Characteristics of hydrocarbon transport systems and migration in slope areas of Qikou Sag, Bohai Bay Basin

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Abstract. The transport system plays an important role in hydrocarbon accumulation in slope area. The geochemical characteristics of the reservoir indicate that the oil and gas in this area generally have the tendency of migration and accumulation from the hydrocarbon generation center to the high part of slope. According to the relationship between source kitchens and traps, the hydrocarbon migration is divided into three types: inside source accumulation, near source vertical migration and outside source accumulation, controlled by the differential pressure between source rock and reservoir, dominant pathway-cap assembly and dominant migration phase respectively. The main types of migration pathway in the slope area are sand bodies, faults and unconformities, and the matching relationship between them controlled the direction and mode of oil and gas migration and accumulation in the slope area. The hydrocarbon migration and accumulation of middle-shallow layer in the low-middle slope are controlled by the dominant pathways and the matching relationship between faults and cap rocks, the hydrocarbon migration and accumulation in the middle slope are controlled by the favorable sedimentary facies, and the hydrocarbon migration and accumulation in the high slope are controlled by the distribution of sand bodies and favorable structures.

1. Introduction
The slope area is located between the uplift and sag, with a wide area and rich types of sedimentary systems. It is the main region for sand aggregation and control in faulted lake basins with various structures and high-quality transport systems, forming the complex accumulation of hydrocarbon distribution pattern. In addition to structural oil and gas reservoirs, non-structural reservoirs such as stratigraphic, lithologic and structural-lithologic reservoirs developed in the slope area have become important targets for fine secondary exploration in oil-rich sag 1,2. Based on fault activity characteristics and the structure of slope, the slope area can be divided into step-style faulted slope, step-style flexure slope, normal slope and rotate-tilted slope. For each slope, the source rock distributions, sedimentary systems and reservoir types are distinctly different in the space, which can also be divided into three parts, high slope, meddle slope and low slope respectively 3,4.

Qikou sag is one of the main oil-rich depressions in the Huanghua depression. Two suites of major hydrocarbon source rocks were developed in the third member of the Shahejie Formation(Es3) and the first member of the Shahejie Formation(Es1), and two suites of secondary source rocks were
developed in the second member of the Shahejie Formation (Es2) and the Dongying Formation (Ed). Multiple oil bearing series have been found in Minghuazhen Formation (Nm), Guantao Formation (Ng), Ed, Es1, Es2, Es3, Mesozoic strata (Mz), Permian strata and Ordovician strata (O) by the year of 2005, and many industrial oil and gas enrichment regions have been found such as Chenghai, Beidagang and Banqiao areas. The degree of resources to be proved is up to 45%. As a typical terrestrial rift-subsidence lacustrine basin in eastern China, Qikou sag is characterized by a compound half-graben rift structure with more subsags and less bulges, and a wide range of slope zones, accounting for more than 70% of the total area of the sag, including five major slope areas such as Qibei (step-style flexure slope), Banqiao (rotate-tilted slope), Qinan (normal slope), Chenghai (step-style faulted slope), Beitang (normal slope). The slope areas that adjacent to the hydrocarbon generation subsags control the distribution of sand bodies, and are located in the low potential area for long time, which are the main direction of oil and gas migration, forming large and superimposed lithologic-stratigraphic reservoirs enrichment areas controlled by the main hydrocarbon generation area. As the exploration work continuous, the lithologic-stratigraphic traps away from sources have become one of the main targets of exploration. However, due to the complex and diverse types of transport systems in the slope area, the analysis of the control effect of transport system on hydrocarbon migration and the study of the types of transport systems that play a major role in different regions have become the main problems for the next exploration in the Qikou Sag slope area. In this paper, the reservoir geochemical method is used to prove the migration direction, and the oil and gas migration mode of slope area is established. Combined with the characteristics of oil and gas transport system, the control effect of hydrocarbon migration on hydrocarbon accumulation is analyzed to provide a basis for finding new oil and gas target blocks.

2. Hydrocarbon migration direction in slope areas
The Qikou sag includes five major hydrocarbon generation subsags, such as the main sag of Qikou, the Qibei subsag, the Banqiao subsag, the Beitang subsag and the Qinan subsag. The main source rocks, the third member of the Shahejie Formation and the first member of the Shahejie Formation, tend to become thinner from the center of the sag to the margin, leading to a similar tendency of the hydrocarbon generation intensity, that becomes lower from the center to the margin (Figure 1). Based on the basin scale, the oil and gas generated from the source kitchen will have a trend of flowing along the potential energy from high to low due to the change of potential energy\(^5\). The effective source rocks in the updip area of the slope are gradually thinner and are all in low-potential distribution areas, so the hydrocarbon should have a tendency to migrate from the center of the sag to the high part of the slope\(^6\). The geochemical characteristics of oil and gas have undergone a series of changes during the migration process. And through the change of such elements, the laws and characteristics of hydrocarbon migration could be revealed.

![Figure 1. Location of the Qikou Sag and the distribution of source rocks and hydrocarbon](image)
The physical properties indicate that various physical parameters of the crude oil in Qikou sag vary greatly, but it is generally low-sulfur and medium-high-waxy crude oil, and the physical properties are mainly controlled by the preservation conditions and maturity. The density, viscosity, sulfur content, resin and asphaltene contents decrease with increasing depth vertically, whereas the wax content and freezing point increase with depth. The physical properties of crude oil have larger difference in different depths or regions with different structural conditions in the same area, but the density and viscosity of crude oil in the same layer generally show an increasing trend from center to high parts laterally. Taking the Banqiao slope area as an example, the density of crude oil in the low slope is basically less than 0.870 g/cm³, and the viscosity is below 5 mPa·s, which is light oil with low viscosity. Most of the crude oil in the middle slope is also light oil with low viscosity, but some of the crude oil has large density and viscosity, which is medium oil with medium-high viscosity, and even a small amount of heavy oil. But the proportion of light oil in the high slope is greatly reduced, while the proportion of heavy oil is increasing rapidly (Figure 2). In fact, the crude oil generated in the early stage of the deposition of Es3 has migrated over a long distance to the high slope area for accumulation, and altered after multiple migration and accumulation. The density and viscosity of the oil are relatively large, and the oil-bearing formations are also gradually becoming new as the migration distance becomes longer. However, the hydrocarbon generated by the deep buried high-maturity source rocks now have the characteristics of late in situ accumulation or near-source lateral or vertical migration and accumulation.

3. Characteristics of hydrocarbon transport systems

The transport system is the most critical part of hydrocarbon migration from the source area to the trap away from the source rock. The transport system refers to the spatial combination of the oil and gas migration pathways connecting source rocks and traps, and the migrating capability determines the quality of the transport system[7]. Practices indicate that the secondary migration of oil and gas only takes up limited routes within dominant transport pathways, which is an extremely inhomogeneous process[5,8]. Therefore, the migration and enrichment laws of hydrocarbon accumulated locally in the outside source area are mainly controlled by the transport system. The main elements of the transport system in slope areas of the Qikou sag include permeable sand bodies, faults and unconformities.

The sand bodies are not only the reservoir of continental basins but also the basic pathways for secondary migration of hydrocarbon. The higher the degree of development, the better the type and the stronger the connectivity of the sand bodies, the more they can act as hydrocarbon transport paths.
Hydrocarbon migration and accumulation in the high slope area are mainly controlled by the groove sand bodies. The groove is the main transport channel for the clastic sediments from the uplift provenance, and the deposited sand body within it is also an important reservoir for oil and gas. The deposition of sand bodies in the middle slope area is mainly controlled by the slope break belt, and the sand bodies are enriched in the slope flat where the slope changed from steep to gentle, constituting significant hydrocarbon multiple transport systems with faults and unconformities. While the low slope area is located in the hydrocarbon generation region, and the generated hydrocarbon is primarily charging into the high-quality reservoirs such as the main groove sand bodies. For the widely developed fault-lithologic traps in slope areas, the hydrocarbon migration and accumulation is notably controlled by the configuration relationship between faults and sand bodies. Especially in middle slope areas where sand bodies are relatively developed, the transport system is dominated by faults and sand bodies compound. The unconformity is of great significance for the formation of stratigraphic reservoirs in high slope areas. It has evident characteristic of regional distribution, which can connect the strata of different ages and different lithologies, so that oil and gas can transport over long distances to the strata of high slope areas outside the source and accumulate in stratigraphic or other types of traps.

4. Hydrocarbon migration models
The range of slope areas of the Qikou sag is the gentle slope zone between the pinch-out line of the Paleogene strata near the bulge and the boundary of the main sag or subsags. The types of traps developed in the slope areas are complex and diverse. In addition to structural traps, stratigraphic traps and lithologic traps, combination traps such as structural-lithologic traps are also developed. As the major source rocks, Es3 and Es1 are continuously buried, mature and expelling hydrocarbon, the migration models in slope areas of the Qikou sag can be divided into three types according to the relationship between source kitchens and traps and hydrocarbon accumulation characteristics, which are near-source vertical migration and accumulation, inside source accumulation and outside source accumulation (Figure 3).

![Figure 3](image-url)

**Figure 3.** Characteristics of hydrocarbon migration and accumulation in different parts of the slope area of Qikou Sag (Position of the section is shown in Figure 1)

Low-middle slope areas are adjacent to the deep depression areas, with high quality source rocks, and lithologic traps are developed in the lower parts. The abnormal pressure existing in the deep of the Qikou Sag is the main driving force of hydrocarbon migration, forming self-generation and self-accumulation lithologic reservoirs through pathways such as high-pressure micro-cracks, connected pores of in-source permeable sand bodies, and micro-bedding planes. Or hydrocarbon laterally migrated for only a short distance under buoyancy and accumulated near source to form the inside
source accumulation model, which is affected by the pressure difference between source rock and reservoir, and hydrocarbon tend to be enriched in reservoirs with relatively low potential energy. The sand bodies in middle slope areas are relatively more developed and distributed in strip-shape, which generally matching with the fracture trend at a high angle. Therefore it has favorable conditions for forming fault-lithologic traps in middle slope areas. The hydrocarbon migration is dominated by vertical transport, and it migrates along the source faults to the middle and shallow layers under the action of fluid potential difference and buoyancy. As a result, it forms the near-source vertical migration model. Controlled by the fault-caprock matching relationship, the hydrocarbon migrates generally along the limited pathways of source faults and accumulates in the effective traps that matching the pathways. While in high slope areas, hydrocarbon migrates laterally mainly along sand bodies and unconformities outside the source area, and adjusts along the fault to shallow layers as supplement. Hydrocarbon migrates along sand bodies and faults step by step under the action of buoyancy to layers or structural traps of high parts, thus forming the outside source accumulation model. Controlled by dominant sand bodies, hydrocarbon is mainly enriched along the dominant migration and accumulation facies.

5. Conclusions
The oil and gas of Qikou sag generally have the tendency of migration and accumulation from the hydrocarbon generation center to the middle-high part of the slope. Hydrocarbons generated in early stage have migrated over a long distance to the high slope area for accumulation. While Hydrocarbons generated late has the characteristic of self-generation and self-accumulation, accumulating in the middle-low part of the slope area. According to the relationship between source rocks and traps and characteristics of hydrocarbon accumulations, the migration models in slope areas of the Qikou sag can be divided into near-source vertical migration and accumulation, inside source accumulation and outside source accumulation. The transport system in slope areas of the Qikou sag consists of permeable sand bodies, faults and unconformities. The secondary migration of oil and gas in each part of the slope area is controlled by the development characteristics of different transport systems. The transport pathways in the middle and low slope areas are primarily source faults together with connected sand bodies. And the transport pathways in the high slope area are primarily connected sand bodies together with unconformities, while the faults play a secondary role for adjusting.

References
[1] Zhou L, Xiao D, Pu X and Li H 2010 New pattern of composite superimposed reservoirs and advantageous phase accumulation in continental rifted lake basin: A case study from Qikou Sag of Bohai Bay Basin Lithologic reservoirs 22(1) 7
[2] Zhao X, Jin F, Li Y, Wang Q, Zhou L, Lv Y, Pu X and Wang W 2016 Slope belt types and hydrocarbon migration and accumulation mechanisms in rift basins Petroleum exploration and development 43(6) 841
[3] Li H, Dong Y, Wang G, Dong D and Wnag L 2013 The mechanism and regularity of hydrocarbon accumulation of the lithologic reservoirs in the slope region of Qikou Sag Special Oil and Gas Reservoirs 20(3) 19
[4] Zhao X, Zhou L, Pu X, Xiao D, Jiang W, Han W, Chen C, Zhou L and Guo S 2017 Hydrocarbon enrichment theory and exploration practice in the slope of fault lake basin—a case study of Paleogene in Huanghua depression China Petroleum Exploration 22(2) 13
[5] Luo X, Lei Y, Zhang L, Chen R, Chen Z, Xu J and Zhao J 2012 Characterization of carrier formation for hydrocarbon migration: concepts and approaches Acta Petrolei Sinica 33(3) 428
[6] Li Y, Liang H, Hu Y, Li Z, Chen H and Li J 2004 Hydrocarbon secondary migration modes in Chengbei ladder fault zone in Bohai Gulf and their effects on exploration Journal of Xi’an Shiyou University ( Natural Science Edition) 19(1) 19
[7] Jiang Y, Liu J, Li X and Xu H 2011 Actual Hydrocarbon Migration Paths Based on Ridge-Like
Structures Analysis and Geochemical Indicators Tracking: A Case Study of Puwei Area of Dongpu Depression *Earth Science* 36(3) 521

[8] Jiang Z, Pang X, Zeng J, Wang H and Luo Q 2005 Research on types of the dominant migration pathways and their physical simulation experiments *Earth Science Frontiers* 12(4) 507