable traps, sufficient reservoirs, effective cap rock and better oil and gas resources, but no oil or gas was found. Elsewhere, the researchers proposed two reasons for this. One is an inadequate supply of hydrocarbon (a large amount of hydrocarbon in the deep depression cannot migrate laterally to the structure); the other reason is limited scale reservoir.

However, it appears that Structure CC26-1 is associated with mature source rocks in the deep depression, adequate supply of hydrocarbon and favorable reservoirs. Although the thickness of reservoir is relatively thin, it meets the requirements of migration laterally. The reason for the absence of hydrocarbon accumulation lies in the patterns of migration through faults. There is no sufficient space in the fault-cut sandstone because of the lack of spillway faults. Thus, hydrocarbon can only migrate vertically along the faults without filling the sandstone (Fig. 8). This observation in favour of the theory of reservoir-forming controlled by fault terrace from the reverse side.

5.2 *The drilling results of non-fault terrace Trap YL19-1*

Trap YL19-1 is located in the gentle slope zone of Beijiao Depression (Fig. 1), which was drilled recently. The source rocks drilled include mudstone of littoral shallow marine facies and coal seam of coastal plain facies of Yacheng Formation. At the same time, tidal channel sandstone and fan-delta sandstone are developed in Yacheng Formation. There are two thin limestone oil reservoirs in 2rd member of Sanya Formation, with

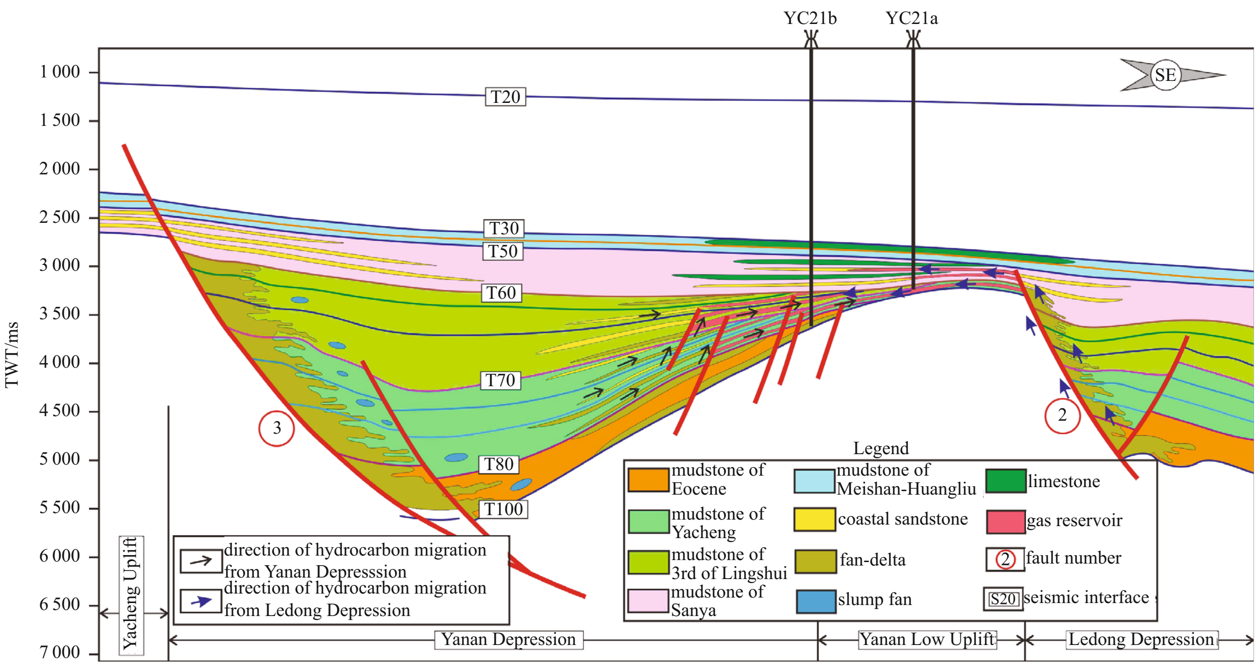

Fig.6. Section of Gas Reservoir YC21-1.

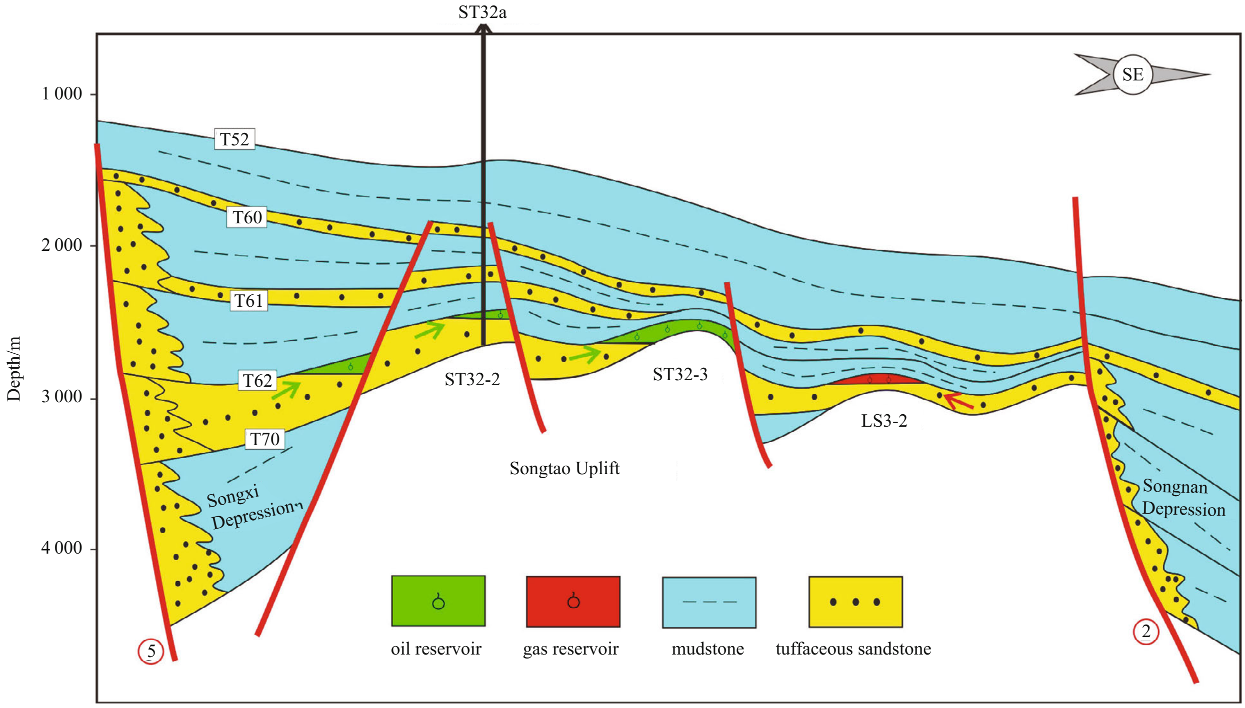

Fig.7. Section of Oil Reservoir ST32-2.

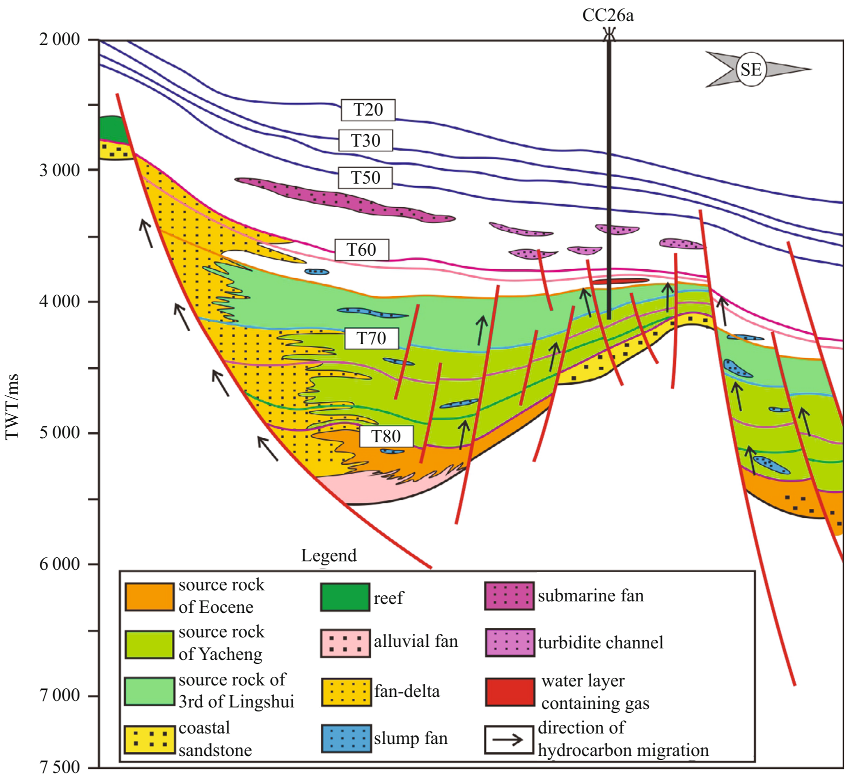

Fig.8. Section of non-fault terrace Trap CC26-1.

high water saturation. No large-scale oil and gas accumulation has been identified so far.

Elsewhere, the researchers believed that there are two reasons that Structure YL19-1 fails to form large-scale gas accumulation. One is that the amount of gas generated by source rocks of Yacheng Formation in the gentle slope zone of Beijiao Depression is so limited that it does not meet the requirement of large-scale migration. The other reason is the poor condition for lateral migration inside the depression and gas has to migrate along the faults vertically.

We found that the limestone strata in this well is associated with only a single fault, without any spillway faults for the filling of oil and gas (Fig. 9). This is a main reason for the lack of oil and gas accumulation atYL19-1. The thin coal seam developed in Yacheng Formation is proved to be a favorable source rock. Moreover, although the thickness of the reservoir at each level is thin, its quality is good with an average porosity of 22%. So, these two factors are not the key to account for the absence of hydrocarbon accumulation.

5.3 *The drilling results of non-fault terrace Trap YL2-1*

Trap YL2-1 is located in the Baodao section of the central canyon, near the border between Songnan Low Uplift and Baodao Depression. The drilling of Well YL2a reveals multi-sets of sandstone in Huangliu, Sanya and Lingshui Formations, but there are no any logging anomalies in the whole length, but the well is dry. Since the trap was formed, YL2-1 has experienced the second peak stage of gas generation of Baodao Depression, with a high-quality reservoir containing a porosity of more than 15%, large differences in source-reservoir pressure, and intense reservoir-forming force. In addition, the developemt of faults between structure and depression stopped at an earlier stage. Consequently, YL2-1 has favorable source rock, reservoir and migration force.

There are three reasons for the failure of trap YL19-1. First, the trap fails to seal hydrocarbon from the side. Second, the system of migration is not suitable for the formation of hydrocarbon accumulation, because the structure is not situated in the dominant migration pathways of oil and gas. Third, the distance of migration is so far that a great amount of hydrocarbon was gradually lost. In this case, the hydrocarbon arrives at the reservoir, but there is only a small quantity. It cannot form a large-scale hydrocarbon accumulation.

We propose here that the major factor for the failure of YL2-1 is that the faults are not well developed in the target zone, which causes the lack of injection faults. Thus, the hydrocarbon generated by the source rocks in the deep of Songnan Depression and Baodao Depression cannot migrate towards the sand body in the trap (Fig. 10).

5.4 *The drilling results of non-fault terrace Trap LS33-1*

Trap LS33-1 is located on the northern Lingnan Low Uplift (Fig. 1), near the south slope zone of Lingshui Depression. LS33a within the trap is the first exploratory well in which rela-

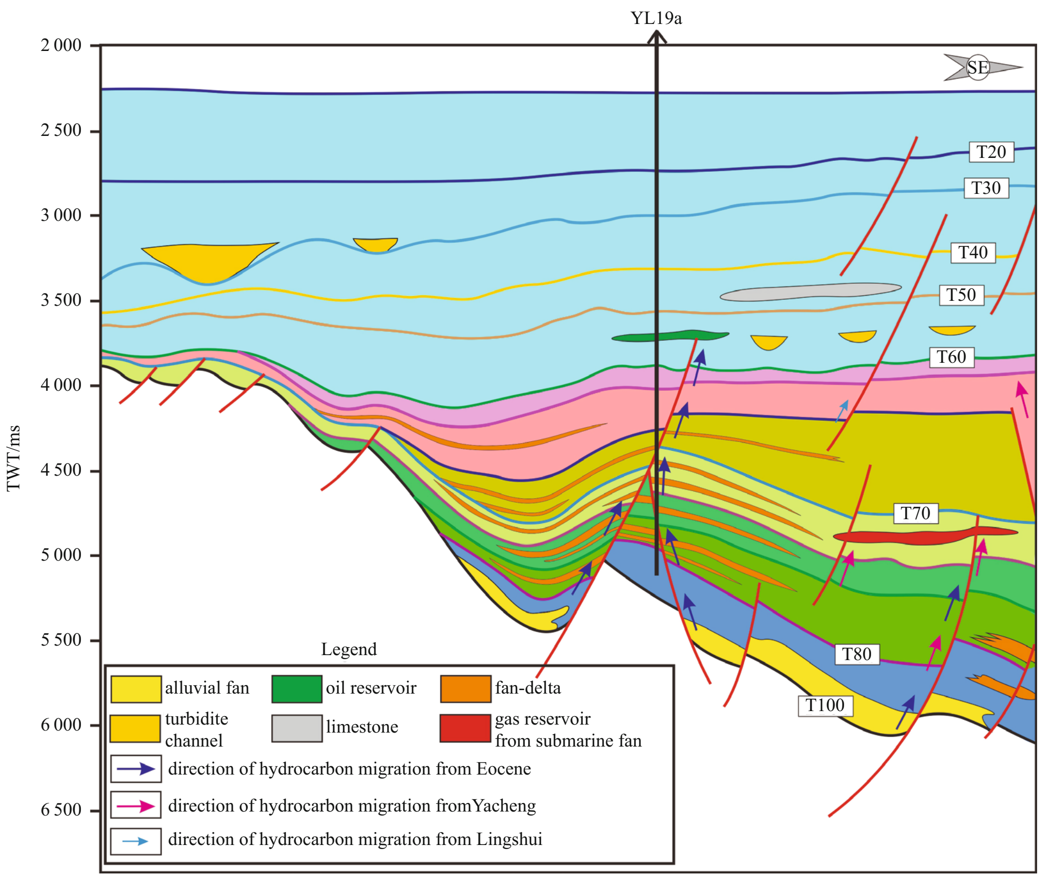

Fig.9. Section of non-fault terrace Trap YL19-1.

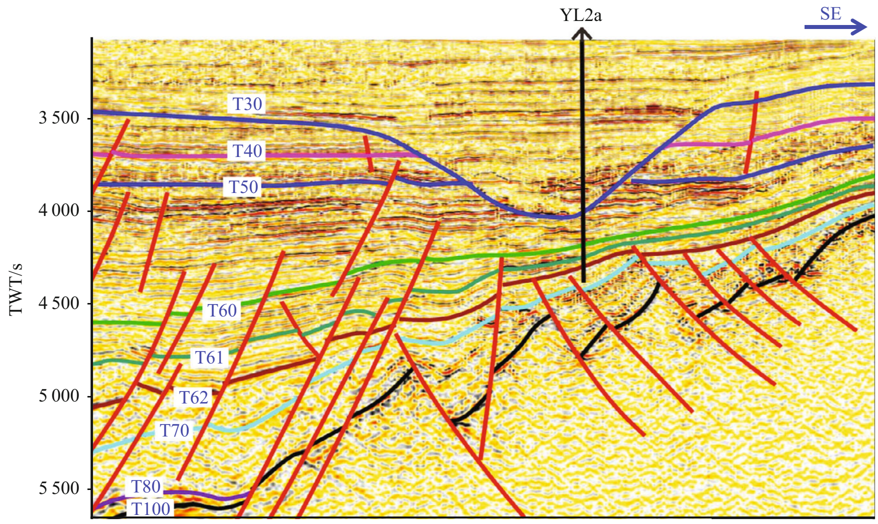

Fig.10. Seismic section crossing Well YL2a.

tively large number of horizons in deepwater areas of the Qiongdongnan Basin were found. The results of drilling show that mud content in the main target zones is high, and there are no logging anomalies in the whole length. The formations in 2rd member of Yacheng Formation and 3rd member of Yacheng Formation are dry layers or water layers.

The main reason for the absence of oil and gas at Trap LS33-1 has been considered to be that the littoral facies sandstone and fan-delta sandstone in Sanya and Lingshui Formations were not developed on Lingnan Low Uplift. Instead, mud content in these formations is high.

Finally, based on the analysis of Well YL19a, although the reservoir quality is poor, the fine sandstone drilled in Yacheng Formation can form a good reservoir-seal assemblage with the thick layer of mudstone covering above it. The reason for the absence is that trap LS33-1 is away from the filling faults so that hydrocarbon from the depression zone cannot migrate to the low uplift area, which makes it difficult for hydrocarbon to accumulate (Fig. 11). This example also supports the theory of reservoir-forming controlled by fault terrace from the opposite side.

6 Prediction of favorable structural zones

According to the difference between hydrocarbon migration through faults and injection and the theory of reservoir-forming controlled by fault terrace, in combination with basic requirements of hydrocarbon accumulation, here we propose four most favorable step-fault zones, i.e., the south steep slope zone of Baodao-Changchang Depression (Fig. 12 Ⅰ), the north steep slope zone of Baodao Depression (Fig. 12 Ⅱ), the north steep

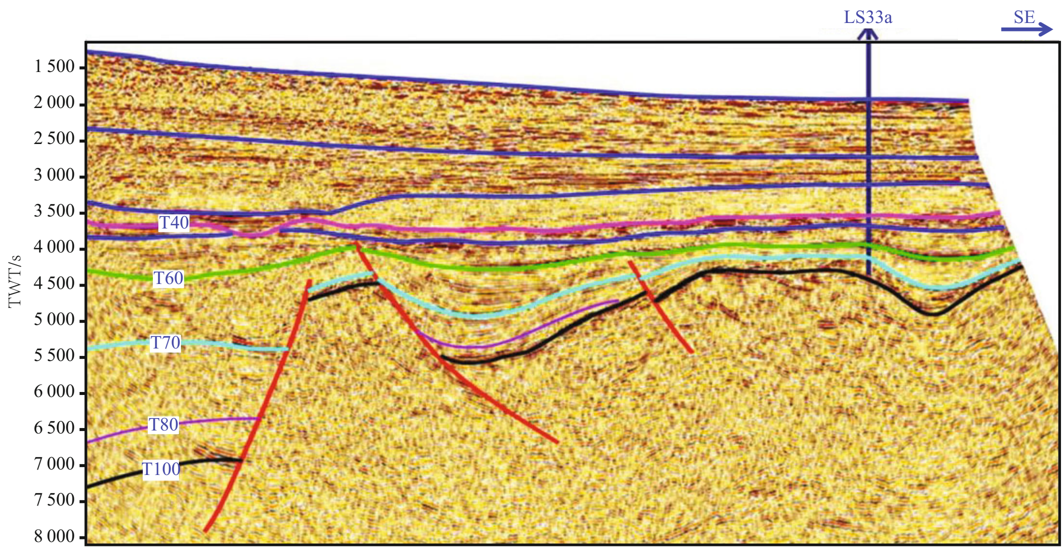

Fig.11. Seismic section crossing well LS33a.

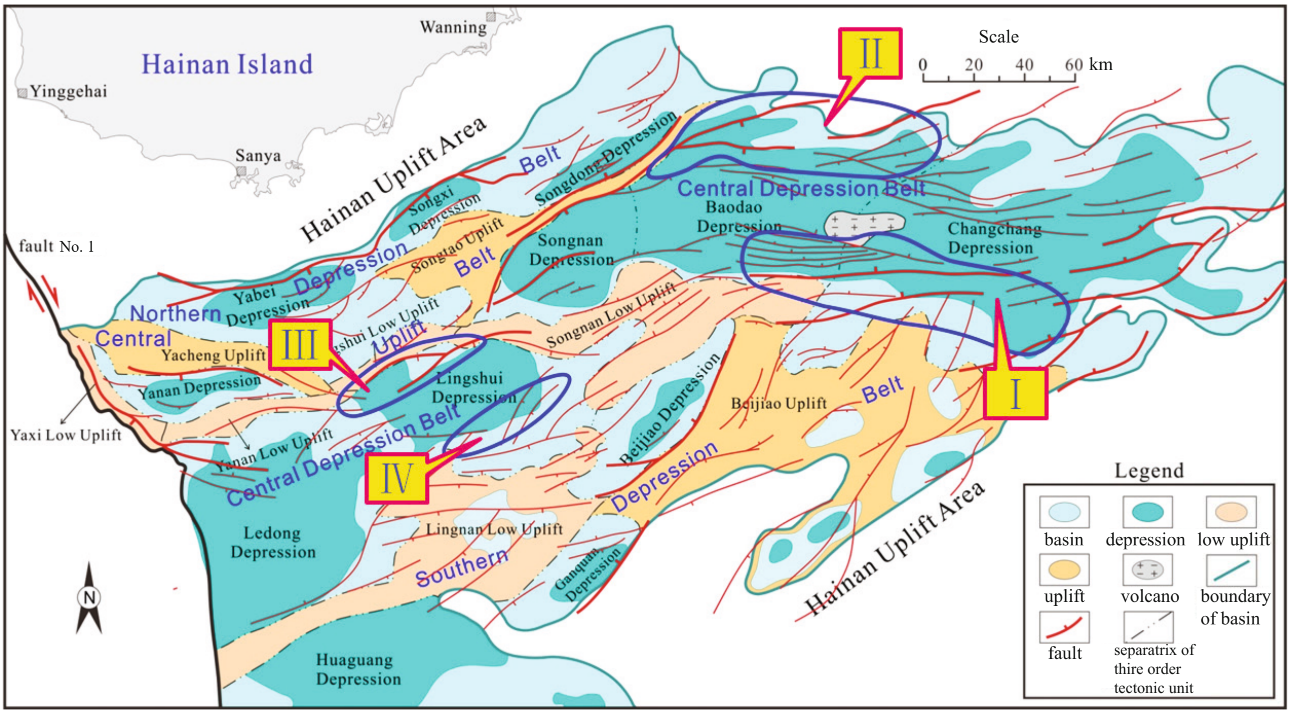

Fig.12. Favorable zones of Qiongdongnan Basin.

slope zone of Lingshui Depression (Fig. 12Ⅲ), and the south gentle slope zone of Lingshui Depression (Fig. 12Ⅳ).

A series of faults are developed in the south steep slope zone of Baodao-Changchang Depression. The pattern of the main faults is characterised by shovel fault-fan, together with a transition to the deep depression in the form of a steep slope. Hydrocarbon from the depression zone migrates to the top of the structure along the step-fault zones. Thus, the fault terrace in the south steep slope zone of Baodao-Changchang Depression is conducive to accumulation.

The north steep slope zone of Baodao Depression is bordered by Fault 2 and Fault 2-1, forming en-echelon faults in the plane. Moreover, in response to the action of regional strike slip, flow structure is developed. In the places where multi-fault exists, a combined condition of source rocks, reservoir and seal around this area would favour the formation of oil or gas reservoirs.

The north steep slope zone of Lingshui Depression is associated with NE-trending Fault 2 and Fault 2-1, with a pattern of ladder-type in the cross section. There are three characteristics of the faults here, i.e., high fault quantity, large activity intensity, and sufficiently long activity time (especially the actitivites at later stages at Fault 2-1). The types of the fault terrace and later-stage activities of faults are beneficial to the formation of hydrocarbon filling.

NE-trending antithetic faults are well developed in the south gentle slope zone of Lingshui Depression, together with the patterns of the horst-garben assemblage and reverse fault terrace in the cross section, which favour hydrocarbon accumulation. Subsequent activities of the faults create an even better condition for the formation.

7 Conclusions

(1) In the present contribution the principle of reservoir-forming controlled by fault terrace is proposed. In a single fault system, hydrocarbon filling into the sand body cut through by the fault may not occur, because: (i) pore water cannot be compressed; (ii) buoyancy is insufficient to break through the resistance of pore; and (iii) the direction of buoyancy is upward. However, if there are two faults or more, the faults at a high position of sandstone would act as the spillway for hydrocarbon to fill into the sand body through the faults at low positions.

(2) The examples from the Qiongdongnan Basin indicate that the patterns of reservoir-forming controlled by fault terrace are consistent with the proposed hypothesis. Multi-fault systems are associated with the reservoir presence, e.g., at BD19-2, YC13-1, LS13-2, YC21-1 and ST32-2, whilst single fault systems associated with absence of reservoirs, e.g., at CC26-1, YL19-1, YL2-1 and LS33-1.

(3) Based on the observations outlined above, the south steep slope zone of Baodao-Changchang Depression, the south gentle slope zone of Lingshui Depression, the north steep slope zone of Lingshui Depression, and the north steep slope zone of Baodao Depression represent the most favorable step-fault zones, which have a potential for future explorations.

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