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Characteristics of the Tan-Lu Strike-Slip Fault and Its Controls on Hydrocarbon Accumulation in the Liaodong Bay Sub-Basin, Bohai Bay Basin, China

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Abstract
The Tan-Lu Fault, one of the major strike-slip structures in China, controlled the development of most of the Meso-Cenozoic NNE trend rifted petroliferous basins in east China. It has cut across the Bohai Bay Basin since the late Cenozoic and played an important role in hydrocarbon accumulation and distribution in the Liaodong Bay sub-basin of the Bohai Bay Basin. The purpose of this paper is to study the geometry of the Tan-Lu strike-slip and how it affected petroleum system development in the Liaodong Bay sub-basin. The innovative seismic interpretation revealed the western branch of the Tan-Lu strike-slip fault cut through the Liaozhong depression of the sub-basin and its eastern branch superimposed on the earlier extensional boundary fault of the sub-basin. The strike-slip movement is characterized by a distinctive strike-slip zone associated with the NE en echelon faults in the central part of the Liaozhong depression and also caused the formation of the Liaodong uplift and the Liaodong depression in the east Liaodong Bay Sub-basin. Rapid movement of the Tan-Lu strike-slip fault has deepened the Liaozhong depression and facilitated the maturation of source rock. Related fault movement formed a series of structural traps and paleotopographic highs and lows that subsequently controlled sediment dispersal and the distribution of stratigraphic-related traps within sequence stratigraphic framework. Exploration practice, geochemical study and petroleum system modeling demonstrate that the Tan-Lu strike-slip and its associated faults acted as good hydrocarbon migration pathways and hydrocarbon accumulated in many traps associated with the Tan-Lu strike-slip zone. Many recent discoveries along the strike-slip zone prove that the petroleum system in Liaodong Bay Sub-basin was mainly controlled by the activity of the Tan-Lu strike-slip. The resulting hydrocarbon accumulation model in this sub-basin may provide a paradigm for the prediction of hydrocarbon accumulation to other east China basins along the Tan-Lu strike-slip fault zone.

Key words: Liaodong Bay Sub-basin; Tan-Lu strike-slip fault; Hydrocarbon accumulation; Petroleum system; Sequence stratigraphy

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INTRODUCTION
Strike-slip faults, such as San Andreas (US), Carboneras (Spain), and Hornelen (Norway) have been the research focus for both hydrocarbon exploration and geo-hazards for many years (Nilsen and McLaughlin, 1985; Dillon and Ehlig, 1993; Morton and Matti, 1993; Keller et al., 1995; Reicherter and Reiss, 2001). Distribution of many oil fields close to restraining bends of the right-lateral fault suggests that petroleum systems in this tectonic setting are tied to the style and movement of the strike-slip

faulting. In most cases, hydrocarbon mainly accumulates in those folding and faulting related traps (e.g., Peters et al., 1994; Mann et al., 2003).

Like other large scale strike-slip faults, the Tan-Lu (Tancheng-Lujiang) strike-slip fault has a regional linear shear fault, associate first and second order faults, transpressional and transextensional zones with some flower structure developed perpendicular to its strike (Hsiao et al., 2004, 2010; Gong et al., 2011). According to Xu et al. (1987) and Gilder et al. (1999), the Tan-Lu fault is a NNE-trending strike-slip fault in east China with an approximate 5000 km long (2400 km in China) extension. Hundreds of kilometers of left-lateral strike-slip movement had occurred along the fault zone during the middle Mesozoic (Xu and Zhu, 1994). During the Cenozoic, it became a right lateral strike-slip fault system (Chen and Nabelek, 1987).

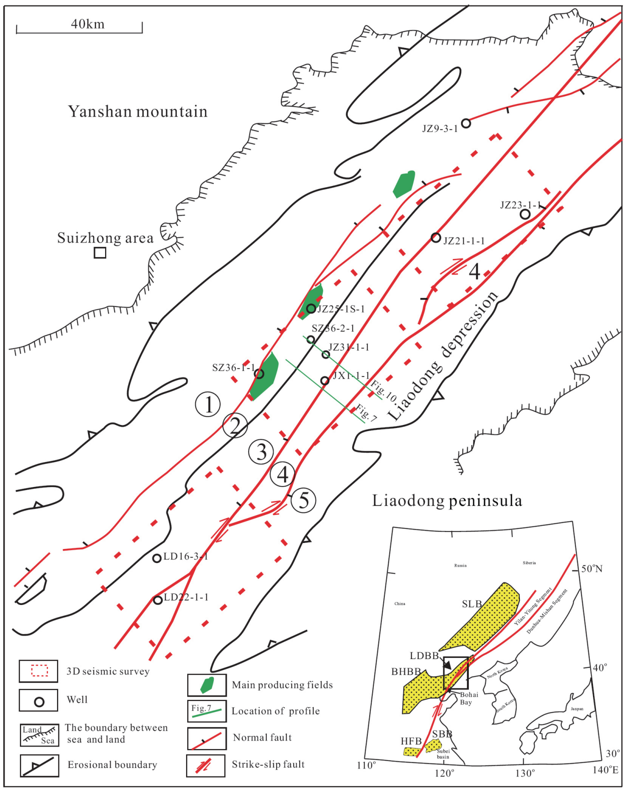

Figure 1
Simplified Map of the Study Area-Liaodong Bay Sub-Basin and Its Structural Units (Inset Map Modified from Hsiao et al., 2004, 2010)
Main 3D Seismic Data Coverage is Shown in Dashed Rectangle. The Cross Sections in Figure 7 and 10 are also Indicated in Solid Line with the Figure Numbers. SLB-Songliao Basin, LDBB-Liaodong Bay Sub-Basin, BHBB-Bohai Bay Basin, HFB-Hefei Basin, SBB-Subei Basin; ①Liaoxi Depression,②Liaoxi Uplift, ③Liaozhong Depression, ④Liaodong Uplift, ⑤Liaodong Depression

From the north to the south in east China, a series of petroliferous basins, including the Songliao Basin, the Bohai Bay Basin, the Subei Basin and the Hefei Basin, have developed along this strike-slip fault zone (Fig. 1). Regional tectonics and basin evolution studies suggest that they are all genetically related with the activity of the Tan-Lu strike-slip fault (e.g., Xu et al., 2007). Three critical evolution stages of the Tan-Lu strike-slip fault are associated with the basin formation, including:

(1) The Triassic to the Mid-Jurassic: in response to the subduction of the Pacific plate towards northwest, the Tan-Lu fault behaved as sinistral transpression in the Songliao Basin. Previous faults were reactivated and merged into one branch of the Tan-Lu strike-slip fault in a transtension regime. The Bohai Bay and Subei basins were formed during this stage.

(2) The Late Jurassic to the early Cretaceous: the Tan-Lu strike-slip fault shifted back and forth between transpression and transtension in response to the intermittent subduction and collision between Pacific and Eurasian plates.

(3) The mid-Cretaceous to Cenozoic: the Tan-Lu strike-slip fault was diversified and segmented by the intense collision between the Indian and Eurasian plates. In the Bohai Bay and Subei areas, the southern Tan-Lu fault was under northwest to southeast trending extension (Wang et al., 1999).

The Liaodong Bay sub-basin is a part of the Bohai Bay Basin. A previous study proposed that the Bohai Bay area was formed as a series of strike-slip pull-apart basins triggered by the Tan-Lu fault system (Allen et al., 1997). However, new seismic data from offshore portion of the Liaodong Bay sub-basin show that the total Cenozoic slip movement of the Tan-Lu strike-slip fault is insufficient (Hisao et al., 2004). This supports another model which suggests that the basin is controlled by both extension and strike-slip activities, and mainly by the former (Li et al., 1995).

One big concern of oil exploration in the Bohai Bay Basin is the seal capability, especially within active strike-slip fault zones (Deng, 2001). Therefore, the majority of exploration and discoveries were mainly conducted in the Liaoxi uplift in the west of the Liaodong Bay sub-basin, far away from the Tan-Lu strike-slip fault zone. However, recent wildcat discoveries are located close to the Tan-Lu strike-slip fault system (Jiang, 2007). Limited research on the Tan-Lu strike-slip fault and its impact on sedimentation have been done in this area (Guo, 2001; Hsiao et al., 2004; Gong et al., 2007; Hsiao et al., 2010; Jiang et al., 2010). Understanding the role of the Tan-Lu strike-slip fault and its impact to hydrocarbon accumulation will have important implications to the hydrocarbon exploration in the Bohai Bay Basin as well as other strike-slip related areas around the world.

This study employs tectono-sedimentation analysis and basin modeling to investigate how the Tan-Lu strike-slip fault controls the basin evolution and petroleum system development within a sequence stratigraphic framework.

1. GEOLOGICAL SETTING

The Cenozoic Liaodong Bay sub-basin, about 2.6×10^4 km^2 (1×10^4 mi^2) in area, is located in the northeast Bohai Bay area, northeast China. From west to east, the basin can be further subdivided into five zones, the Liaoxi depression, the Liaoxi uplift, the Liaozhong depression, the Liaodong uplift and the Liaodong depression, respectively. Major oil producing areas are located in the Liaoxi uplift (Fig.1).

Similar to other Cenozoic basins in east China, the Liaodong Bay sub-basin shows two-stage development: the Paleogene rifting and Neogene post-rift stages (Ye et al.,1985). The syn-rift megasequence consists of the Kongdian, Shahejie and Dongying formations (Fig. 2). The Kongdian formation is composed of alluvial conglomerate, fluvial and lacustrine deposits. The Shahejie formation is characterized by dark lacustrine mudstones, sandstones and some coarse-grained marginal lacustrine deposits. The Dongying formation is mainly deltaic to fluvial facies of interlayered mudstone and sandstone. The main reservoir rocks are sandstones of delta, fan delta and turbidite systems, especially the Oligocene Dongying Formation (Fig. 2) (Jiang et al., 2010).

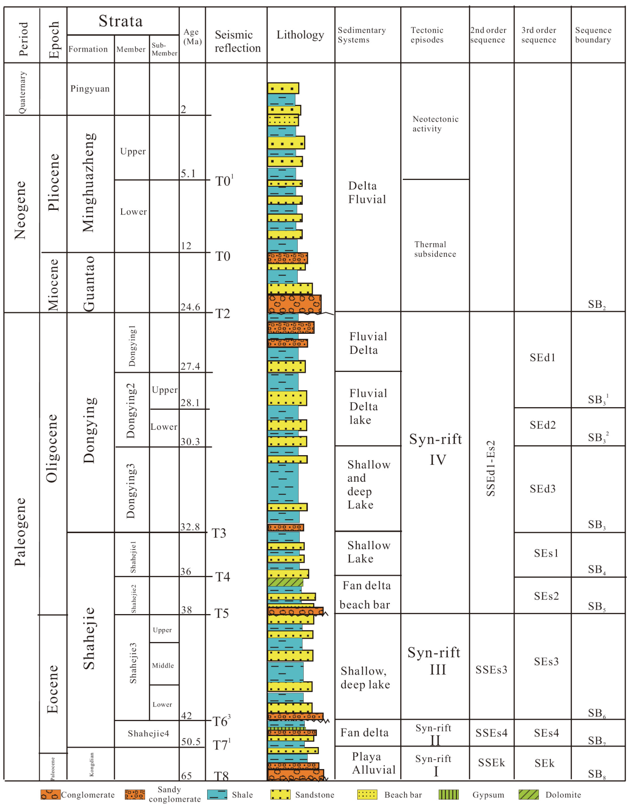

Figure 2
Stratigraphic Column and Sedimentary Systems in the Liaodong Bay Sub-Basin
The stratigraphic nomenclature and age data are from CNOOC (China National Offshore Oil Corporation). The depositional system evolution and sequence stratigraphic interpretation are from the CNOOC's research (By Shu Jiang, 2006). SB-sequence boundary. SSEs- Paleogene Shahejie Super-sequence, SSEd-Paleogene Dongying Super-sequence, SEs- Paleogene Shahejie Sequence set, SEd- Paleogene Dongying Sequence set, SEd3-Dongying1 sequence, SEd2-Dongying 2 sequence, SEd1-Dongying1 sequence, SEs2-Shahejie2 sequence.

2. DATA SETS

After 30 years exploration, 120 exploration wells were drilled in the Liaodong Bay sub-basin. Regional 2D seismic data cover the whole basin with density of 1km×1km. A major portion of the basin, with an area of 5490 km^2 (2120 mi^2), is covered by 3D seismic data (see Figure 1 for the 3D seismic coverage in three surveys). Data sets used in this study include 100 cross sections of 2D seismic data covering the whole area, 3D seismic data from 3 surveys, 80 well logs, cores from 30 wells, paleontological and geochemical data from 20 wells. All these data were provided by China National Offshore Oil Corporation (CNOOC) Research Institute.

3. METHODOLOGY

Seismic interpretation was employed to document the basin-wide variation in the structure framework and its features (geometry, orientation, kinetics) of the Tan-Lu strike-slip fault in different areas in the Liaodong Bay Sub-basin. Depositional systems and Sequence Stratigraphy analysis was pursued within chronostratigraphic framework. Geochemical analysis and petroleum system modeling was utilized together to understand the relationship between the Tan-Lu strike-slip fault in the Liaodong Bay sub-basin and the hydrocarbon migration and accumulation.

4. CHARACTERISTICS OF THE TAN-LU STRIKE-SLIP FAULT IN LIAODONG BAY SUB-BASIN

The Tan-Lu strike-slip fault was bifurcated into two nearly parallel branches in east Liaodong Bay sub-basin. Recent wildcat discoveries are closely tied to these two branches of the Tan-Lu strike-slip fault (Fig. 3a). To the north, the eastern branch (close to Liaodong uplift) follows a former extensional boundary fault plane to the west of Liaodong uplift, while the western branch forms the negative flower structure (Fig.3b). In the central area of the Liaodong Bay sub-basin, the west branch bisected the Liaozhong depression with a central reverse flower structure in the Liaozhong depression (Fig.3c). CNOOC's exploration and research suggested that the deposition of the Liaodong uplift and some part of Liaodong depression started at the early Oligocene, which suggest that the Liaodong depression and Liaodong uplift were formed in the early Oligocene. In the southern area, some central reversed horst structures had been formed due to the Tan-Lu strike-slip movement (Fig.3d).

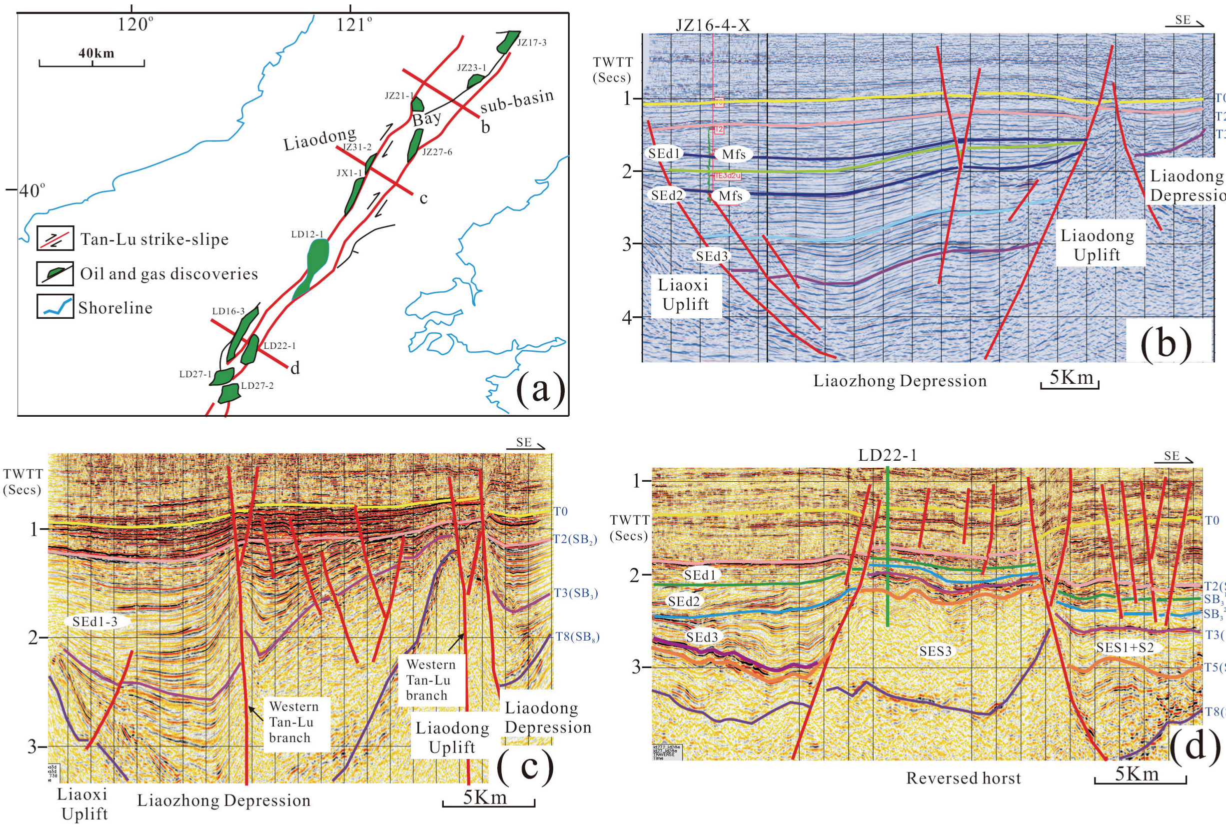

Figure 3
Wildcat Oil Discoveries in Tan-Lu Strike-Slip Zone and the Cross-Section Features Perpendicular to Tan-Lu Strike-Slip Orientation in Different Areas in the Liaodong Bay Sub-Basin
(a) The distribution of recent wildcat discoveries and its relation to Tan-Lu strike-slip fault. The locations of cross sections in B, C, D are showed in figure a. (b) Sequence stratigraphic framework in Northern Liaodong Bay sub-basin. (c) Sequence stratigraphic framework in Central Liaodong Bay sub-basin. (d) Sequence stratigraphic framework in Southern Liaodong Bay sub-basin. These cross sections shows sequence stratigraphic frameworks varying in different areas due to the control of Tan-Lu strike-slip fault. See explanations in Figure.2 for the meanings of name codes (e.g. T2 (SB2), SEd2, etc.) of interpreted sequences and their boundaries. Seismic data courtesy of CNOOC Research Institute.

3D seismic data provide the opportunity to study the areal characteristics of the Tan-Lu strike-slip fault. In this study, we chose the variance seismic attributes to demonstrate the detailed Tan-Lu fault pattern in plan view. Two variance seismic attribute maps were generated at time depth of 1500ms (millisecond) in the Tan-Lu fault zone, one from central 3D seismic survey (Fig. 4a) and the other one from southern 3D seismic survey in the Liaodong Bay sub-basin (Fig. 4b). Both maps suggest the strike-slip fault consists of western and eastern branches. In central Liaodong Bay sub-basin (Fig.4a), the western branch exhibits linear feature and associates with northeast oriented en echelon faults, the east branch offsets and/or obliquely superimposes on previous extensional faults to the west of the Liaodong uplift (Fig.4a, 3b, c). The southern strike-slip fault system mainly consists of northeast oriented en echelon fault systems. A reversed horst was formed between two branches of Tan-Lu strike-slip fault and all en echelon faults were distributed within two those branches as well (Fig.4b, 3d).

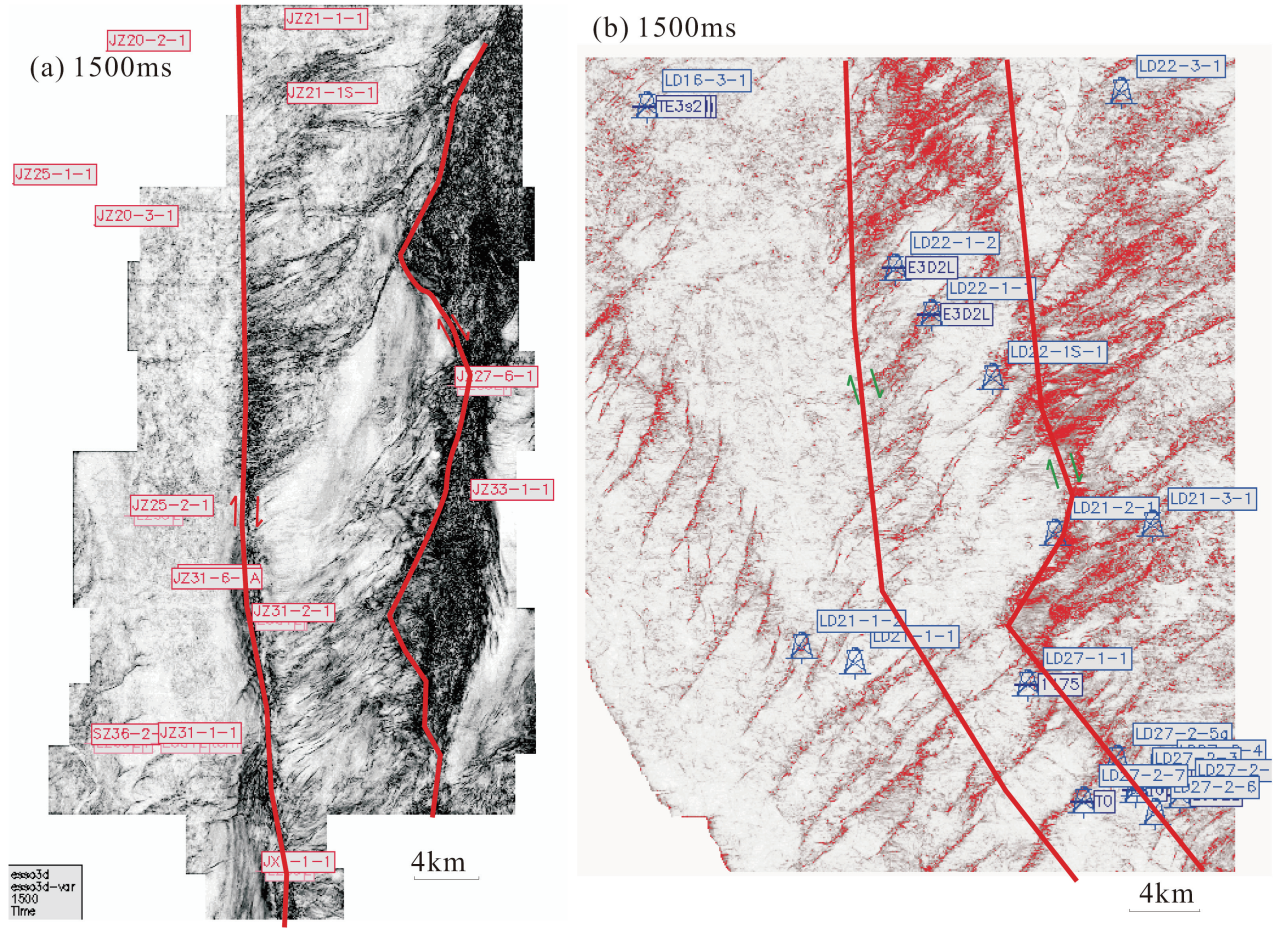

Figure 4
Variance Seismic Attribute at the Same Depth of 1500 msec in Central (a) and Southern (b) Liaozhong Depression, Showing the Areal Characteristics of the Tan-Lu Strike-Slip Fault

5. CONTROLS OF THE TAN-LU STRIKE-SLIP FAULT ON HYDROCARBON ACCUMULATION

The Tan-Lu strike-slip fault has direct impact on the hydrocarbon accumulation within the Liaodong Bay sub-basin and surrounding area.

5.1 Source Rock Distribution and Maturation

The Strike-slip motion of the Tan-Lu fault accelerated the subsidence of the depocenters along the strike-slip zone since the deposition of Oligocene Dongying formation as suggested by CNOOC'S research. Subsidence analysis shows that the rapid subsidence started around 32.8 Ma and ended at 27.4 Ma (Fig. 5). The Oligocene Dongying Formation mainly occurs along the strike-slip fault zone was deposited during this time. Its lower section is mainly thick shale, which has been confirmed as another source rock in addition to main source rock from Eocene Shahejie Formation. Different from the Oligocene source rock of Dongying formation that mainly located close to the strike-slip zone, the Eocene source rock of Shahejie formation is well developed both in Liaozhong depression and Liaoxi depression and far away from Tan-Lu strike-slip zone (Fig.6). Studies of other sub-basins in the Bohai Bay area also show similar results. The Oligocene Dongying formation only distributes in areas bisected by the Tan-Lu strike-slip fault and apparently controlled by the rapidly subsidence caused by neotectonic activity (i.e., the Tan-Lu strike-slip fault) in east China (Gong et al., 2007). Furthermore, Qiu et al. (1997) reported that the thermal gradients decrease with the increasing distance to Tan-Lu fault zone in East China. Higher thermal gradients along the fault zone facilitated the maturation of this Oligocene Dongying source rock.

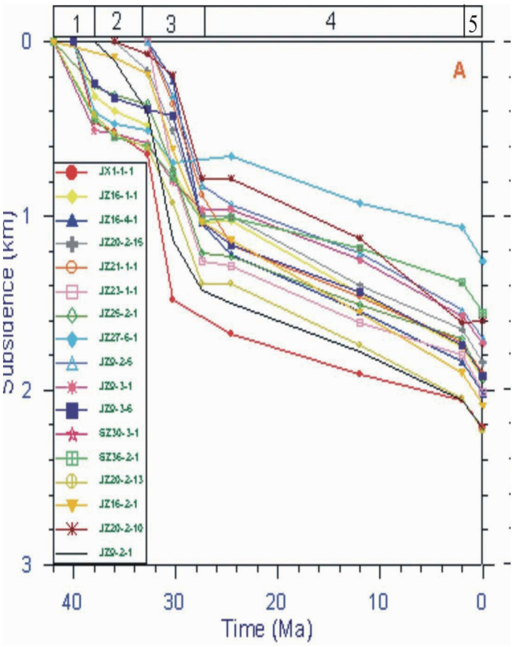

Figure 5
Subsidence Rate and Its Tectonic Stages in the Liaodong Bay Sub-Basin
1-5 Means Different Subsidence Stages. 1 Fast Tectonic Subsidence Stage; 2 Slow Tectonic Subsidence; 3 Fast Tectonic Subsidence; 4 Thermal Subsidence; 5 Neotectonic Subsidence (Original Data was Provided by CNOOC-Tianjin and Different Wells Represent Different Locations in the Basin).

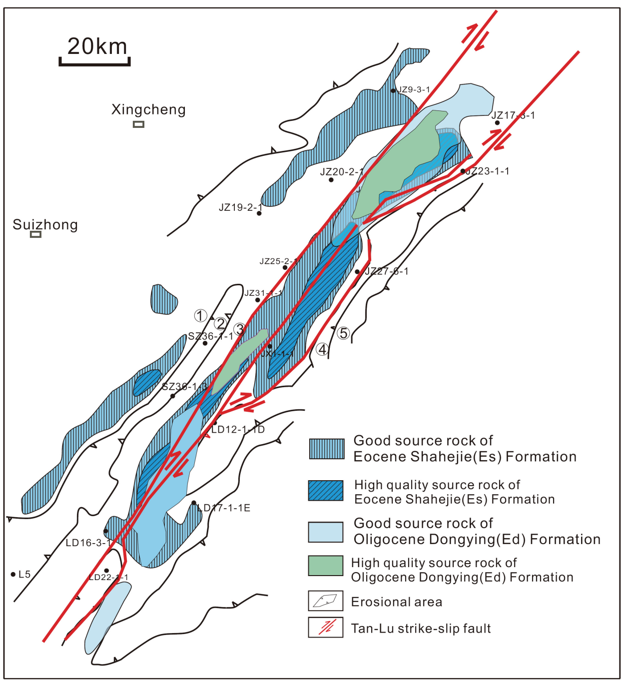

Figure 6
Distribution of the Eocene and Oligocene Source Rock in the Liaodong Bay Sub-Basin
Note that the Oligocene Dongying Source Rocks Distribute Close to the Tan-Lu Strike-Slip Zone and Eocene Shahejie Source Rocks Distribute Widely in Liaoxi Depression and Liaozhong Depression. ①Liaoxi Depression, ②Liaoxi Uplift, ③Liaozhong Depression, ④Liaodong Uplift, ⑤Liaodong Depression.

5.2 Acting as Hydrocarbon Migration Pathway

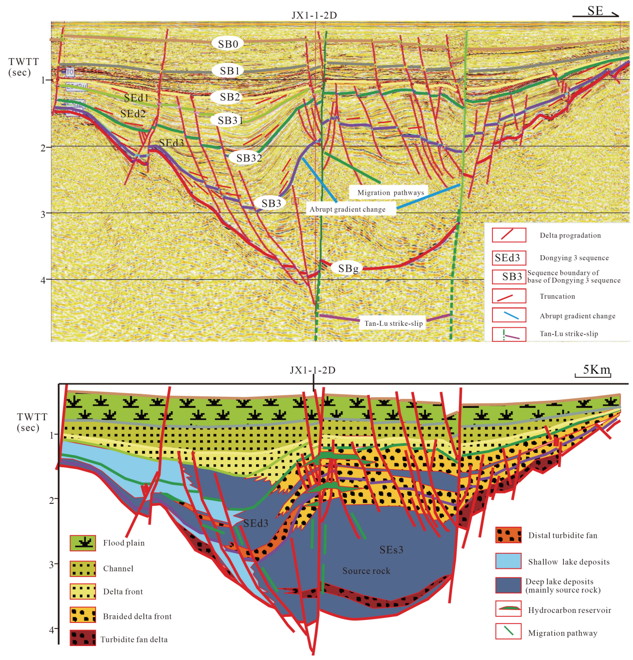

Figure 7
(a) Seismic Sequence Stratigraphy and (b) Stratigraphic Framework Interpretation
See Figure 1 for the Location of This Cross Section. The Two Figures Showing Tan-Lu Strike-Slip Fault as Migration Pathway and Causing Abrupt Gradient Change to Control the Turbidite Sandstone Distribution Across JX1-1 Structure in Central Liaodong Bay Sub-Basin. The Distribution of Reservoir Facies and Source Rock Were Interpreted from Sequence Stratigraphic Study and Validated by Drilling Result and Geochemical Analysis. See Figure 2 for the Meaning of the Stratigraphic Codes.

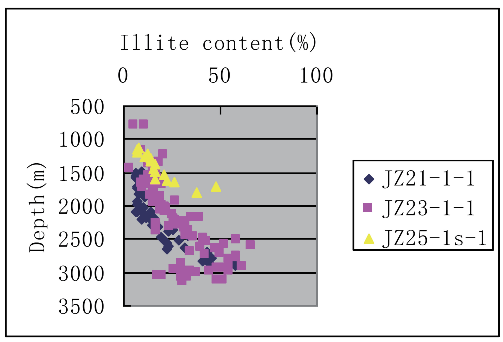

Figure 8
The Illite Content Distribution Versus Depth, the Three Wells Chosen from Different Structure Zones (See Figure 1 for the Locations of the Three Wells)
JZ25-1s-1 is from the Liaoxi Uplift, JZ23-1-1 is from Tan-Lu Strike-Slip Zone, and Jz21-1-1 is from Liaozhong Depression Zone Away from Strike-Slip Zone. The Abnormal Illite Content Indicating the Hydrocarbon Migration. For the Same Depth, Illite Content from JZ25-1s-1 is Highest and JZ21-1-1 is Lowest, Which Reveals the Hydrocarbon Migration in Liaoxi Uplift is Most Active, then Followed by the Tan-Lu Strike-Slip Zone (Data Courtesy of CNOOC).

The long-lived Tan-Lu strike-slip fault was deeply rooted down to the basin basement and connected the younger overlying reservoir rocks with the source rock beneath (Fig.7). Abnormal illite clay mineral distribution has been used as an index to determine if certain rocks/strata/areas are a hydrocarbon migration pathway and its conduiting ability (Zeng and Yu, 2006). Three typical wells were chosen to analyze fault migration ability from different structure zones: JZ25-1s-1 from the Liaoxi uplift, JZ23-1-1 from Tan-Lu strike-slip zone , and JZ21-1-1 from Liaozhong depression zone away from Tan-Lu strike-slip zone. All three wells show abnormal illite distributions: 1500m in well JZ21-1-1(illite content of this depth is higher than that at 2000m), 1300m in well JZ23-1-1(illite content at this depth is greater than that at 1500m), and also at 1700m from in JZ25-1s-1(abrupt increase in illite content) (Fig.8). Even though all three structure zones show abnormal distributions of illite content and suggest they all had been hydrocarbon migration paths, the conduiting capabilities are different in the three zones. At the same depth, illite content of well JZ25-1s-1 is the highest and the content of well JZ21-1-1 is the lowest, which indicates the hydrocarbon migration in the Liaoxi uplift (represented by the well JZ25-1s-1) is the most active, then followed by the Tan-Lu strike-slip zone (represented by the well JZ23-1-1), the Liaozhong depression (represented by well JZ21-1-1) is the relatively least active zone. This result is consistent with current oil discoveries: the Liaoxi uplift contributes to the most reserves in the Liaodong Bay sub-basin. Areas along the Tan-Lu strike-slip zone will be the second largest hydrocarbon migration and accumulation areas as suggested by the data presented here.

5.3 Structural and Stratigraphic Traps

The Tan-Lu strike-slip fault zone directly formed some structural related traps (e.g., JX1-1-2D trap in Fig. 7). Abrupt topography changes due to the strike-slip movement controlled the sedimentation and stratigraphic distribution. For example, the turbidite fan deltas (e.g., in Shahejie formation) mainly occur within the downdip of the current strike-slip zone or the former boundary fault. The overlying Dongying sequence was also deposited in the downdip of those abrupt gradient change areas caused by strike-slip fault movement (Fig.7). Based on the paleogeography reconstruction and seismic data, we interpret that strike-slip movement caused the abrupt slope gradient change in paleo-topography that directly related to the development of those turbidites in deep lake setting (Fig.9).

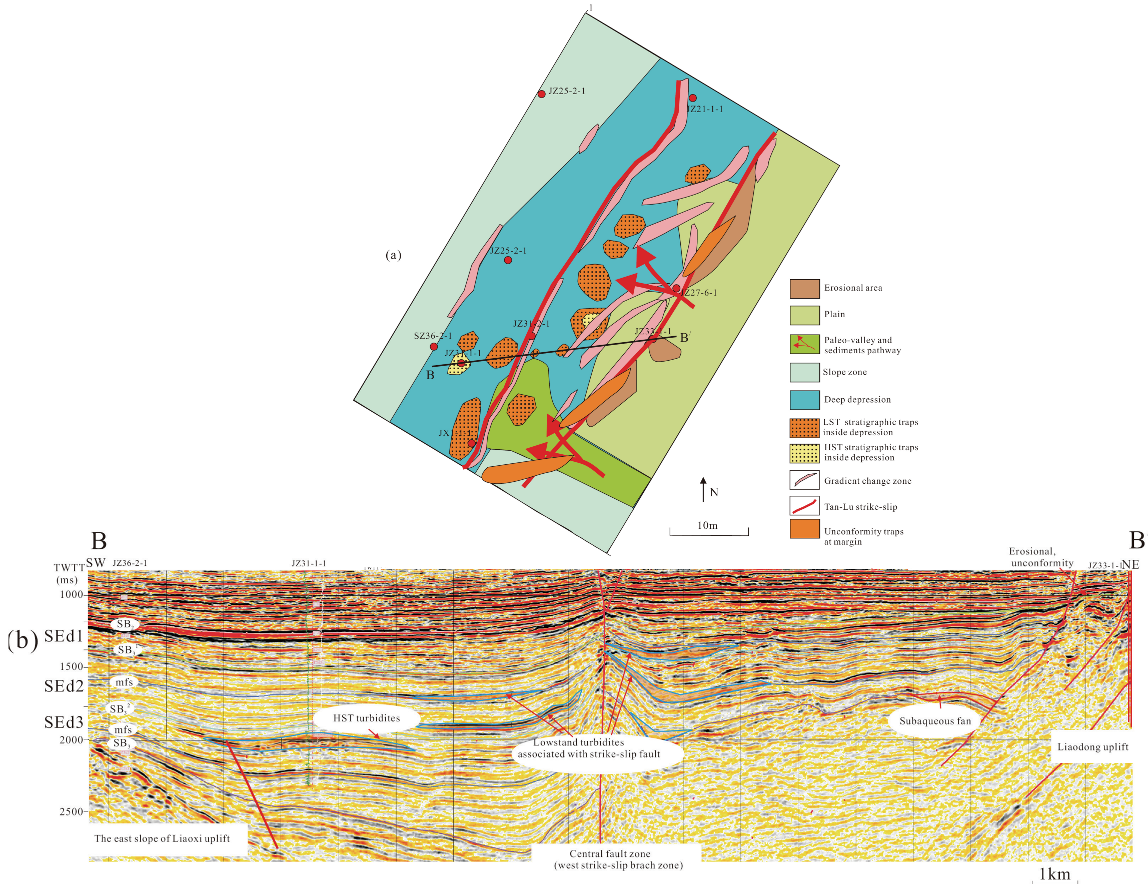

Figure 9
Distribution of Stratigraphic Traps and Its Relation with Tan-Lu Strike-Slip Fault and Associated Faults
(a) Areal Distribution of Stratigraphic Traps and Relation with Tan-Lu Strike-Slip Fault. (b) Seismic Cross Section Showing Controlling of Tan-Lu Strike-Slip Fault on Stratigraphic Trap Distribution.

6. PETROLEUM SYSTEM MODELING

2D petroleum system modeling was preliminarily applied to the Liaodong Bay Sub-basin area to understand the role of Tan-Lu strike-slip fault in hydrocarbon migration and accumulation (Jiang et al., 2007a). Core description, well log interpretation, well-tied seismic data interpretation and seismic attribute analysis within the sequence stratigraphic framework were integrated together to determine detailed lithofacies (Jiang et al., 2007b). The petroleum system modeling results by detailed lithofacies input within tectono-stratigraphic framework show that the west Tan-Lu strike-slip zone in the Liaozhong depression is definitely the main hydrocarbon migration and accumulation area (Fig. 10a, b). The potentials (warm color in Fig. 10b) are predicted stratigraphic traps and combination traps associated with Tan-Lu strike-slip fault deformation zone. Modeling results show that the Tan-Lu strike-slip fault acted as an active conduit during hydrocarbon migration in earlier Neogene, even though it is generally sealed fault at present. This is consistent with development of the Tan-Lu strike-slip fault which was an active fault since the Oligocene (e.g., hydrocarbon migration period) and it stopped during the neotectonic compression period after the Neogene (Liu et al., 2002). This result is consistent with the drilling result of JZ31-1-1 well (Fig.10b).

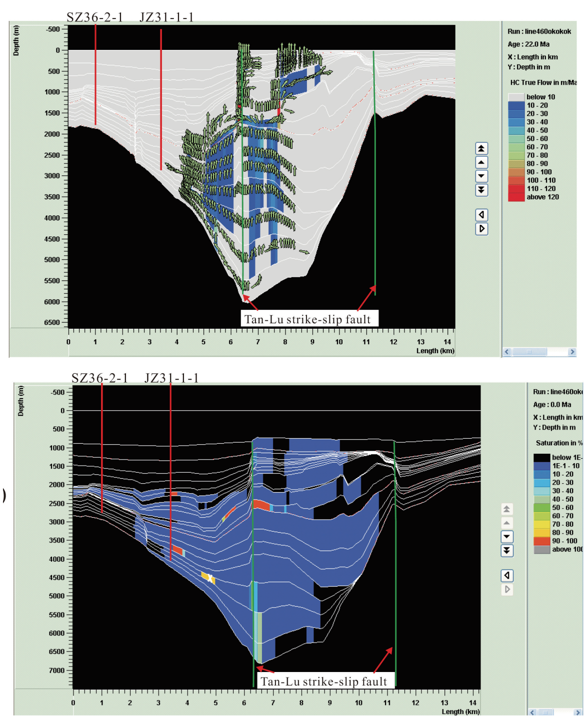

Figure 10
Petroleum System Modeling of Liaodong Bay Sub-Basin Showing the Tan-Lu Strike-Slip Zone is an Area of Active Hydrocarbon Migration and Accumulation
(a) Plot Showing True Hydrocarbon Flow in m/Ma at the Age of 22Ma and (b) Plot Showing the Hydrocarbon Saturation at Present. Warm Color Representing Predicted Reservoirs (the Location of This Profile Shown in Figure 1).

The modeling results also suggest that there is no obvious oil accumulation in the Liaodong uplift. Hydrocarbon exploration in this area confirms this result. This can be explained: 1) The Tan-Lu strike-slip fault superimposed on basin boundary faults which made this region tectonically active and the lateral sealing capacity in this region is poor; 2) There is no effective top seal rocks developed on the Liaodong uplift. Similar to this, the modeling did not show any good potential from the Liaodong depression to the east. This depression was formed later due to the activity of Tan-Lu strike-slip fault and all strata have not been deeply buried, therefore, it is lacking effective source rock. The Liaoxi uplift is bounded by the Liaoxi depression to the west and the Liaozhong depression to its east. A large delta front draping over the paleo-high have formed reservoir rocks on the top. Both depressions to its west and east have thick source rocks developed. As mentioned before, the highest abundance of illite content in the Liaoxi uplift at the same depth among different structural zones suggests that it has the most active hydrocarbon migration on this structural high (Fig.8). For future exploration, the Liaozhong depression, especially along Tan-Lu strike-slip zone also show some potential. In this area, reverse structural traps and stratigraphic traps directly developed above the source rock. Hydrocarbon from lower Paleocene could directly migrate to shallow strata by those active faults associated with strike-slip movement (Fig. 10).

Based on the drilling, geological/geophysical analysis, and predictions from numerical modeling within the sequence stratigraphic framework, we summarized the hydrocarbon accumulation in the Laodong Bay sub-basin along a regional cross section perpendicular to the Tan-Lu fault (Fig.11). The Liaoxi uplift and the Liaozhong depression are the main hydrocarbon accumulation areas. In Liaoxi uplift, traps are formed along paleo-highs, reservoir rocks are mainly delta front facies sandstones, and source rocks are mainly from the Liaozhong depression with some contribution from the Liaoxi depression. The hydrocarbon migrated along sand carriers located mainly on the sequence boundaries and long-lived active faults. The Liaozhong depression is rich in both source rock and reservoirs. Hydrocarbon migrated vertically up to Oligocene Dongying 2 sequence (SEd2). However, the major part of its overlying Dongying1 sequence (SEd1) lacks an effective seal and no significant hydrocarbon accumulation has been found.

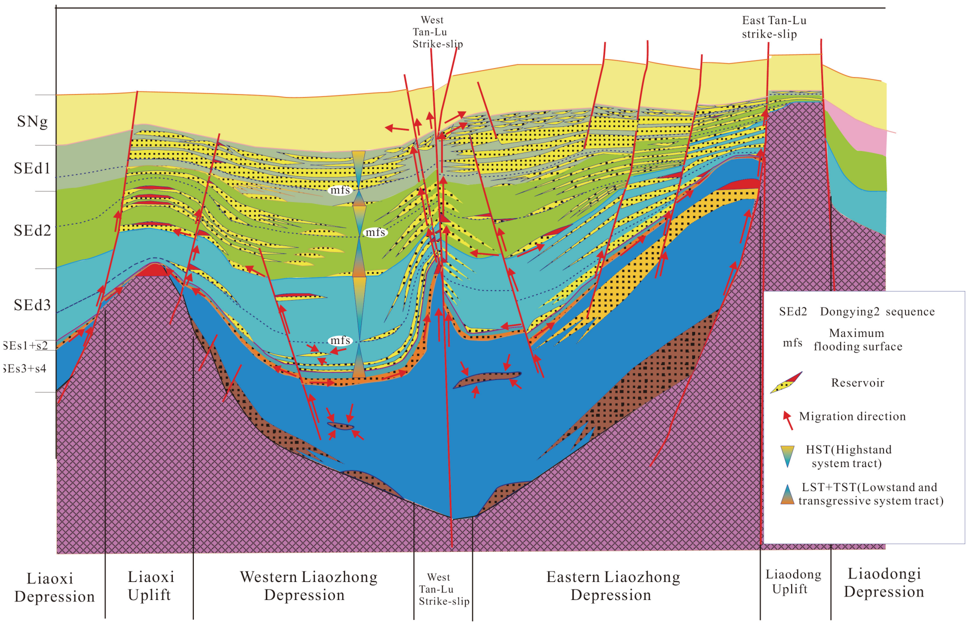

Figure 11
Hydrocarbon Accumulation Model in Liaodong Bay Sub-Basin Within Sequence Stratigraphic Framework, Showing the Tan-Lu Strike-Slip Fault Controls the Basin Structure, Stratigraphy and Petroleum System
All the Petroleum System Elements (Source Rock, Reservoir, Caprock, Trap, etc.) Were Summarized from Detailed Study on Sequence Stratigraphy, Depositional System and Stratigraphic Reservoir Prediction by Shu Jiang in 2006 for CNOOC.

The reservoir distributions vary across the study area from east to west. The eastern Liaozhong depression generally developed lowstand and highstand system tracts in the half grabens confined by extensional faults. The system tracts are mainly composed of delta and fan delta where sand bodies are deposited along the downdip of the faults, which formed a series of the structural-stratigraphic combination reservoirs. Different sand bodies were connected by faults to form ladder or "T" shaped pathways for hydrocarbon migration. Moving toward the west Tan-Lu branch, it mainly develops stratigraphic and structural-stratigraphic traps. The movement of the Tan-Lu strike-slip created a reverse structure near main slip zone and controlled the distribution of sand bodies. Stratigraphically, the delta front and turbidite reservoir rocks overlie the 3rd and 4th sequence boundaries. The sand bodies connected by the vertical faults form "tree" shaped pathways for migration. Reservoir rocks in the western part of the Liaozhong depression are controlled not only by the west Tan-Lu strike-slip branch but also by paleogeography and gradient change of the western slope in the Liaozhong depression and delta system from west. The Oligocene turbidites in Dongying 3 sequence (SEd3) in the western Liaozhong depression are sourced from east. However, the sediments of Dongying 2 sequence in the same area are derived from west and overlied the 4th, 5th and 6th order sequence boundaries. The migration pathways on the western slope of the Liaozhong depression are laterally "ladder" shaped and vertically "T" shaped consisting of unconformities, faults, sand bodies and sequence surfaces.

As a whole, the hydrocarbon accumulation habit within the sequence framework in the Liaozhong depression of Liaodong Bay sub-basin is generally attributed to the Tan-Lu strike-slip fault, which controls the structural framework, sequence stratigraphic framework, deposition process, depocenter, hydrocarbon generation, trap forming, hydrocarbon migration and entrapment.

DISCUSSIONS AND CONCLUSIONS

Comparing the Liaodong Bay sub-basin to other similar strike-slip related basins e.g. Hornelen Basin (Norway), Ridge Basin (California) and the Little Sulphur Creek basins (northern California) (Nilsen and McLaughlin, 1985; Nilsen and Sylvester, 1999), we found that strike-slip faults in Norway and California basins mainly acted as boundary faults and controlled basin development and coarse sediments distributed along the strike-slip faults in these basins (Nislen, 1999). But for the Liaodong Bay Sub-basin, the Tan-Lu strike-slip fault developed after the extensional boundary fault. Those strike-slip faults actually were superimposed on the previous rift basin. Therefore, the strike-slip fault did not control its early development of basin, but it did change the basin framework and control its depositional system distribution since it became active.

The main conclusions from this study include:

(1) The Liaodong Bay sub-basin in the Bohai Bay rift basin, which consists of the Liaoxi depression, the Liaoxi uplift, the Liaozhong depression, the Liaodong uplift and the Liaodong depression from west to east, was bisected

and reformed by the Tan-Lu strike-slip fault. Even though the current major oil and gas fields are mainly found in the Liaoxi uplift, recent wildcat discoveries show that the Tan-Lu strike-slip zone has a good potential for further hydrocarbon exploration.

(2) Seismic stratigraphic interpretation and seismic attributes analysis show that the vertical and areal characteristics of the Tan-Lu strike-slip in the Liaodong Bay Sub-basin. The Tan-Lu strike-slip in this area consists of western and eastern branches in the Liaozhong depression and close to the Liaodong uplift, respectively. The Liaodong uplift and the shallowly buried Liaodong depression were formed subsequently due to the movement of the east Tan-Lu strike-slip branch. The sequence stratigraphic framework varies from north to south and is mainly controlled by the different activities of the Tan-Lu strike-slip fault segments. The Tan-Lu strike-slip fault developed along earlier normal faults in the northern Liaozhong depression. The strike-slip formed reverse structure in western branch and superimposed obliquely on the former boundary fault in eastern branch in the central Liaozhong depression. Both branches formed reverse horst in the southern Liaozhong depression. The Tan-Lu strike-slip fault appears as linear features with associated en echelon northeastern oriented faults.

(3) Sandbody distribution in the Liaoxi uplift and western slope of the Liaozhong depression is far away from the strike-slip fault zone and not controlled by strike-slip fault; the sandbody distribution in the rest of the Liaozhong depression was influenced by the Tan-Lu strike slip.

(4) Movement of the Tan-Lu strike-slip fault in the Liaozhong depression accelerated the subsidence of the Liaozhong depression and created some structural traps for hydrocarbon accumulation. Strike-slip faulting also facilitated the deposition and maturation of the Oligocene Dongying source rocks. The paleo-topography differentiation caused by the movement of fault blocks controlled the formation and distribution of stratigraphic reservoirs. Exploration practice, geochemical analysis and petroleum system modeling show that hydrocarbon could both vertically migrate along the long-lived Tan-Lu strike-slip and associated faults and laterally migrate along sand carriers.

(5) The Tan-Lu strike-slip fault controls the areal distribution of hydrocarbon reservoirs and sequence stratigraphy controls the vertical distribution of these hydrocarbon reservoirs. Potential subtle hydrocarbon reservoirs in the strike-slip zone are turbidite sandbodies deposited on downdip of those abrupt dip changing areas. Hydrocarbon distribution model in the Liaodong Bay sub-basin can provide a reference for the prediction of hydrocarbon accumulation in eastern China basins along the Tan-Lu strike-slip fault and other similar setting areas throughout the world.

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