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Relationship between Tanlu Fault and Hydrocarbon Accumulation in Liaozhong Sag, Bohai Bay, Eastern China

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ABSTRACT: Tanlu fault (Liaozhong segment) goes straight through Liaodong Bay along NNE direction and it is divided into three segments, i.e., the northern segment, the middle segment and the southern segment, according to the differences in structural features. There are obvious changes in deposit thickness, sag structure, tectonic nature and other aspects of the layers. Tanlu fault is a special controlling factor concerning the reservoir formation in Liaozhong sag. First, its activities affect paleogeomorphology and paleogeographic framework and control the distribution of the sedimentary facies and then they proceed to control the distribution of the source rock and reservoir sand bodies. Second, its activities affect the formation and deformation of the structure, control the formation of abundant traps and cause the destruction of some traps. Third, its activities also affect the juxtaposition relation among the fault, the sand bodies and unconformity surfaces and control the function and efficacy of the three as the main hydrocarbon translocation system. In this paper the hydrocarbon reservoir formation process of JZ21-1, JX1-1 and LD27-2 oil and gas fields, the representatives of Tanlu strike slip fault zone are mainly analyzed. The modes of hydrocarbon reservoir formation can be generalized as follows—hydrocarbon source acts as "soil" and oil and gas as "nutrient"; hydrocarbon expulsion relies on "roots"; hydrocarbon migration relies on "trunks"; reservoir forms in "brunches" and the whole process follows the pattern that "hydrocarbon accumulates in strike slips and oil and gas reservoir forms like the growth of trees".
KEY WORDS: Tanlu fault, strike-slip fault, Liaozhong sag, formation of hydrocarbon.

1 INTRODUCTION

The controlling factors of hydrocarbon formation include "source control" (Jin, 2008; Hu, 2005), "facies control" (Liu et al., 2009) and "fault control" (Jonathan, 1997). Based on 18 basins (Songliao, Liaohe, Bohai Bay, etc.) and 40 typical oil and gas fields (Saertu, Fuyu, Gudao, etc.) all over China, Luo et al. (2007) made a research on the five reservoir formation factors, i.e., the faults' control over the sources, the migration, the traps, the accumulation and the distribution. Their statistics show that the control rates are all over 70%. They thus conclude that the exploration strategies of the fault control hydrocarbon theory are "picking the fruit (the hydrocarbon reservoir) along the branches (the faults)" and "following the vine (the faults) to get the melon(the hydrocarbon reservoir)" (Luo et al., 2007). Having researched on the reservoir migration and accumulation in the dustpan-like steep slope zone of the fault basin in eastern China, Zhang (1994) proposed the reservoir formation model that oil and gas "migrate in stepladder shape and accumulate in fish-bone shape" along the faults and the sand bodies. In foreign countries, along San Andreas fault, there exist a series of Cenozoic sedimentary basins which are rich in hydrocarbon. They are closely related to strike slip fault distribution. Among them are the following relatively large-scale ones that are running from south to north: Los Angeles Basin, Santa Barbara O Ventura Basin and Santa Maria Basin. These basins are found to be rich in hydrocarbon reservoir both on land and offshore. Los Angeles Basin is especially so (Zoback et al., 1987). In the research area, numerous oil and gas fields and several favorable exploration targets already found in Liaozhong sag and its adjacent areas are basically distributed on both sides of Tanlu fault (Liaozhong segment), which soundly explains the fact that strike slip faults have a special controlling effect on hydrocarbon formation. They are closely related and the research on their relationship has important theoretical significance and practical values.

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2 THE CHARACTERISTICS OF TANLU FAULT (LIAOZHONG SEGMENT)

2.1 The Segmentation Characteristics

Tancheng-Lujiang fault zone is a giant, ancient but now active

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fault zone in the east of China. In Liaodong Bay, the two extension faults on the eastern and western sides of Tanlu fault have created two fault uplifts respectively, forming the general pattern of "three sags and two salients", i.e., Liaoxi sag, Liaoxi salient, Liaozhong sag, Liaodong salient and Liaodong sag (Fig. 1). Tanlu fault (Liaozhong segment) has two main branches stretching along NNE direction, the west strike slip fault and the east strike slip fault. The former one is located in the central part of Liaozhong sag with mainly horizontal dislocations. The latter one is a boundary fault among Liaozhong sag, Liaodong sag and Liaodong salient. There are both horizontal and vertical dislocations.

The analysis of the tectonic profile structure in Liaodong Bay shows that Tanlu fault has obviously different deformation features by area and by segment. The influences upon the deformation features of the stratums of different times in vertical direction are also different. Tanlu fault can be roughly divided into the southern, the central and the northern segments with LZ160 and LZ215 survey lines as demarcation lines (Fig. 2).

In Liaodong Bay area, the main source rock formations include the 3rd member of Dongying Formation (E_3d^3), The 1st and 3rd members of Shahejie Formation (E_2s^1, E_2s^3), while the main reservoir formations include the Guantao Formation (N*g*), Minghuazheng Formation (N*m*), 1st member of Dongying Formation (E_3d^1), the upper 2nd member of Dongying Formation (E_3d^{2L}), the 2nd and 3rd members of Shahejie Formation (E_2s^2, E_2s^3).

In the southern segment of Tanlu fault (Liaozhong segment), Liaodong salient doesn't develop. Liaozhong sag and Liaodong sag are directly connected with Liaozhong No. 1 fault as the boundary fault. From the profile, it manifests typical negative flower structure character. The Shahejie Formation in Liaozhong sag and Liaodong sag has relatively thin deposits and mainly develops pop-up structure related to negative flower structure. In western areas, the Cenozoic group is shallowly buried. Paleogene is absent in Liaoxi salient (Xu et al., 2011).

Compared with the southern segment, the Cenozoic group in the central segment of Tanlu fault (Liaozhong segment) is buried deeper and the Shahejie Formation is thicker both at the site of sag and the salient. Liaozhong No. 1 fault changes its direction from SEE to NWW, experiencing fierce twist-compression during the late stage. The middle segment can be further divided into central south sub-segment and

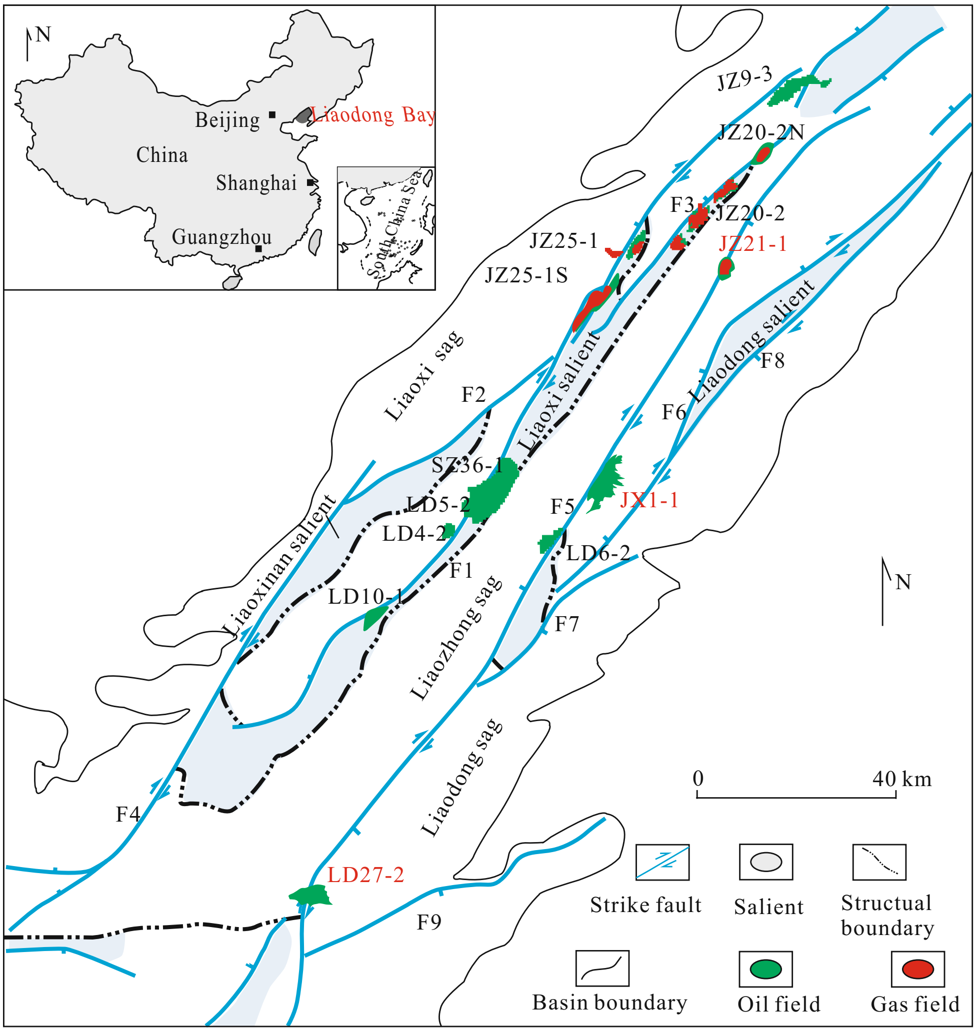

Figure 1. Divisions of geotectonic unit in Liaodong Bay area. F1. Liaoxi No. 1 fault; F2. Liaoxi No. 2 fault; F3. Liaoxi No. 3 fault; F4. Qingnan No. 1 fault; F5. Liaozhong No. 1 fault; F6. Liaozhong No. 2 fault; F7. Liaodong No. 1 fault; F8. Liaodong No. 2 fault; F9. Bodong No. 1 fault.

central north sub-segment. There are three salients in the central south sub-segment, i.e., Liaodong salient, Liaoxi salient and Liaoxinan salient, displaying the tectonic character of "four sags and three salients alternate". There is only one Liaoxi salient in the central north sub-segment. Liaoxinan salient pinches out in transverse while Liaodong salient is split by Liaodong No. 2 fault (Xu et al., 2011).

In the northern segment, Tanlu fault (Liaozhong segment) includes three faults, i.e., Liaozhong No. 1 fault, Liaozhong No. 2 fault and Liaodong No. 2 fault, displaying the tectonic character of "three sags and two salients alternate". Compared with the central segment, the Cenozoic group is buried deeper and Shahejie Formation deposits in Liaoxi salient. The direction of Liaozhong No. 1 fault changes from up-right to east inclining, with strike slipping decreasing. However, there is intense strike slipping in Liaozhong No. 2 and Liaodong No. 2 faults and they replace Liaozhong No. 1 Fault to be the main strike slip faults. Late-stage faults mainly develop around Liaodong salient (Xu et al., 2011).

2.2 The Relationship between the Segmentation and the Hydrocarbon Distribution

The Tanlu fault demonstrates obvious differences which are separated by sections LZ160 and LZ215 (from north to south) and by its eastern and western branches (from east to west). Meanwhile, the hydrocarbon accumulates much more in the north of the Liaodong Bay than in the south. Most of the oil and gas accumulations are fund in the Eogene and are near the eastern branch of the Tanlu fault. From the north to south, the hydrocarbon gradually occurs in younger strata (Wang et al., 2011). There is a tight relationship between the segmentation of the Tanlu fault and the hydrocarbon distribution in this area.

There exit three sets of source rocks in Liaodong Bay, among which the 3rd member of Shahejie Formation has the best hydrocarbon generation potential, followed by the 1st member of Shahejie Formation and then the 3rd member of Dongying Formation (Jiang et al., 2010a). From south to north, the Cenozoic is buried deeper and deeper and the Shahejie Formation becomes thicker and thicker controlled by the Tanlu fault (Liaozhong segment). The hydrocarbon accumulations in the north part of the Liaodong Bay are mainly sourced from the thick mudstones in the Shahejie Formation which stably distributed in this area with a relatively higher quality and maturity. In contrast, the hydrocarbon accumulations in the south are mainly sourced from the 3rd member of Dongying Formation which has relatively a lower maturity and poorer quality (Li et al., 2012; Liang et al., 2012; Tian et al., 2011; Pang et al., 2009).

Since the Eogene, the fault activities in Liaodong Bay have become weaker, which is beneficial for the preservation

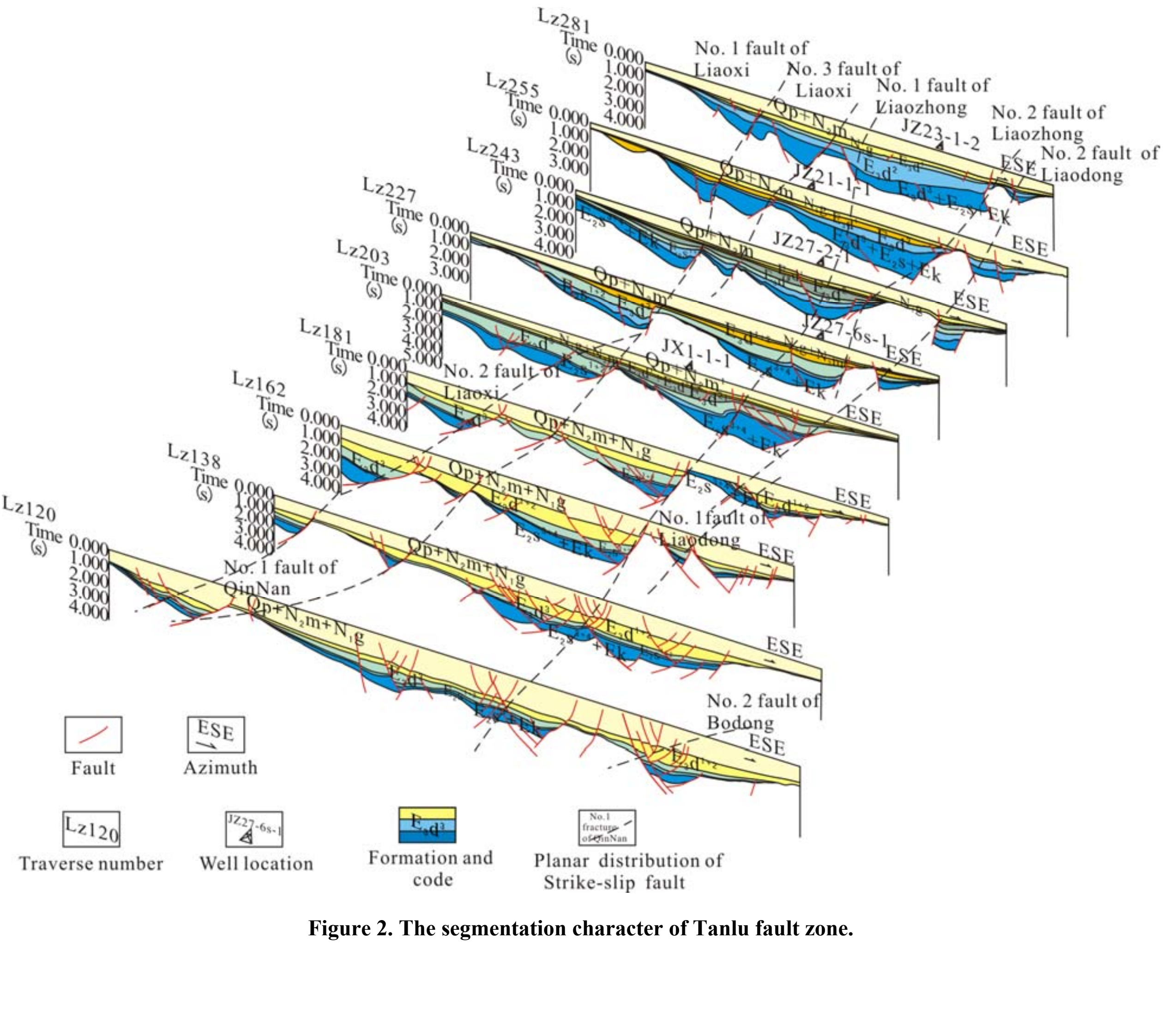

Figure 2. The segmentation character of Tanlu fault zone.

of the oil and gas in general (Zong et al., 2009). Meanwhile, the activity of the eastern branch of the Tanlu fault zone is stronger than that of the western branch, resulting in a more favorable preservation conditions for the traps along the western branch of the Tanlu fault zone. Most of the oil and gas fields discovered in Liaodong Bay are near the western branch of the Tanlu fault zone. Despite the generally higher activity of the eastern branch, there still exits possibilities of the oil and gas accumulation near its sections with a lower activity such as JX1-1 oil field (Xu et al., 2011).

The developing intensity of the derived faults in Liaodong Bay becomes weaker from the south to the north. These derived faults together with the main faults, construct a large quantity of negative flower structures in the southern part of the Liaodong Bay. The hydrocarbon migrates upward along the main faults which have inheritably developed since the Eogene, and finally charges into the Neocene traps which are connected to the main faults through the derived faults. As a result, some Neocene petroleum accumulations have been founded in the southern part of the Liaodong Bay, such as LD27-2 oil field.

This special character determines the differentiation among the oil and gas transportation and reservation in the southern, central and northern segments of Liaodong Bay, and further determines the series of strata where oil and gas accumulate and the probability of reservoir formation in the three segments.

3 THE CONTROLLING EFFECTS OF TANLU FAULT ON RESERVOIR FORMATION

3.1 Tanlu Fault's Control over the Sedimentary System

Strike slip activities of the faults lead to the horizontal displacement of the sedimentary system and further the sedimentary lateral migration, causing the asymmetry of the basin's sedimentary filling (Su et al., 2011; Bryce and Robert, 2002; Jackson et al., 2002; Cartwright et al., 1995). Along the base sliding direction of the sedimentary lateral migration, the migration of alluvial fan facies takes place. In pure strike slip deformation, the progradation of the alluvial fans is not obvious, manifesting horizontal equivalent radius migration (Matmon et al., 2005). In case of oblique slip, the alluvial fans or the fan deltas migrate and superimpose in the oblique posture (Xu, 1994).

It can be seen from the dispositional environment map of central E_3d^3, strike slip fault zone of Liaodong Bay (Fig. 3) that sedimentary facies that develop include delta plain, delta front, shore-shallow lake and shallow-/semi-deep lake. The eastern branch of Tanlu fault goes through this area and its southeast plate delta front subfacies in the eastern strike slip fault migrate horizontally towards southwest while the northwest plate towards northeast because of the dextral strike slipping, causing the mutation and in coordination of the two plates in the fault on one same plane. In the northern part, the delta front subfacies exist alone. The delta plain subfacies which belong to the same sedimentary system as the delta front have already migrated southward. Therefore, according to normal sedimentary order, the delta plain subfacies cannot be found in the northern part of the southeast plate. This sedimentary structure has not been fully recognized in early hydrocarbon reservoir exploration of Bohai Bay, which once drove the exploration into trouble.

During the sedimentary period of E_2s^3 and E_3d^3, the basin is in the rapid fault deposit stage, with lacustrine deposits in the main. Small-scale fan deltas develop near the shore. Lacustrine mud shale deposits are the main hydrocarbon source rocks in the research area. The overall thickness of E_2s^1 and E_2s^2 of the whole area is around 100 m, with lacustrine deposits in the main and followed by fan delta. During the sedimentary period of E_3d^1 and E_3d^2, the activities of fault deposit decrease and the meandering river delta sedimentation reaches the maximum range. However, the most large-scale regional inversion activities in the late stage of Dongying cause E_3d^1 to be subjected to strong erosions and to survive only in the deep part of the sag. Tanlu fault controls the evolution of the basin. Three-stage chasmic activities and four-stage inversion activities make the hydrocarbon source rocks to undergo "three downs and four ups", accelerating or interrupting the thermal evolution of the hydrocarbon source rocks. Meanwhile, the strike slipping of Tanlu fault forces sedimentary sand bodies to undergo migration and transformation. This kind of multiple-stage structure activities brings up the complicated distribution of sand bodies and source rocks in Liaodong Bay and the complex thermal evolution process of hydrocarbon source beds.

3.2 Tanlu Fault's Control over the Translocation System

Early production experience shows that faults are disadvantageous to oil and gas accumulation (Mayuga, 1987). The exploration practice has proved that even the completely squeezing faults in western China are also qualified to transport oil and

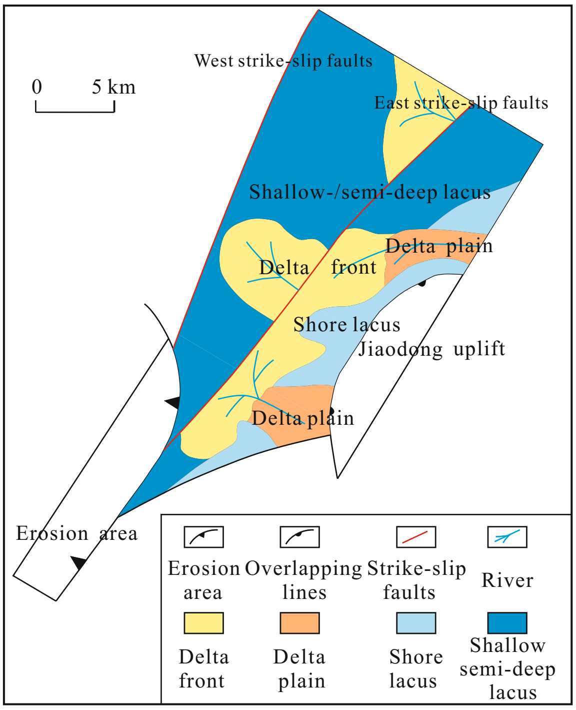

Figure 3. Dispositional environment map of the 3rd member of Dongying Formation (E_3d^3) in the central part of Liaodong Bay area (referring to Exploration and Development Research Institute of Tianjin Branch, CNOOC).

gas (Deng et al., 2010; Jiang et al., 2010b; Zeng, 2010; Zhang et al., 2007; Kennedy et al., 1997). There are many examples showing strike slip faults as the main translocation system in eastern China, among which are PL19-3 oil field in the southern part of the research area and Yandong oil and gas bearing structure of Liaohe oil field beside the strike slip. Both oil fields employ Tanlu fault as the main migration pathway. San Andreas strike slip fault in Los Angeles basin is the main migration pathway for fluid and gas in the mantle or the earth crust (Song, 2006).

Oil and gas translocation system usually consists of thefault, the unconformity surface and sand bodies. In rifted basins, the fault is the pivotal factor. During its active stage, the fault is usually the main oil and gas migration pathway (An, 2009; Song, 2006; Watkinson and Geraghty, 2006; Barton et al., 1995; Roure et al., 1994; Allan, 1989). The translocation system of Liaozhong sag can be divided into six types (Fig. 4). They are the fault translocation system, the unconformity translocation system, the sand body translocation system, the fault-sand body translocation system, the fault-unconformity translocation system and the fault-sand body-unconformity translocation system.

The regional sand body transport layer in E_2s^2, E_2s^3, E_3d, N*g* and N*m* of Liaozhong sag follows the pattern of pore type. Superimposed and continuous sand bodies control the macroscopic translocation efficiency and the reservoir property of sandstones controls the microcosmic translocation efficiency of oil and gas. During the Cenozoic era, Tanlu fault inherits the structural character of the Mesozoic era. Its late-stage activities develop numerous branch faults. The strike slips and the main faults are developed deep, early, far and scarce while the branch faults are developed shallow, late, near and dense. Continuous active faults link up multiple layers of source rocks and are main pathways of oil and gas migration. The steep dip and activity of the faults decide the efficiency of oil and gas translocation. Late-stage branch faults that developed widely partially link up the source and the sand bodies, enabling the oil and gas to translocate to the shallow layers and then accumulate to form reservoir. The unconformity of Liaozhong sag has mainly four stages, i.e., Kongdian early stage, E_2s^4 late stage, E_2s^3 late stage and Dongying late stage. The unconformity during the late stage of Dongying develops widely in the area of Liaodong Bay. For example, the eluvial zone under the unconformity surface of JZ21-1 hydrocarbon reservoir in the slope zone plays a decisive role in the lateral migration of oil and gas.

The translocation system is not of single type. It is usually a combination of two or more basic types or gives priority to one type with other types as subsidiary. In general, the translocation system in the research area gives priority to the fault-sand body translocation with the fault-unconformity translocation as subsidiary. In the migration and accumulation of oil and gas the faults play a decisive role. Starting from Miocene epoch, the inherited movements of Tanlu fault and the faults of the neotectonic period have formed the Neogene-epoch translocation network for hydrocarbon reservoir formation.

3.3 Tanlu Fault's Control over the Trap Formation

The extension and strike slipping of Tanlu fault have created a large number of various traps. Gong et al. (2007) divided them into the following three types: traps related to extensional fault activities; traps related to the congruent effect of both the extension and the strike slipping and traps formed under the reconstruction of the neotectonic movement (Gong et al., 2007). When studying the neotectonic movement's control over reservoir accumulation in the eastern Bohai Sea, Deng, (2001) divides the traps of Tanlu fault into the following 4 types: extensionally wrenchedly faulted anticlines, compressionally wrenchedly faulted anticlines, diapir anticlines and later reformed drape anticline traps (Deng, 2001). In the light of the geologic features of the typical structures in Liaozhong sag and its adjacent areas, following the two basic principles of being both scientific and practicable in the classification of hydrocarbon reservoirs, with the help of such data as structural property, structural shape and drilling results, the trap types in the research area are analyzed and identified in this paper (Zhang et al., 1999). At present, Liaozhong sag mainly develops fault block traps, faulted anticline traps, anticline traps, fault nose traps, semi-anticline traps, etc. and these traps are also the focal points of exploration. As far as this section is concerned, only the features of the former four traps are introduced and the semi-anticline traps will be discussed later.

3.3.1 Fault block traps

Since the traps in this area develop very well, such fault block traps are commonly seen. When the faults are active, they act as the migration pathway of oil and gas. Oil and gas generated from underlying hydrocarbon source rocks or primary reservoirs migrate to the overlying traps to accumulate through the faults, forming a series of fault block reservoirs distributing along the fault zone. This kind of traps is usually related to the following three groups of faults, namely strike slip faults, main faults and branch faults, and is composed of several fault blocks between the two or three above mentioned faults. Fault block traps enjoy the advantages of large quantity and good reservoir formation conditions. The drilling and exploration of this kind of traps in Liaozhong sag has been a great success. For example, the JZ23-1-1 and JZ23-1-2 wells in fault block traps in the steep slope zone east of the northern sub-sag of Liaozhong sag are successfully exploited.

Although the opening of faults contributes to the migration of oil and gas, it can also destroy the primary reservoirs, leading to the remigration and redistribution of oil and gas. The surface dip angle of Tanlu fault is large, almost erect, and its sealing characteristics are inferior during its active stages. It is still quite active during Neogene. The fault throw of Guantao Formation can reach up to 225 m, which can destroy primary reservoirs, causing lower hydrocarbon-filling degree or complete dissipation of the primary reservoirs and further leading to partial failure of the drilling. For example, the LD12-1-2 and LD12-1-1D wells in the middle segment of Liaozhong Sag fail to yield oil and gas after testing.

3.3.2 Anticline/faulted anticline traps

Anticline traps mainly develop in the uplift areas within the sag. The traps are usually complicated by the cutting of secondary faults and then form fault blocks or faulted anticlines. Faulted anticlines develop very well in the whole area of Liaodong Bay, attaching to the fault on one side. They are sealed by the faults and then form traps. Although there is a high successful drilling ratio in this kind of traps, the test results are not as satisfactory as expected. Some traps are empty or with low hydrocarbon-filling degree.

JZ17-2 structure is located at the upheavals in the northern sub-sag of Liaozhong sag, which is formed under the control of the major faults at the boundaries of Liaozhong. The anticline and faulted anticline traps in this structure are formed during the late sedimentary stage of Lower Minghuazhen Formation and their forms are fixed during Quaternary period. The JZ17-2-1 well is situated in this structure. There is no indication of oil and gas in the geological log and the log interpretation shows that there are all water layers in the well. After analysis, the cause of failure is the lack of fault channel that connects the traps and oil sources. The traps are not on the pathway of oil and gas migration and therefore are not filled with oil and gas.

LD21-3 structure is located on the downthrown side of the major faults in the eastern branch of LD22-27 overturned structure zone, representing a reserve drag faulted anticline with favorable reservoir forming conditions on the downthrown side of the strike slip major fault (Fig. 4). LD21-3 structure is covered by Minghuazhen Formation and Guantao Formation. That is to say, the upper layer of reflector T_2 is a negative flower shaped structure formed under the tension-shear effect of the shear fault. Minghuazhen Formation and Guantao Formation are split by many EW trending faults into the northern, the middle and the southern parts, forming multiple small-scale faulted anticlines whose EW part is longer than the SN part. The LD21-3-1 well is located at the flower heart of the negative flower shaped structure (the southern part) and in the high position of the reserve drag faulted anticline. All the drillings into multiple strata of traps in vertical direction are successful.

3.3.3 Fault nose traps

Fault nose traps are mainly developed in the slope zone and the overturned structure zone. JZ27-6 structure is situated on the east slope of Liaozhong sag and the downthrown side of Liaodong salient. The traps of E_2s^1, E_2s^2 and the lower segment of E_3d^2 in this structure have fine forms and form nose structure attached to Liaozhong No. 2 fault as a whole. The structure is split by a series of NE-SW trending echelon faults and is also divided into two local high points in the north and in the south bounded by the recess in the middle. The traps mainly develop from the lower segment of E_3d^2 to E_2s^2 and are all effective traps. LD16-3E structure is located in the overturned structure zone in the north-central part of southern Liaozhong sag. One fault block of Dongying Formation and 4 fault block of E_2s^1 are fault nose traps. The strike slipping adjusts the development of faults and split the structure into many blocks from north to south. LD16-3E structure is a long-term developed inherited structure in which oil and gas can migrate smoothly and accumulate easily.

4 ANALYSIS OF HYDROCARBON RESERVOIR FORMATION IN TYPICAL OIL AND GAS FIELDS

Several oil and gas fields (such as JX1-1 oil field, JZ21-1 oil and gas field, LD27-2 oil field, etc., see Fig. 1) and many favorable exploration targets already found in Liaozhong sag and its adjacent areas are basically distributed on both sides of Tanlu strike slip fault (Liaozhong segment). LD27-2 is located in the southern segment where tectonic inversion and activities are intense and has undergone three phases of tectonic inversion. JX1-1 is located in the tectonic transformation zone and has undergone two phases of tectonic inversion, which causes part of the hydrocarbon reservoir to be destroyed. The tectonic activities of JZ21-1 are relatively less intense and the preservation conditions of oil and gas are better (Gong et al., 2007; Wang, 1998). Through analyzing the following representative oil and gas fields, JX1-1, JZ21-1, and LD27-2, it is intended to establish the mode of oil and gas reservoir formation and reveal the reservoir formation pattern of Tanlu strike slip fault zone.

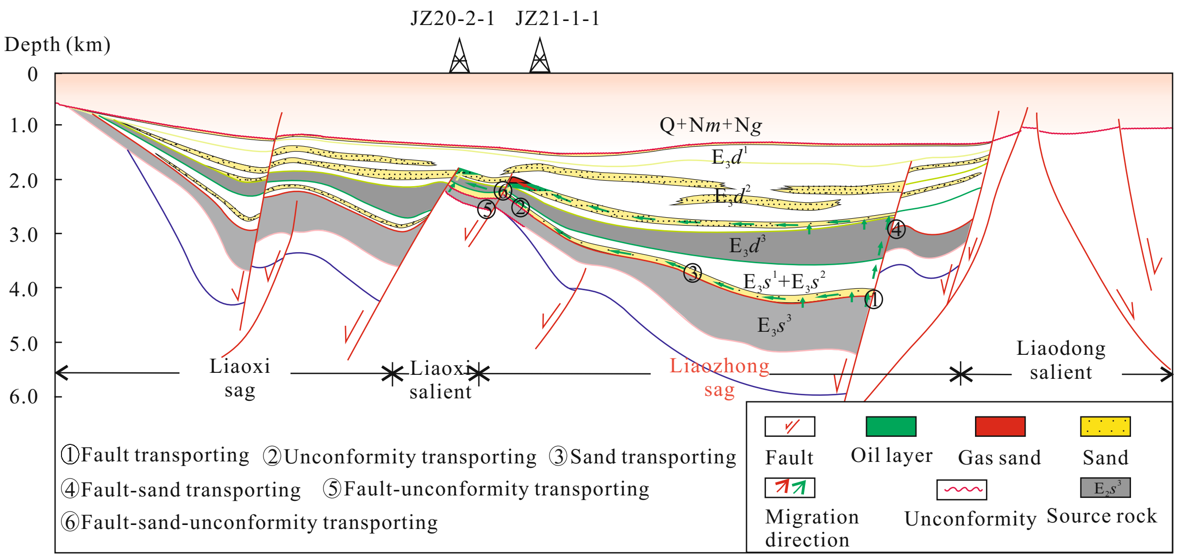

Figure 4. Main modes of translocation system in Liaozhong sag.

4.1 Analysis of Hydrocarbon Reservoir Formation in JX1-1 Oil and Gas Field

JX1-1 oil and gas field is located in the overturned structure zone in the northern sub-sag of Liaozhong sag and is divided into two parts, i.e., the east part and the west part, by Liaozhong No. 1 strike slip fault in Tanlu strike slip fault zone. Its structure has an inheritance nature from top to bottom. The west part is a long-strip semi-anticline trap with a relatively intact shape attached to the strike slip fault. The east part is a complex fault block trap under the control of the strike slip fault. From 1987 to the end of 2006, 8 wells have been drilled in this area in which the oil and gas reservoir in Dongying Formation and Shahejie Formation has been found.

Based on the research of oil source correlation, hydrocarbon generating history and the formation and evolution of structures, the reservoir formation process of this oil and gas field is reproduced as shown in Fig. 5.

During the late sedimentary period of E_3d^3, the hydrocarbon source rocks of E_2s^3 near JX1-1 field enters hydrocarbon generation threshold, generating mainly crude oil with low maturity and migrating towards traps in existing Shahejie and Dongying formations.

With the continuous sedimentation of E_3d^1 and E_3d^2, the source rocks of Lower E_2s^3 bury deeper with higher maturity. During the late sedimentary period of E_3d^1, the burial depth of source rocks reaches the maximum and enters gas generation threshold. The oil and gas accumulate in traps in Shahejie and Dongying formations to form reservoir. Due to the tectonic uplifting movement during the late sedimentary period of E_3d^1, the faults are strongly active, causing the infiltration of meteoric water and permeation of oil and gas along the faults. The paleo-oil reservoir formed earlier is destroyed due to the influence of biodegradation, which can be strongly proved by the saturated hydrocarbon chromatogram of crude oil and $NaHCO_3$-type formation water (Fig. 6).

It can also be perceived from the saturated hydrocarbon chromatogram that the oil and gas in the east part has been damaged more than that in the west part. Due to the fact that the original sedimentary thickness of the mudstone cap rock of E_3d^3 in the east part is thin under the influence of strike slip faults and the faults develop, the oil and gas of E_2s^3 have been destroyed. However, the oil and gas in Shahejie Formation in the west part are protected by the thicker mudstone cap rock of E_3d^3 and the faults are not as fully developed as the ones in the east part, therefore the oil and gas filled earlier in the traps in Shahejie Formation are better preserved.

Since the uplift denudation, the maturity of the source rocks of E_2s^3 has further increased because of the sedimentation of Guantao and Minghuazhen formations. Influenced by Liaozhong No. 1 strike slip fault, the source rocks in the

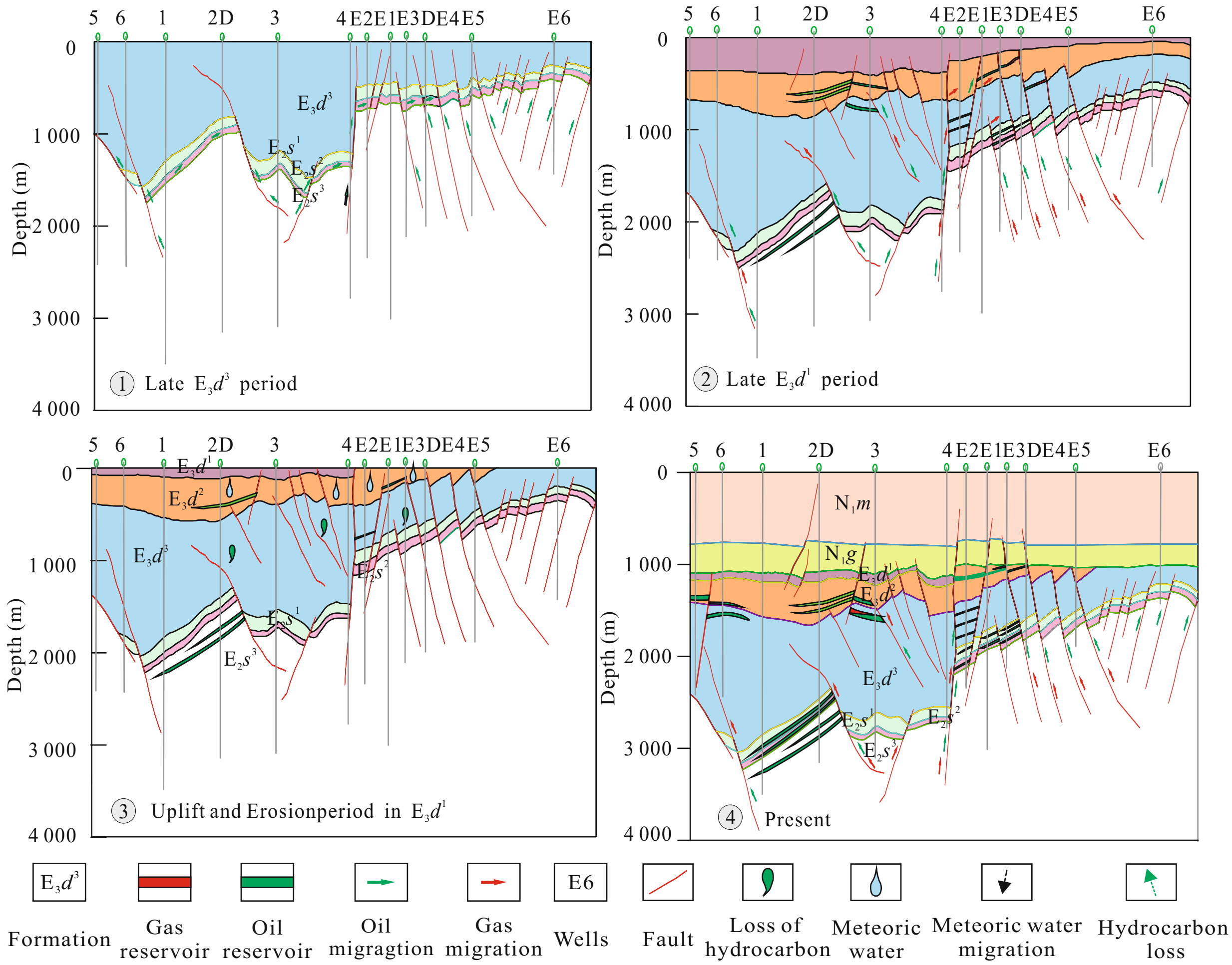

Figure 5. Pattern of the reservoir formation in JX1-1 oil and gas field.

western part has been buried deeper and the generated oil and wet gas with higher maturity first fill into the faulted anticline traps in the western 1-2D-3-well zone. The components of natural gas show that the solution gas of Shahejie Formation in the western part exhibits the features of wet gas and the dry coefficient is 77.4%–76% without obvious oil and gas differentiation. The dry coefficient of the solution gas in JX1-1-2D well in Dongying formation is 93.03%, which is the result of the obvious oil and gas differentiation caused by the migration of the solution gas from the deep part to the shallow one.

The dry coefficient of the natural gas in Shahejie and Dongying formations in the east part is much higher than that in the west part, exhibiting the features of dry gas. The maturity of the source rocks has not reached the criteria for dry gas generation, which is the result of component differentiation during the migration process of oil and gas generated from the source rocks in the deep west part along the strike slip fault to the east. There are two main reasons for the eastward migration. The first is that the east part lies in the high position of the strike slip fault, which is the favorable zone of oil and gas migration. The second is that the Shahejie Formation in the west part contains the lithologic structural reservoir in the faulted anticline traps with high closure. The height of closure of Well 1-2D and Well 3 is between 720 and 840 m. However, the limited lateral sealing ability of the faults leads to the failure of sealing the oil column of 720–840 m high (Fig. 7).

When the oil and gas generated from the source rocks continue to fill into the traps, they will leak sideways along the traps to the reservoir in the shallow part. The distribution feature of oil and gas in this zone shows that the leaked hydrocarbon fluids are mainly solution gas. The leakage of the oil is limited and the leaked oil has not migrated into Dongying Formation in the east shallow part because the saturated hydrocarbon chromatogram of the crude oil in that Dongying Formation shows no additional filling of crude oil generated during the late geological stage. But the saturated hydrocarbon

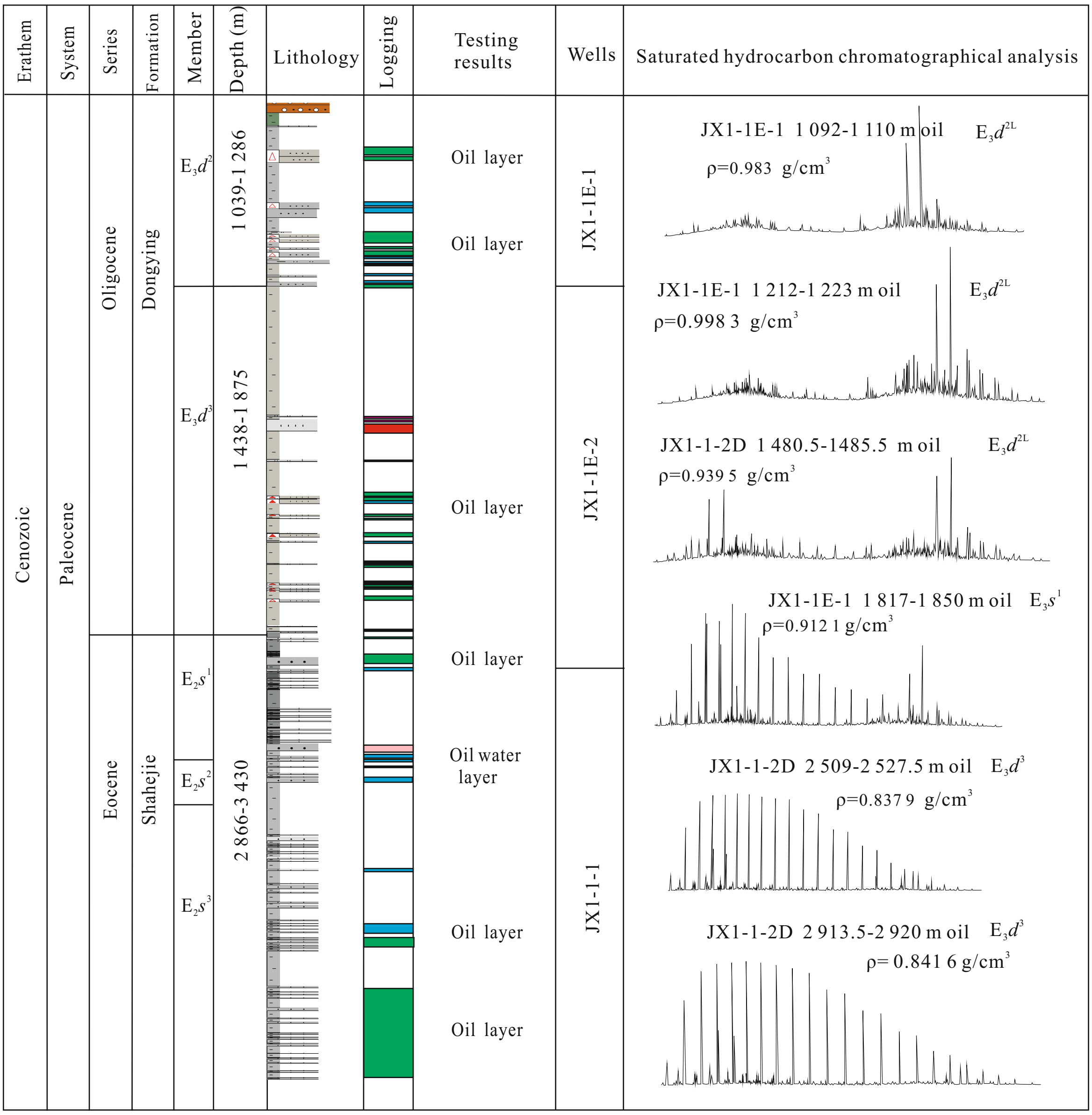

Figure 6. The saturated hydrocarbon chromatogram in JX1-1 oil and gas field.

chromatogram of oil in Shahejie Formation in JX1-1E-1 well tells the overlying feature of the filled crude oil generated during two different stages. The leaked solution gas along the faults evidently migrates into the reservoir stratum in the shallow E_3d^2. Even with the sealing and capping of the mudstone cap rock of E_3d^3, it is easier for the natural gas to migrate along the faults than for the oil.

4.2 Analysis of Hydrocarbon Reservoir Formation in JZ21-1 Oil and Gas Field

JZ21-1 oil and gas field is located at the northern sub-sag of Liaozhong sag. Liaozhong No. 1 fault in Tanlu strike slip fault zone goes through this field. This block is one of the most favorable oil and gas enrichment areas with excellent reservoir forming conditions. In structure, JZ21-1 is a late-stage reverse faulted anticline. There are three drilling wells in the main region (the north high point) and the south high point. After testing, commercial oil and gas flows are discovered in E_3d^2 of the wells.

JZ21-1 structure is located in the sub-sag. Compared to the oil and gas fields in Liaoxi low salient, this upheaval of the sag displays the feature of oil and gas migration and reservoir formation within a short distance. Oil-source correlation proves that the oil and gas mainly come from the source rocks of E_3d^3 buried deeper down. The strike slip fault and the derivative faults are good pathways for the oil and gas to migrate upward. The oil and gas migrate upward along the faults and accumulate to form reservoir in E_3d^2 within Dongying Formation. The reservoir formation process and the pool size are obviously controlled by faults (Fig. 8).

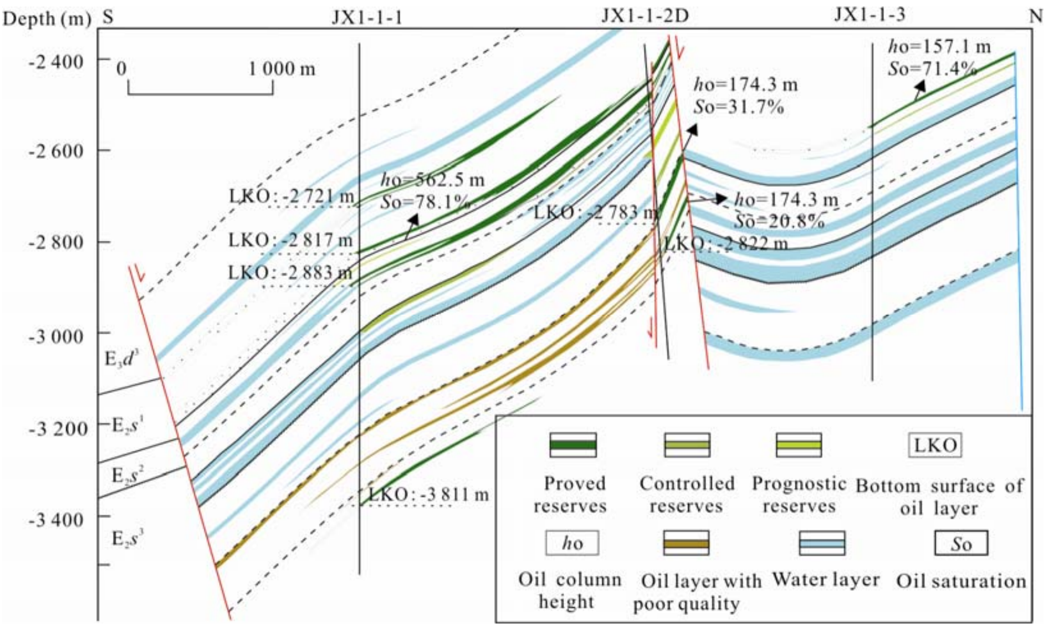

Figure 7. Reservoir section in JX1-1 oil and gas field.

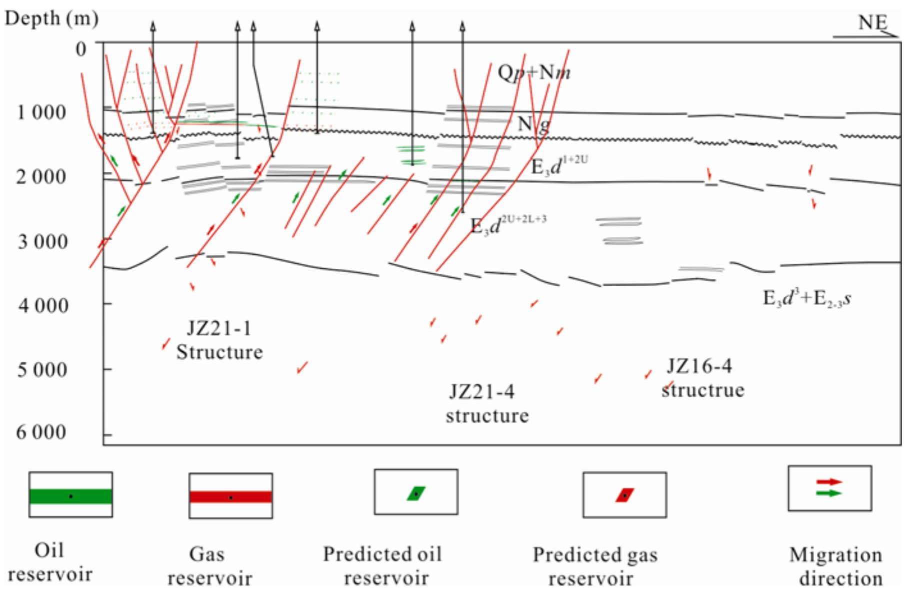

Figure 8. Pattern of the reservoir formation in JZ21-1 oil and gas field.

4.3 Analysis of Hydrocarbon Reservoir Formation in LD27-2 Oil and Gas Field

LD27-2 structure is located at the pitching end of Bodong low salient stretching northeastward in the transitional belt of lower Liaohe depression and Bozhong depression in Tanlu strike slip fault zone. It is situated at a favorable place for oil and gas accumulation with Bodong and Bozhong source rock depressions on the east and west sides and Liaozhong source rock depression on the north side.

It can be seen from the parameter figure of C_{29} sterane isomer's maturity (Fig. 9) that the maturity of the crude oil is low. However, there are natural gas (solution gas from the oil reservoirs) outputs from the reservoirs in Dongying, Guantao and Minghuazhen formations in this area, which come from the source rocks with relatively high maturity. This indicates that there are two stages of crude oil filling in LD27-2 area. The crude oil density decreases as the depth increases (Fig. 10). The oil generated during the early stage occupies the traps in the higher position in the structure while the light oil generated later accumulates in deeper parts. Vertically speaking, the gas-oil ratio is higher in deeper parts but lower in shallower ones. Most of the natural gas generated during the late stage from the source rocks with high maturity accumulates in the deep part instead of migrating to the shallow layers. The distribution of oil and gas stated above shows that the activities of the faults during the early and late stages are the key factors to control oil and gas distribution in this area and the reservoir formation mode of LD27-2 oil and gas field are thus established (Fig. 11).

4.4 Reservoir Formation Patterns of Tanlu Strike Slip Fault Zone

Multi-stage and multi-time fault activities play an active role in the formation of multiple reservoir accumulation zones with the fault zone as background (Hunt, 1990; Allan, 1989; Magoon, 1987). Researches and exploration practice prove that Tanlu strike slip fault zone is a favorable area for fluid migration and reservoir accumulation. The inherited structure of the strike slip fault and its main faults acted as the major pathways for oil and gas migration, connecting the underlying high-quality source rocks of E_3d^3 and E_2s^3. During the sedimentary period of E_3d^3 and E_3d^2, the source rocks of E_2s^3 mature gradually and first fill into the reservoir strata of E_2s^2 and Dongying Formation to form ancient hydrocarbon reservoir. Because of the tectonic uplifting and strata erosion during the late sedimentary stage of E_3d^1, the ancient hydrocarbon reservoir formed earlier is partly destroyed or adjusted during the migration and accumulation process. During the sedimentary period of Guantao and Minghuazhen formations, E_2s^3 and E_3d^3 bury deep again and generate hydrocarbon reservoir for the second time. The oil and gas fill into the reservoir strata of Shahejie-Dongying and Guantao-Minghuazhen formations to form today's reservoir. The reservoir in Shahejie-Dongying Formation is formed during both the early stage and the late one and then overlies each other while the reservoir in Guantao-Minghuazhen Formation is mainly formed during the late stage. It naturally follows that the modes of hydrocarbon reservoir formation in Tanlu strike slip fault zone can be generalized as follows—hydrocarbon source acts as "soil", oil and gas as "nutrient"; hydrocarbon expulsion relies on "roots"; hydrocarbon migration relies on "trunks"; reservoir forms in "brunches" and the whole process follows the pattern that "hydrocarbon accumulates in strike slips and oil and gas reservoir forms like the growth of trees".

5 CONCLUSION

Large quantities of oil and gas fields in this area accumulate on both sides of Tanlu strike slip fault in eastern China. Tanlu fault has undergone the sinistral movement, the dextral movement, the compressive activities and the extension activities successively. Liaozhong segment of Tanlu fault can be divided into three segments, i.e., the southern segment, the central segment and the northern segment. Clear changes are displayed in the sedimentary thickness, sag structure, tectonic nature and other aspects of these different sets of strata. Tanlu strike slip fault zone controls the burial depth of source rocks

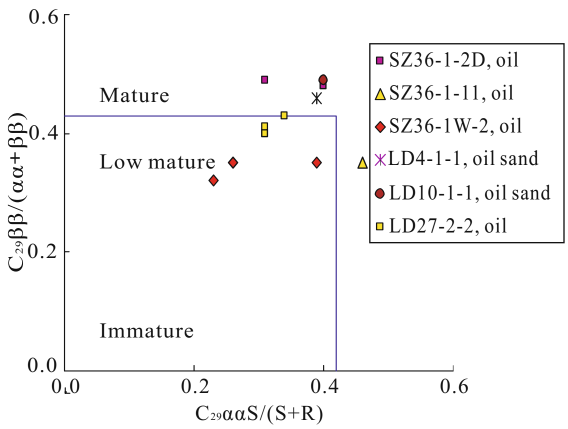

Figure 9. Parameter of C_{29} sterane isomer's maturity in LD27-2-2 Well.

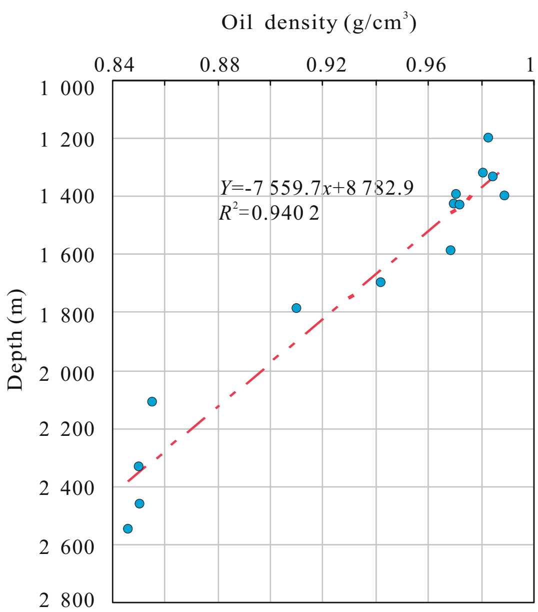

Figure 10. Relationship between oil density and the depth in LD27-2 oil and gas field.

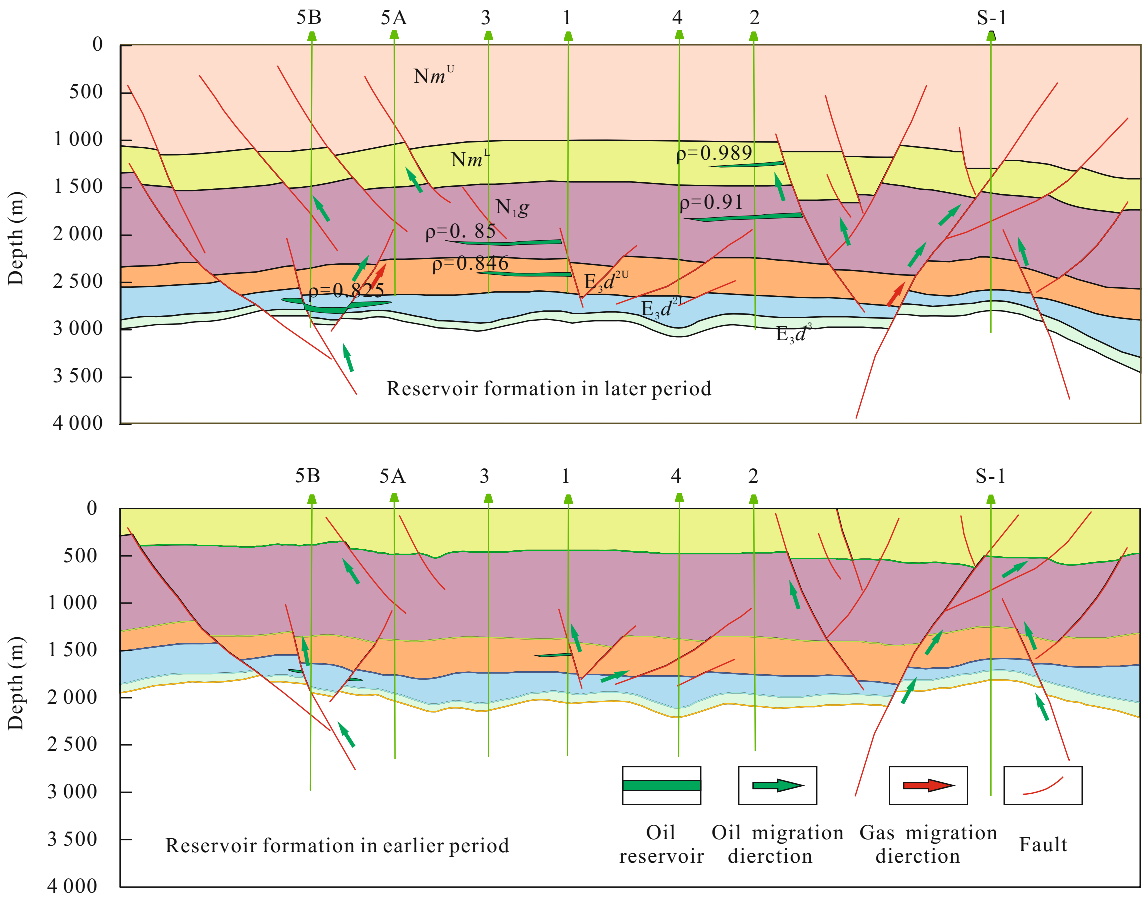

Figure 11. Pattern of the reservoir formation in LD27-2 oil and gas field.

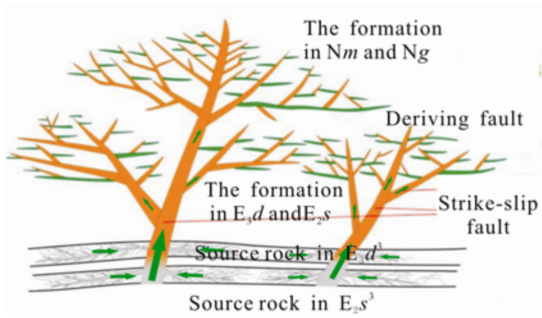

Figure 12. Pattern of the reservoir formation in Tanlu fault zone, Liaozhong sag.

and the sand body distribution, connects the source rocks in the deeper part and the reservoir strata in the shallower part, influences the type, the shape and the distribution of traps and greatly affects the migration and accumulation of oil and gas as well as the distribution of oil, gas and water. It is safe to say that the strike slip fault is the special controlling factor of the oil and gas distribution in this area. Hydrocarbon accumulation of the strike slip faults is the outstanding contribution made by Tanlu fault (Liaozhong segment). The modes of hydrocarbon reservoir formation in Tanlu strike slip fault zone can be generalized as follows—hydrocarbon source acts as "soil", oil and gas as "nutrient"; hydrocarbon expulsion relies on "roots"; hydrocarbon migration relies on "trunks"; reservoir forms in "brunches" and the whole process follows the pattern that "hydrocarbon accumulates in strike slips and oil and gas reservoir forms like the growth of trees".

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