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Research on Fault Controlling Petroleum Accumulation in Nanpu Sag

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Abstract

This paper analyzed the factors controlling hydrocarbon accumulation associated with fault evolution, and pointed out favorable exploration directions by establishing pattern of fault controlling petroleum accumulation. Research showed that positive local structural belts were favorable positions for hydrocarbon accumulation; While the juxtaposition thickness of Ed_2 caprock was less than 90-95m, hydrocarbon could penetrate the caprock and accumulate in middle-shallow layers; mode Ⅴ and Ⅵ fractures were oil source faults, intersected faults are the preponderant pathways of hydrocarbon vertical migration, hydrocarbon flowed to reservoirs with sand content of more than 20%; Strong fault sealing ability was necessary for hydrocarbons of injecting into fault trap to accumulate and be preserved; Positive local structural belts, which are related to mode Ⅴ and Ⅵ fractures, with caprock juxtaposition thickness of less than 90-95m, high sand content and good fault lateral sealing ability, were oil exploration targets and directions of middle-shallow layers.

Keywords: *fault, fault controlling petroleum accumulation, hydrocarbon accumulation model, nanpusag*

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1. Introduction

NanpuSag, locating in north-central of Bohai Bay Basin, consists of land and shallow water areas. There are 11 NE and NW trending fault structure zones caused by late fault tension-torsional formation [1], including Xinanzhuang, Bogezhuang, Gaoliu, Nanpu No. 1, northern Nanpu No. 2, southern Nanpu No. 2, Nanpu No. 3, Nanpu No. 4, Nanpu No. 5-Laoyemiao, northern Nanpu No. 5, and southern Nanpu No. 5 fault structural belts (Figure 1). There are several oil fields are discovered around the fault structure zones, including Liuzan, Gaoshangbao, Laoyemiao, Tanghai, Beibao and Nanpu (Nanpu No.1, No.2, No.3, No.4 and northern Nanpu No. 5 oil fields) oil fields. From base to top, the strata of NanpuSag are Shahejie, Dongying, Guantao, Minghuazhen Formations, and Quaternary layers (Figure 2a). Among them, Es_3 and Es_1- Ed_3 Formations are the main source rocks [2-4], Es_3, Ed_2 Formations, and Nm_s- Quaternary layers are three regional caprocks. Three sets of petroleum systems are finally formed in the late hydrocarbon migration and accumulation period [5-6].

The complicated lateral and vertical distribution features of oil and gas in Nanpu Sag are closely related to the superposition and deformation of “multi-phase and multi-attribute” faults. The evolution of these faults can be divided into three stages, include continuous extensional deformation during Es_3-Es_2 rift period, strike-slip extensional deformation during Es_1-Ed transitional period of rift and depression, and tensor-shear deformation during Nm-Quaternary depression period [7]. Severe deformation of faults happened in Es_3 Formation sedimentary period (early stage), late Ed_1 Formation sedimentary period (middle stage), and late Nm_s-Quaternary layers sedimentary period (late stage) [8].

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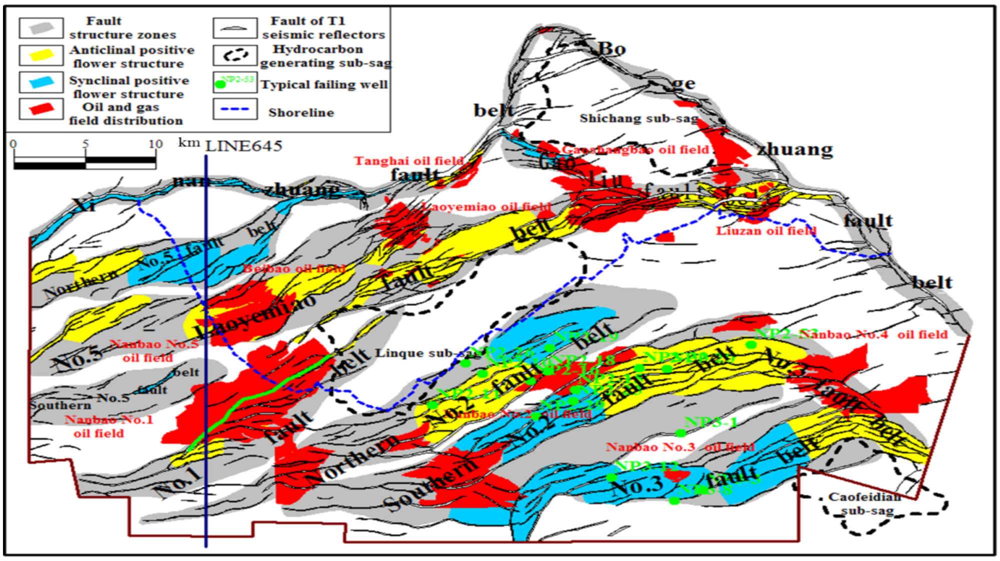


Figure 1. Diagram of Tectonic Location, Generating Hydrocarbon Sags, Fault Concentrating Belts, and Hydrocarbon Distribution

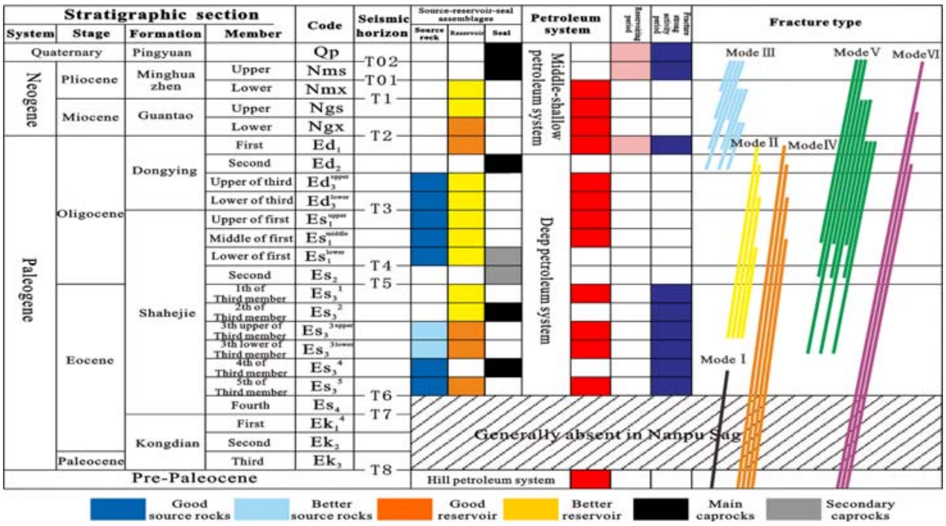
Six kinds of faults can be distinguished from the profiles in Nanpu Sag (Figure 2), which are extensional fault in early stage (mode I), strike-slip extensional fault in middle stage (mode II), tensor-shear fault in late stage (mode III), fault with extension in early stage and strike-slip extension in middle stage (mode IV), fault with strike-slip extension in middle stage and tensor-shear in late stage (mode V) and fault with early stage, strike-slip extension in middle stage and tensor-shear in late stage (mode VI). Influenced by vertical connectivity of various multi-phase faults, hydrocarbon accumulation sealed by different seal differs greatly in different oil-rich area (Figure 2a). The discovered oil and gas spread annularly around the hydrocarbon generation depressions (mainly mean Linque sub-sag and Shichang sub-sag), but petroleum accumulation in tectonic belts with similar distribution features with hydrocarbon generation depressions is varied. To reveal the lateral and vertical distribution rule of oil and gas, focusing on the effect of faults, by using 3-D seismic data and log information this paper studies the shallow and deep petroleum system. The control of faults on the migration, accumulation and distribution of oil and gas is analyzed systematically [9]. Hydrocarbon accumulation models controlled by faults are established and favorable exploration targets are put forward. This paper provides basis for the exploration in the other petroleum-rich areas similar to Nanpu Sag in Bohai Bay Basin.

2. Faults Impact to Hydrocarbon Accumulation and Distribution

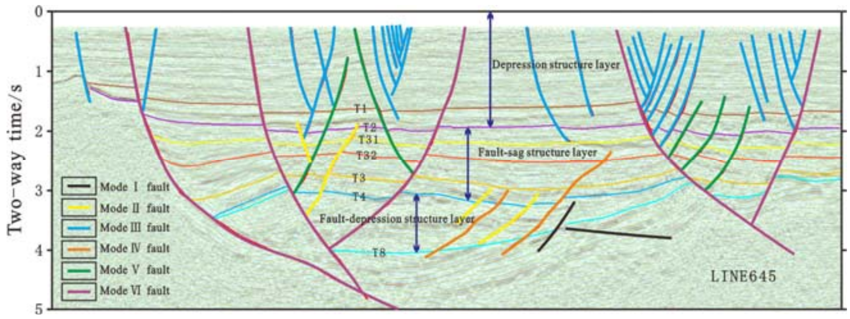
2.1. Positive Local Structural Belts Indicate the Accumulation Horizon of Hydrocarbon

Large-scale oil and gas migration and accumulation happened in NanpuSag during late of Nm Formation sedimentary period to Quaternary period, which correspond to the period of last fault tensor-shear formation, traps typed at last in this period [10]. A serial of NE and NW arrayed fault structure zones, distribute around Linque, Shichang, and Caofeidian sub-sags, were formed in this period. Fault structure zones, high points of the structure, which promote hydrocarbon primarily migration towards lower fluid potential area, are the favorable zones of oil and gas accumulating.

However, positive local structural belts are the most favorable areas of petroleum enrichment. Statistics show that there are three kinds and six patterns of local structural belts developed in fault structure zone (Figure 3). Three kinds of local structural belts include horst - graben structure, negative flower structure, and fault-terrace belts, while six patterns of local structural belts include horst or half horst, graben or half graben, anticlinal positive flower structure, synclinal negative flower structure, anticlinal fault terrace, and synclinal fault terrace. Positive local structural belts of anticlinal positive flower structure, horst or half horst, and synclinal fault terrace are the main enrichment areas of the hydrocarbon, while the drilling failure rate of traps in negative local structural belts is relatively high (Figure 1, Figure 3). Hence, the positive local structural belts are favorable hydrocarbon accumulation areas, especially anticlinal negative flower structures, which is controlled by late fault tension-torsional formation [11], are the most favorable accumulation areas for oil and gas.



a. Characteristic of Petroleum System, Pool-Forming Time, Fracture Mode and Activities



b. Division of Tectonic Layers And Fracture Types (The Profile Position Is Shown In Figure 1)

Figure 2. Drawings of Hydrocarbon Vertical Distribution Regularity and Fracture Types

2.2. Combined Effect of Faults and Caprocks Controls the Hydrocarbon Accumulation Horizons

Oil and gas vertical distribution is mainly controlled by regional seal rocks [12, 13]; fault activities often caused caprocks damage which results in the complex hydrocarbon distribution. The destructiveness of fault to caprock mainly depends on the fault scales in seal rocks [14]. The larger the fault scale, the bigger the fault displacement is, the larger the degree of caprocks dislocated is, which cause the caprocks blocking effect become weaker, and hydrocarbon can migrate into shallower layers much easier. In order to better understand the relationship of seal destruction degree and hydrocarbon accumulation, this paper calculates the seal juxtaposition thickness (juxtaposition thickness equal to seal thickness minus fault displacement, if the value is negative, standing for seal completely staggered by faults). Ed_2 seal juxtaposition thickness statistics of 42 wells show that when the juxtaposition thickness is larger than 90-95m, oil and gas accumulated in the reservoir beneath the Ed_2 regional seal; While the juxtaposition thickness is less than 90-95m, the fault displacement is relatively large, the destructiveness of fault to caprock is large, hydrocarbon expelled from source rocks or the early accumulated hydrocarbon penetrated the Ed_2 seal formation and migrated into shallower layers forming oil and gas reservoirs. For Nm_s-Quaternary seal layers, late fault activities results in small fault scale, the thickness of fault displacement is 100-150m, while the thickness of seal layer is 800-1000m, so the juxtaposition thickness is large, with shallow burial depth and strong plasticity, the destructiveness degree of fault to caprock is small, so seal layer can effectively block hydrocarbon vertical accumulation. Because the Ed_2 seal layer is thick and integrated, oil and gas are enriched mostly in middle-shallow layers of Nanpu Sag.

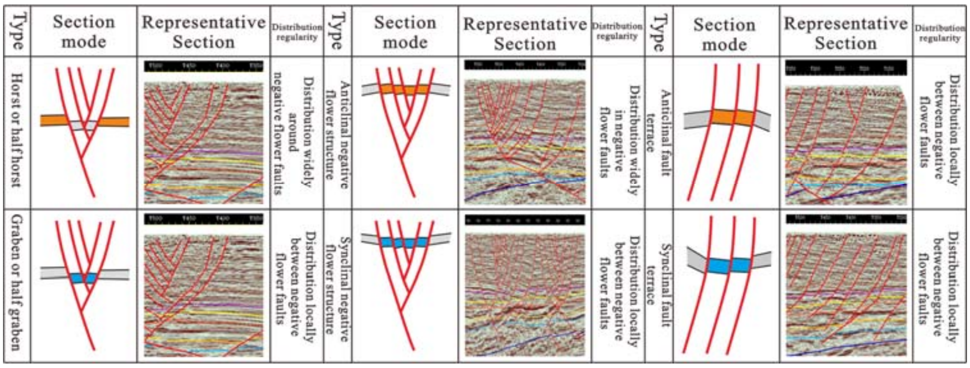


Figure 3. Section Configuration Drawings of Local Structural Belts in Nanpu Sag

2.3. The Type and Composite Mode of Faults Control Hydrocarbon Vertical Migration

Only faults which acted during the key reservoir-forming periods can be the mainly migration pathway. Oil exploration practice shows that the main oil and gas migration and accumulation periods are the late of Nm Formation to Quaternary layers sedimentary period. During this period, the active fault types are mode Ⅲ, Ⅴ, and Ⅵ. Mode Ⅲ fault, which did not penetrate the source rock, is not oil and gas migration pathway, can be the fault trap boundary to block hydrocarbon migration and accumulation; Mode Ⅴ and Ⅵ faults, two and three period activities, penetrate the source rocks of Es_1- Ed_3 and Ed_3 Formations, are the main oil and gas migration pathways (Figure 4a). However, not all of the penetrated are effective oil and gas migration pathways. Statistical results of the control fault assemblage types show that the relationships of intersecting fault assemblage types and hydrocarbon vertical migration are close, and indicate that fault intersections are the favorable channels of hydrocarbon vertical migration (Figure 4b). Fault intersections are the position of large dependent variable, stress and deformation concentration, which can control oil and gas vertical migration. Oil and gas migration pathway estimated by using nitrogen compounds also shows that fault intersections are usually the favorable channels of hydrocarbon migration [15].

2.4. Paleo-transition Zone Controls Reservoir Sand Content and Effects the Hydrocarbon Migration along this Area

Vertically migrating along the faults of oil & gas largely depend upon the sand content of reservoir, the higher the sand content, the reservoir physical properties are better, and the hydrocarbon injection intensity is stronger. The reservoir sand content is generally larger than 20% in successful oil layers through the statistics of main oil and gas production members in 18 wells, while the reservoirs with sand content less than 20% are no or bad oil bearing layers. The physical properties of Ed_1 Formation are better, so the discovered oil and gas are mainly in this layer.

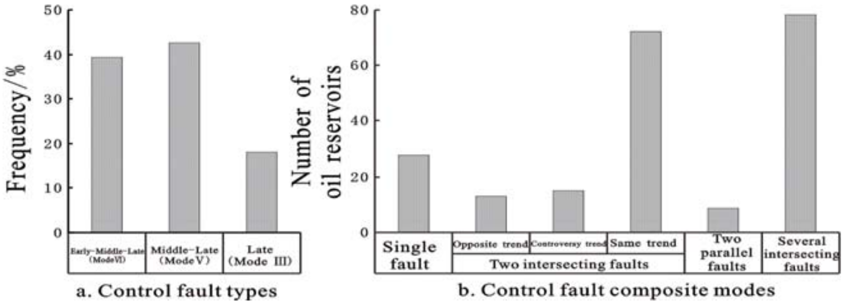


Figure 4. Statistical Histograms of Types and Composite Modes of Control Faults in Nanpu Sag

Reservoir physical parameter is influenced by the distribution of sedimentary facies. From the displacement-distance curve of Nanpu No.1 structure (Figure 5a), faults of late Ed period developed in segment, the joint of segment is also the transition zone of Ed_1 Formation sedimentary period. This paper use diagram of Ed_1 deposition facies calibrate the seismic profile (Figure 5b), the location of paleo-transition zone lies to the distributary channel, and the distributary channel has the trend of divaricating along the strike of fault downthrown block. Influenced by river parting, Well NP103x1 locates in inner channels, Ed_1 reservoir with high sand content and good physical parameter, and industry oil flow was obtained in this well. And the Well NP1-9 is relatively away from the Nanpu No.1 structure, influenced by the river parting, the well lies in the shallow lake sedimentary zones, the Ed_1 reservoir of this well with low sand content and bad physical parameter, and drilling indicates that this formation is water layer.

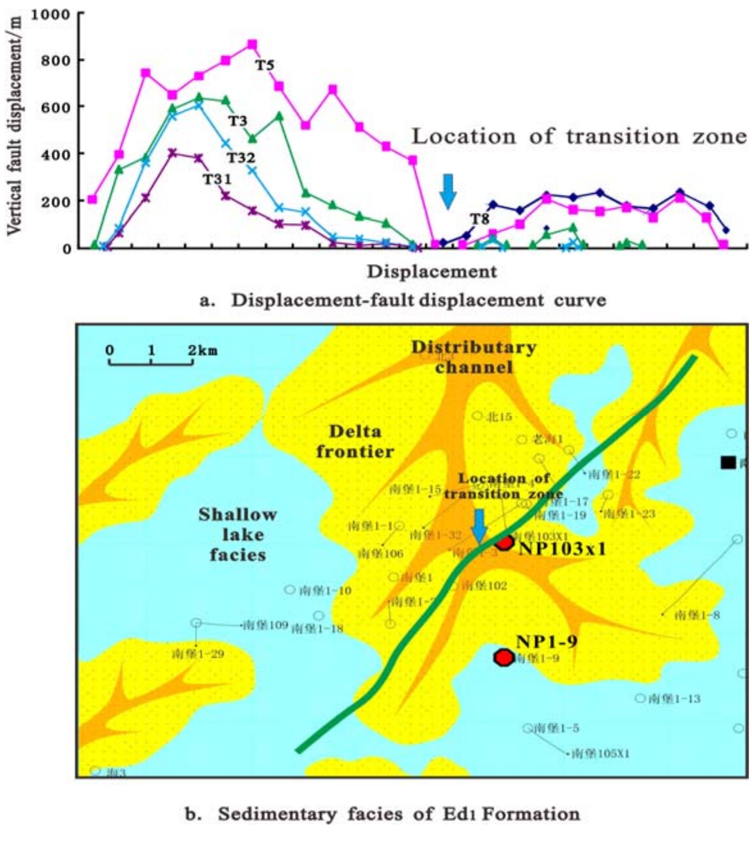


Figure 5. Relationship Diagram of Nanpu No.1 Fault Growth and Sedimentary Facies during late Ed_1 Formation Sedimentary Period

Synthesizes the above analysis, fracture development controls the forming of paleo-transition zone, the location of transition zone influences the direction of flow in distributary channel, resulting in the variable sand contents in different parts of the same layer, and finally influencing the regularities of oil & gas vertically migrating along the faults.

2.5. Fault Lateral Sealing Ability Controls Hydrocarbon Accumulation and Preservation in Traps

Oil & gas accumulation is controlled by the lateral sealing of faults. The activities of faults controlling traps during the late of Nm Formation sedimentary period to Quaternary period are the results of multistage pulsing activities. Influenced by fault multistage dislocations and the constantly accumulating fault displacement, the lateral-sealing property of faults developed with the evolution of faults. Fault traps are effective with only strong fault sealing property, drilling risks are relatively small. By using back stripping technology of fault displacement, SGR (Shale Gouge Ratio) method, which can evaluate lateral-sealing property of faults [16-18], is chosen in this paper to evaluate the failing fault traps fault lateral-sealing property during the late Nm period and present. Through the evaluation of 69 layers from 27 wells of failing fault traps in south Gaoliu structure, the first to five zones of Nanpu No. 1 structure, Nanpu No. 2, No. 3, No. 5 structures, there are 38 failing fault traps caused by bad fault lateral-sealing property. Among them, there are 32 failing traps have bad present sealing property, amounting to 46.38% of the total failing fault traps, 6 failing traps have bad paleo-sealing property, amounting to 8.7% of the total failing fault traps, there are 14 failing traps caused by undefinition of traps, amounting to 20.29% of the total failing fault traps, and there are 17 failing traps caused by other reasons (analysis of above contents), amounting to 24.64% of the total failing fault traps. Hence, through data comparison, it is found that fault lateral-sealing property is the key factor of large oil and gas pools accumulating in fault traps.

3. The Hydrocarbon Accumulation Model of Fault and Exploration Directions

There are two main stages of petroleum migration and accumulation in NanpuSag, including the end of Ed Formation and the late of Nm Formation to Quaternary period, most of hydrocarbon pools formed in the later stage [10]. During the later stage, the source rocks of Es_1–Ed_3 Formations reached to the peak of oil generation, and source rock of Es_3 reached effective stage of gas generation. The vertical oil and gas migration was carried out by passing through the fault and their lateral migration and accumulation were realized along sand bodies. Much oil and gas of vertical migration pierced the Ed_3 caprocks with small juxtaposition thickness, migrated and injected into shallow layers. Under the caprocks blockage of Nm_s - Quaternary Formations and reservoirs of Ed_3–Ng–Nm_x Formations with high sand content, hydrocarbon accumulated in positive local structural belts and formed middle-shallow petroleum system (Figure 6). After fracture deformation of Nm_s-Quaternary periods, there are six types of faults developed in NanpuSag. Mode Ⅰ, Ⅱ and Ⅳ faults are not active, are important seals for petroleum lateral migration and accumulation. Mode Ⅴ and Ⅵ fractures are long-term active, influenced by most faults, the juxtaposition thickness of Ed_2 caprock is less than 90-95m, which becomes main migration pathways of the vertical oil and gas migration. Mode Ⅲ faults are new formed with small size, which cannot communicate source rock layers, so these faults act as lateral-sealing structures.

Based on the above analysis, it could be concluded that positive local structural belts are favorable positions for hydrocarbon accumulation. For deep layers, positive local structural belts, which are related to mode Ⅰ, Ⅱ and Ⅳ fractures, with high sand content, or are related to mode Ⅴ and Ⅵ fractures, the juxtaposition thickness of Ed_2 caprock is more than 90-95m, with high sand content, are oil exploration directions; In middle-shallow layers, positive local structural belts, which are related to mode Ⅴ and Ⅵ fractures, the juxtaposition thickness of Ed_2 caprock is less than 90-95m, with high sand content and good fault lateral sealing ability, are oil exploration targets and directions.

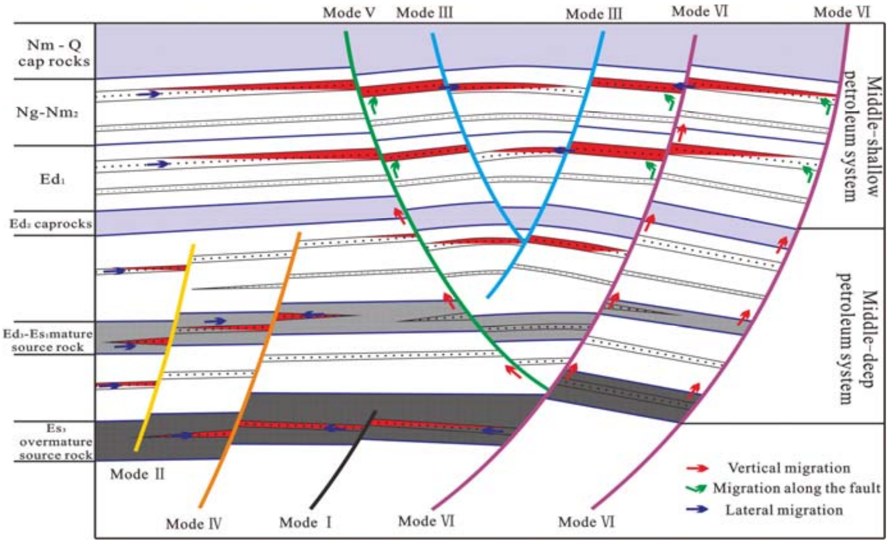


Figure 6. The Mode Chart of Hydrocarbon Migration and Accumulation along Faults during Efficient Reservoir Forming Period in Nanpu Sag

4. Conclusion

(1) Fault zones around hydrocarbon-producing sag of NanpuSag, the favorable belts for oil and gas accumulation, are higher positions of structure, and petroleum usually accumulates in the positive local structural belts. Caprocks and faults control the accumulation horizon of hydrocarbons. While the juxtaposition thickness of Ed_2 caprock is less than 90-95m, destructiveness of fault to caprock is big, hydrocarbon can penetrate the caprock and accumulate in the middle-shallow layer.

(2) Mode Ⅴ and Ⅵ fractures are long-term active, and intersected faults are the preponderant pathways of hydrocarbon vertical migration. Under the influence of the mechanism of fracture development and sand body controlling function of paleo-transform zone, hydrocarbon flows to reservoirs with sand content of more than 20%. Strong fault sealing ability is necessary for hydrocarbons of injecting into fault trap to accumulate and be preserved.

(3) For middle-shallow layers, positive local structural belts, which are related to mode Ⅴ and Ⅵ fractures, the juxtaposition thickness of Ed_2 caprock is less than 90-95m, with high sand content and good fault lateral sealing ability, are oil exploration targets and directions.

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