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Research Article

Petroleum Exploration System Based on Main Migration Pathway and Nanohydrocarbon

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Nanohydrocarbon is a new concept for oil accumulation mechanism, and oil can be found in nanosized pore throats. At Qikau Sag, the source and reservoir are found coexisting along the slopes of this basin. It is a complex process for nanopores to converge into the reservoir. Source-control theory and multiple oil-gas accumulative zone theory are the efficient petroleum exploration theories in the areas of low-middle developed exploration degree in the continental basin, but they are not suitable for middle-high developed exploration areas. For this reason, in this research work, the theory of the Petroleum Exploration System based on main migration pathway and nanohydrocarbon is proposed. In complex middle-high developed petroleum exploration area, we focus on the premise of determining the source and use the abundant data of seismic, logging, coring, analysis and testing, production performance, and a large number of research results of predecessors, to detect the geometry of the main migration channels of oil and gas and to make clear migration trajectory of oil and development history of traps, track clues, and dig the optimization exploration areas based on the assessment condition. The risk for petroleum exploration in a new area can be minimized and led to the utmost advantage of exploration by using this option.

1. Introduction

Recently, nanohydrocarbon has become an important area of research. Oil and gas are exhibited in nanosized pore throat, especially for the coexisted source with reservoir. A more detailed hypothesis for framework accumulation of nanometer hydrocarbon was put out. It is considered that the migration of nanohydrocarbon may be similar to the mineralization of solid nano-ore-forming materials, that is, the effect of structural mineralization and accumulation. Hence, we can research it by systematically thinking, such as Metallogenic System Theory, tied with resource, transportation, channel, and storage. The ability to transport nanoparticles has interesting applications [1]. The nanosized pore throat is a new view for the source [2], but the channel is more important. Therefore, Petroleum Exploration System is based on the main migration pathway and nanohydrocarbon.

Vertical pathways and migration paths are the two most common components of shallow plumbing systems [3]. Faults provide the best potential vertical migration routes in many petroleum basins, but the same faults must also provide lateral migration obstacles for reservoirs to form legitimate traps. This duality of fault behaviour was examined [4, 5], and one proposed explanation was that vertical leaking may be temporary and limited to active faulting periods, whereas static 60 lateral sealing would be the norm during inactive fault activity. In terms of migration and accumulation properties, a PS can be classified into several petroleum migration–accumulation systems [6].

Alipour et al. [7] discussed the concept of the Petroleum System. In recent years, a lot of studies pay attention to investigating the Petroleum System [8–13]. But, some questions are in suspense, such as the hydrocarbon accumulation process is challenging [14]. The issue of accumulation and migration of oil and gas in carrier systems is always a

difficult subject in petroleum research [15–17]. Petroleum exploration technologies made an important contribution to the development of the Chinese petroleum industry, but they are not aiming at the direct target of petroleum exploration—the oil-gas reservoir. Source-control theory and multiple oil-gas accumulative zone theory are the efficient petroleum exploration theories in the areas of low-middle developed exploration degree in the continental basin. They have played very important roles in the enhancement of exploration efficiency and the addition of oil-gas reserves and output in the development history of the Chinese petroleum industry, but they have a lot of limitations and nonadapt abilities in the areas of middle-high developed exploration degree. In light of the characteristic of oil-gas exploration in the areas of middle-high developed exploration degree in the continental basin, the authors put forward a new theory "Petroleum Exploration System Based on Main Migration Pathway and Nanohydrocarbon." The theory connotation is that the spatial distribution location and the scale of oil and gas reservoir are controlled by the type, location, and transition ability of the main migration path. The theory is relatively systematically discussed in this paper; the plane distribution model scheme of the oil-gas main migration path's origination and the seven types of oil-gas reservoir models' formation are all based on the "main migration path controlling hydrocarbon theory." So long as to ascertain the oil gas main migration path, people can find out the oil-gas reservoirs located near or in the main migration path and select a proper target oil-gas reservoir to drill. In this way, the oil-gas exploration risk will be reduced greatly, the successful ratio of oil-gas exploration boosted maximally, and the oil and gas exploration effect enhanced.

2. Nanohydrocarbon

Nanohydrocarbon is tied with unconventional hydrocarbon; it is focusing on nanosized pore throats. Nanohydrocarbon exists in poor phase separation and percolation; they are controlled by pressure and subjected to pervasively and continuously coexisting. Considering the accumulations, there are coexisting sources and reservoirs in Qikau Sag, Bohai Bay. Nanohydrocarbon accumulated between nanosized pore throats. Pore-throat diameter of oil and gas is even locally developed micrometer-sized pores. Nanohydrocarbon consists of four features, including a few industrial production capacities for a single well, coexisting source and reservoir, nonbuoyancy accumulation, and short-distance migration.

An in-depth understanding of nanohydrocarbon resources, the invisible trap, and the main migration pathway is the key idea through the theoretical research on the gas accumulation mechanism and hydraulic fracturing. The trap is the most favorable enriched position for the gas and results closely from the tectonic stress, regional structural background, and petrological properties. Under the action of the tectonic stress, the strata of the shale and low permeability sandstone have no significant deformation and only structural fractures are produced. The oil and gas reservoir is accumulated in the formed interconnected fractures and pores in the above microsize opening. The shale gas reservoir is generated from the action of the buoyancy on the above pores; on the contrary, the nanopores are not connected and are unable to accumulate into the reservoir and are not needed to fracture. There are no essential differences in the accumulating mechanism between the shale gas reservoir and conventional oil and gas reservoir. The power of the oil and gas enrichment in the reservoir pores is the buoyance generated from the density differential of the liquids.

2.1. Distribution Regulations of Effective Hydrocarbon Source Rock. Effective hydrocarbon source rocks are known as rocks that may not only generate but also expulse hydrocarbon. The rocks with especially enriched organic matter are called high-quality source rocks. Previous studies focused on the content of hydrocarbon generation but ignored the action of hydrocarbon expulsion. Quantitative evaluation of hydrocarbon expulsion action and distribution rules in abundance bed of organic matter is required in modern reservoir forming theory. Thus, the study of the effective and high-quality hydrocarbon source rock is growing vigorously. According to the recent study combined with literature investigation, effective source rock is considered to be formed in an overlay area with the prospering organism and anoxic environment. Geochemical measures of the actual profile, simulation experiments of source rocks with various organic contents, and lithology should be done to recognize it. Effective and high-quality source rocks make a tremendous contribution to hydrocarbon reservoir forming despite a few thicknesses and special distribution.

Normally, it is common that hydrocarbon source rocks depend on basin type in the continent basin, focusing on the sediment center, hydrodynamic conditions, sedimentary facies, provenance, thermal evolution, and charging process. Based on mass well-logging data, the effectiveness of source rock of Qikou Sag has been studied on the whole wells, which overcomes the difficulty to hold the distribution of source rock restricted from unsystematically geochemical data and discontinuous single-well data. We analyzed a ratio, of source volume of high-quality to effective, as the evaluation criteria for distribution quality. With the ratio criteria, we can evaluate source effectiveness and quality in the different oil-bearing beds of Qikou Sag and can more objectively reveal that the distribution of source rock in the study area is dominated by a sedimentary environment. With this study, it is found that the main developed area for high-quality sources developed in deep-lacustrine and semi-deep-lacustrine facies near the basin center and predicted the main exploration area for conventional and unconventional petroleum in the study area.

2.2. Migration of Nanohydrocarbon. Nanooil and gas are mainly distributed in source rocks and near the source, tight reservoir systems in close contact with a large area, including shale oil, shale gas, coalbed methane, tight sandstone oil, tight sandstone gas, and tight limestone oil. The pore throat diameter of the reservoir is generally nano. The seepage capacity of oil, gas, and water in the nanopore throat is poor, and the phase differentiation is difficult. It is mainly driven by overpressure. Oil and gas are retained and adsorbed and continuously distributed in a large area in the source reservoir symbiotic tight formation.

Hydrocarbon migration is a series of processes that drive oil and gas from an effective source rock to the surface of the Earth. With the progress of diagenesis, organic matter generates hydrocarbons, inorganic minerals transform and dehydrate, and rock structure changes accordingly. The results of this series of changes will lead to the discharge of hydrocarbons. Therefore, the hydrocarbon expulsion power is mainly the inner fluid pressure of source rocks formed by the combined action of compaction, geothermal stress, and fluid generation, but the size of various actions is different in different evolution stages. Generally, in the early stage of diagenesis, the porosity of source rock is high, and a large amount of hydrocarbon fluid can be discharged. In the late stage of diagenesis, the change of porosity is not much. When to start hydrocarbon expulsion and the main hydrocarbon expulsion period can be studied by basin simulation. The contour map of hydrocarbon expulsion intensity of effective source rocks is an important map to reveal the quantity of oil and gas transported by the main migration channel and the location and scale of oil and gas reservoirs. In millimeter-scale-sized pores, the fluids flow unrestrictedly, in micrometer-scale-sized pores, fluid flows are restricted by capillary resistance; in nanoscale pores, let alone pore throat diameter less than 1 μm, fluid flows lead to "retention" [18].

3. Accumulation

The migration path of hydrocarbons in the petroliferous basin is confirmed by the 3-D spatial distribution of the discontinuous sealing surface. Under the sealing surface, oil and gas choose the path with the most favorable structure and the least migration resistance—the main migration channel. Among them, the structural form, long-term or multistage active faults or fractures, high permeability and porosity reservoirs, and unconformities act as key actions facing the main migration channel [19].

3.1. Main Migration Pathway. In petroliferous basins, faults, sand bodies of the framework, and unconformities are the key elements. Generally, oil and gas migrate laterally along the framework sand body, laterally along the unconformity surface, and vertically along the fracture and fault system. The main migration channels of hydrocarbons mainly appear in the form of composite, especially the two or even all combinations of faults, skeleton sand bodies, and unconformities. From source rocks to traps, the main migration channels gradually diverge to converge, from fine to coarse and from more to less, in the shape of "inverted branches."

3.2. Faults and Fractures. The faults often cut through source rocks and reservoir rocks in different horizons. They are the main vertical migration channel. Generally, active faults act as channels for oil and gas. If the fault is not active, it will block oil and gas. The channel action and sealing action of faults are relatively complex [20–25]. Faults and fractures have the characteristics of penetrating layers, vertical migration, and periodic migration for long distance. When Sibson [26] put forward "seismic pump" theory of hydrothermal migration along the fault, he believed that the migration of hydrothermal fluid along the fault was caused by the earthquake. The fault pumped the hydrothermal fluid from the deep part and lifted it into the shallow part above like a pump. Hooper [27] introduced this principle into oil and gas migration and pointed out that when the fault layer is inactive, the fault section is closed. When the fault is active, oil and gas migrate along the fault in a short and rapid form. In addition, according to Losh et al. [28], the analysis of the structure of a scientific exploration well core and the vertical and horizontal flow of fluid relative to the growth fault in the 330 block of Eugene Island in the south of Louisiana coast shows that the growth fault plays a very important role. In the analysis of the relationship between the fault activity period and oil-bearing property, it shows that the fault activity period is the same as the generation and migration period of oil and gas. The fault is conducive to the migration of hydrocarbons along the fault and fracture, and a lot of fluid accumulated along the fault trend is complex, indicating that the section shape plays an important role in controlling hydrocarbon migration. Therefore, fractures and faults are an important part of the main migration channel of hydrocarbons, especially those that cut through effective source rocks. Studying oil migration from the clastic sediments, Cordell [29] pointed out that the frequent sand and mud interstratification and pressure were the reasons for the long-distance vertical migration of the impending oil and gas from the clastic rocks.

3.3. Skeleton Sand Body. Magara [30] believed that the discharge capacity of hydrocarbons in source rocks usually increases with the increase of contact area with sandstone, and the content of sandstone in the formation is 20%~60%, with a median of 30%~40%; Xin et al. [31] believed that the migration channels of hydrocarbons are selective, and the migration channels are very limited, accounting for only 1/10 of the reservoir; Rhea et al. [32] believed that oil and gas enter the framework sand body from the source rock, and its migration direction is controlled; It can be seen that the channel, delta, and other framework sand bodies with good porosity and permeability are the main migration channels of lateral short-distance oil and gas[33]. Generally, the framework sand body with lateral migration and the fault (oil source) with vertical migration constitute the main ladder oil and gas migration channel of the fault framework sand body.

3.4. Unconformity. Unconformity, as the oil and gas migration pathway, has the following characteristics: (1) long-term weathering and erosion increase porosity; (2) plane of unconformity is usually the oil and gas migration pathway for long distances; and (3) unconformity is the "bridge" between the source rocks and reservoir rocks. The unconformity is the main lateral migration pathway on the slope and plays a considerable role in onlap hydrocarbon reservoirs. Because of long-term weathering and erosion, it often forms a permeable formation, along which oil and gas can migrate horizontally for a long distance and accumulate. Unconformity and incise waterway filling complex are both the main hydrocarbon

migration pathways. The unconformity is beneficial to the oil and gas accumulation and migration, and it is the main lateral migration pathway for a long distance. It connects the faults and sand bodies of the framework, a long-distance network of main oil and gas migration pathways, which benefits forming erosion oil fields and interior reservoirs.

In addition to the scouring unconformity, there are also incised channel filling complexes on the sequence boundary, which can be used as the main migration channel of oil and gas. It is the main channel of lateral and long-distance migration of oil and gas [33]. It connects faults and skeleton sand bodies of different ages, forms a regional and long-distance main migration channel network of oil and gas, and is conducive to the formation of large corrosive oil and gas fields and insider oil and gas reservoirs [34, 35].

3.5. Space of Vertical and Horizontal Migration. The structure contour map of fault morphology is one of the main results of the accurate hydrocarbon exploration methods (Figure 1), which reflected the convex is the main migration pathway location. Section shape description is useful. The seismic technology is used to find out the shape, occurrence, and combination relationship of faults.

Thus, it provides a powerful tool for implementing the main migration channel of oil and gas. The contour map of section shape and structure is one of the main achievement maps of important maps of accurate oil and gas exploration methods. It can express various properties of deposition, stratigraphy, structure, and oil reservoir, to understand the enrichment characteristics of oil and gas, and determine favorable exploration direction, well placement position, and oil and gas field development plan. When oil and gas migrate from the sag to the shallow layer, the migration path has the characteristics of divergence to convergence, and the dominant migration direction of different section shapes and stratigraphic occurrence strokes is different. The shape of the section forms the dominant convergence point of vertical migration of oil and gas, and the relationship between the shape of the section and the occurrence of the formation controls the lateral dominant migration path of oil and gas. According to the analysis of the configuration relationship between the fault plane and the strata, the convex surface of the downside of the fault forms the dominant migration direction of oil and gas and converges to the low-potential area.

The description of sand bodies of the framework. In areas with more drillings, the description can directly be taken through log data, while in areas with fewer drillings, there is a need to use the logging data, the GLOG inversion, and logging constrained inversion of seismic wave impedance inversion, as well as neural network technologies to predicate the porosity. The top surface structural map and the contour map of physical properties are the important result maps with accurate oil and gas exploration methods, in which the areas with high porosity and permeability are the important positions of the main migration pathway. In Figure 1, the framework sand bodies with the high porosity and permeability and the faults run nearly east-west and are north trending, forming the ladder-shaped main migration pathway.

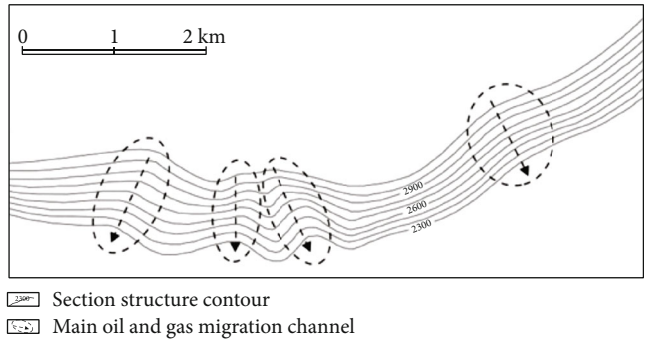

Figure 1: Sketch map of main migration paths in the fault cross-section structure contour.

The description of unconformity. In addition to the regional unconformity, the unconformity during the formation and evolution of continental basins is usually found in the nonsedimentary province around the source sag and has good porosity and permeability within a certain thickness. The structure ridges on the top of unconformity are important migration paths. The description of the unconformity is mainly the structure description which can be studied according to 3-D seismic data and logging data. The top surface structural contour map of unconformity is the important result map of the geometrical description of the main migration pathway, in which the distribution area of the structure ridges is the main migration pathway.

Based on the geometrical description of the fault, unconformity, and sand bodies of the framework, the distribution map of the main migration pathway for oil which consists of the morphology of fault, the structural contour map of unconformity, and the physical properties contour map of sand bodies of the framework is an important result while in accurate oil and gas exploration. According to the maps combined with hydrocarbon expulsion intensity contour map, oil-source correlation, and other information, several possible and most likely main oil and gas migration pathways can be identified.

3.6. Transmission Capacity of Main Hydrocarbon Migration Pathway. Studies show that when it has vertical expulsion direction, fixed length, and volume, the buoyancy of the oil neck is several orders of magnitude than that when the expulsion direction is low-angled and horizontal. At the same time, the volume of the rock through which oil and gas migrate horizontally is several orders of magnitude than that when the expulsion direction is vertical; that is, the loss when oil and gas migrate horizontally through the reservoir is much greater than that when the migration is vertical through faults and cracks. Through theoretical calculations, Liu et al. [36] suggested that the transporting capacity of the large fault zone is much larger than that of reservoirs. Zeng and Wang [37] suggested that the sands with high permeability are the main migration path. Thus, in general, the horizontal migration with a low angle is less efficient than vertical migration and the long-term active systems of the faults and fracture are the highly efficient vertical migration

paths of oil and gas. And due to the high efficiency in oil and gas migration through faults and cracks, we should pay close attention to the study of the main migration pathway related to faults or cracks.

As a migration channel of oil and gas, it has the following characteristics: (1) long-term weathering and erosion enhance porosity; (2) unconformity is often the channel of long-distance hydrocarbon migration; and (3) unconformity is the "bridge" between source rock and reservoir rock. The unconformity is an important channel for lateral migration of oil and gas under the slope background and plays an important role in hydrocarbon reservoirs in the overbreak zone of the basin. Due to long time weathering and denudation, permeable layers with certain porosity and permeability are often formed, and hydrocarbons can migrate and form reservoirs laterally and remotely along the unconformity surface (Figure 2).

Figure 2 detailed descriptions are illustrated in (a–g). (a) Reservoir controlled by paths which consists of faults, framework sand bodies, and planes of unconformity; (b) reservoir controlled by paths which consists of faults and planes of unconformity; (c) reservoir controlled by paths which consists of faults and framework sand bodies; (d) reservoir controlled by paths which consists of framework sand bodies and planes of unconformity; (e) reservoir controlled by fault-type paths; (f) reservoir controlled by paths with type of framework sand bodies; (g) reservoir controlled by paths with type of unconformity.

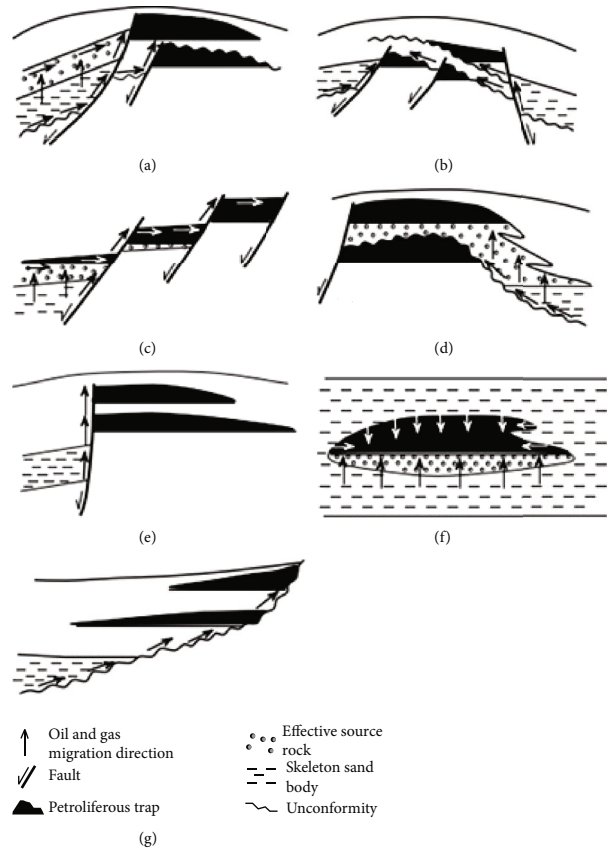

Figure 2: The resource-migration-reservoir sketch map.

4. Storage for Oil and Gas

We make use of the existing data of drilling, well logging, and seismic record. The hydrocarbon generation of effective source rocks is a continuous process with peak hydrocarbon generation, but the discharge of hydrocarbons is not continuous. Episodic hydrocarbon expulsion is usually related to periodic tectonic activities. Among the basic elements of the main migration channel, only faults have the characteristics of episodic activity. Therefore, the period of fault activity is the main period of episodic hydrocarbon expulsion and oil and gas migration of source rocks, and faults or fractures are the main migration channel of large-scale and efficient hydrocarbon migration. The hydrocarbon migration of skeleton sand body and unconformity surface in contact with effective source rock usually changes with the change of hydrocarbon generation process of source rock.

Above all, effective source rocks as well path and geometric description of main migration channels and the formation and evolution of traps are basic elements; we can further determine the target with the most oil and gas exploration potential in or near the main migration channels—oil and gas reservoirs, and carry out drilling [38, 39]. According to the "source transport reservoir" model map in the accurate oil and gas exploration method, in the practice of oil and gas exploration, the "source transport reservoir" under different geological backgrounds will be studied, which will minimize the risk of oil and gas exploration in the medium and high exploration degree area of the continental basin and improve the benefit of oil and gas exploration to the greatest extent. The comprehensive map including effective source rock top structure contour map, section shape, unconformity surface and skeleton sand body structure contour map, skeleton sand body physical property contour map, and trap top structure contour map is a valuable map of accurate oil and gas exploration.

We got a successful test by the use of this theory, at the Qikou Sag, the Es2 member in the Gangdong fault's downthrow side could also be a good place for Es2 source rock to accumulate. At this sag, the faults and unconformities together form the main migration channel of oil and gas, so that the oil and gas generated by the lacustrine source rocks in each sag up to 60 km away can migrate over a long distance and accumulate in the large-scale reef trap, forming 100 million-ton large oil field.

5. Conclusions

For previous exploration theories in China's oil and gas exploration enterprises, such as "fixed concave selection" and "progressive exploration and development," the problem of oil and gas exploration in continental basins with petroleum characteristics cannot be solved, such as "one source multilayer," "one layer multisource," and "multisource, multilayer, and multireservoir," and cannot effectively guide the oil and gas exploration in continental basins.

We propose the main migration pathway to study oil-gas migration. It is focusing on the premise of determining the source, detecting the geometric spatial distribution of the main migration channels of oil, making a clear migration trajectory of oil and development history of traps, tracking clues, and digging for the best of all targets for the oil-gas reservoir. This method is based on the fact that the source of oil and gas has been "determined" in early and midterm exploration and uses the abundant data of seismic, logging, coring, analysis and test, production performance, and a large number of previous research results in the middle and high exploration degree areas to make a detailed description and distribution study of faults, sand bodies of framework, and unconformity surface, to clarify the type and main migration pathway. Combined with trap forming time and spatial distribution, the favorable oil and gas exploration target is accurately located and drilled. The role of the oil exploration method is obvious. It will minimize the risk of exploration in higher exploration degree areas of the continent basin and benefit oil exploration. At the same time, we need to pay attention to some more performance metrics to strengthen the research work, such as a comprehensive resource evaluation of various oil accumulating units in the depression.

Similar to Metallogenic System Theory, tied with source, transportation, channel, and storage, Petroleum Exploration System has the same elements, source, main migration pathway, and storage. The new concept focuses on nanohydrocarbon for source. Nanohydrocarbon in coexisting sources and reservoirs becomes easier to understand. Nanosized pore throats have been paid attention to. Once nanopores are not connected, there is inability to accumulate into oil, so nanohydrocarbon needs a channel or pathway.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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