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Prediction Method for the Distribution of the Effective Dominant Path of Sand Bodies Transporting Oil and Gas and Its Application

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Abstract: To study the oil and gas distribution law in the slope area of a hydrocarbon-bearing basin, one must first define the dominant hydrocarbon transport paths of sand bodies as the superimposed area of the contiguously distributed area of the sand bodies and the paleotectonic ridges at the top interface of the formation. Then, the oil and gas supply area of the oil source faults must be defined, as the overlapped area of the favorable transport paths of oil source faults and the width of their associated fracture zones. Stacking the two areas, we can delineate the distribution of the effective dominant paths of sand bodies transporting oil and gas. The results from our case study of the Qinan area show that the effective dominant paths of sand bodies transporting oil and gas in the lower sub-member within the first member of the Shahejie Formation (Es_1^L) in the Qinan area are distributed throughout the region, with better development in the west than in the east. And, the effective dominant paths in the eastern part extend from north to south, while those in the western part extend from northeast to southwest. These are favorable for the convergence of oil and gas generated from source rocks in the third member of the Shahejie Formation (Es_3) in the main depression of Qikou Sag in the Es_1^L in the Qinan area. The results are consistent with the fact that oil and gas discovered in the Es_1^L in the Qinan area are mainly distributed in the central and western regions, with a small amount in the southeast. Therefore, the suggested method is feasible for predicting the effective dominant paths of sand bodies transporting oil and gas.

Keywords: sand bodies; transporting oil and gas; effective dominant path; distribution prediction

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1. Introduction

In the late 1980s, the view of "Slope type multiple oil and gas accumulation zone" prevailed [1,2], which aroused the attention of the petroleum industry to the slope area of hydrocarbon-bearing basins; following expansions in oil–gas exploration, research finding the slope area usually takes place outside the oil's source area. The location of hydrocarbon accumulation in the slope area generated by the oil's source area mainly depends on whether the dominant path of sand body transportation is effective [3,4]. Only when the dominant path of sand body transportation connects to the hydrocarbon expulsion area of the source rock or of the oil source fault (i.e., the faults that connect the source rock with the studied layer and are active during the period of hydrocarbon accumulation [5,6]), can hydrocarbon migrate through the dominant path, and effective hydrocarbon reservoirs can be found around. Otherwise, no hydrocarbon reservoirs can be found here; only traps located on or near the effective sand body transportation path can obtain hydrocarbon accumulation from the oil source region, regardless of how good other hydrocarbon accumulation conditions are. Therefore, it can be concluded that judging the range of the effective dominant path of sand body transportation is crucial for correctly

understanding the hydrocarbon distribution law of the slope area of the hydrocarbon-bearing basin and guiding its hydrocarbon exploration.

Generally speaking, previous research [7–14] on the effectiveness of the dominant paths of sand bodies transporting oil and gas can be summarized with the following two aspects: one is the studying of the effectiveness of the transporting property of the sand bodies themselves by identifying the paleotectonic ridges at the top interface of the stratigraphic layer containing the sand bodies and the contiguously distributed area of sand bodies [15,16]. The paleotectonic ridges in the area of connected sand bodies are believed to be the effective dominant transport paths for sand bodies carriers. The other aspect is the judging of the effective dominant hydrocarbon transport path of sand bodies, based on the spatial relationship between the studied paths and the upward migration of oil and gas from depressions [17–19]. Only the dominant hydrocarbon transport path of the sand bodies connected to or near the vertical transport area of oil and gas in the depressions is an effective dominant path for oil and gas migration in sand bodies. These research results play an important role in correctly understanding the distribution of oil and gas in the slope area of a petroleum basin and guiding its oil and gas exploration. However, there is a lack of quantitative research on the distance between the dominant oil and gas transport path of a sand body and the dominant oil and gas transport path of an oil source fracture which will become the dominant oil and gas transport path of a sand body. This cannot accurately determine the effective advantage path for transporting oil and gas from sand bodies, nor can it predict its distribution, and it cannot effectively guide oil and gas exploration in the slope areas of oil-bearing basins.

The Qinan area is located in the southern part of Qikou Sag of Bohai Bay Basin, and has proven oil and gas reserves of 5×10^8 t. With relatively enriched oil and gas resources, it has become an important real-scale reserve-increase area in Bohai Bay Basin [20]. Therefore, the author will carry out research in the Qinan area by determining the effective dominant paths of sand bodies transporting oil and gas, determining the hydrocarbon supply area of oil source faults, and summarizing the distribution of effective dominant paths for oil and gas transport in sands. It is of great significance to correctly understand the distribution of oil and gas in the slope area of petroliferous basins, so as to guide the direction of oil and gas exploration in similar areas.

2. Geological Setting

Qikou Sag is located in the belly of the Bohai Bay Basin in eastern China and is one of the largest oil-rich sags [21], with an exploration area of nearly 6000 km^2 (Figure 1a) [22]. The sag is surrounded by the Cangxian Uplift, Chengning Uplift and Shaleantian Uplift, controlled by the Cangdong Fault on the west side, connected with the Cangxian Uplift on the southwest side, and connected with the Kongdian Uplift and Cangdong Sag, overlapping the Chengning Uplift, on the south side, divided by the Shalietian Uplift, Nanpu Sag, and Shannan Sag on the east side, and the Hangu Fault on the north side (Figure 1b) [23,24]. Qikou Sag developed on the Pre-Cenozoic basement, experienced the Paleogene post-rifting period and Neogene syn-rifting period in the Cenozoic, and became a half-graben depression with a north fault and a south fault. Drilling results indicate that Qikou Sag was mainly deposited from bottom to top in the Shahejie Formation (Es), Dongying Formation (Ed), Guantao Formation (Ng), and Minghuazhen Formation (Nm) (Figure 2) [25]. Es is divided into the first, the second, and the third member (i.e., Es_1, Es_2, and Es_3), and Es_1 is divided into the lower, the middle, and the upper sub-member (i.e., Es_1^L, Es_1^M, and Es_1^U); Ed is divided into the first, the second, and the third member (i.e., Ed_1, Ed_2, and Ed_3) (Figure 2).

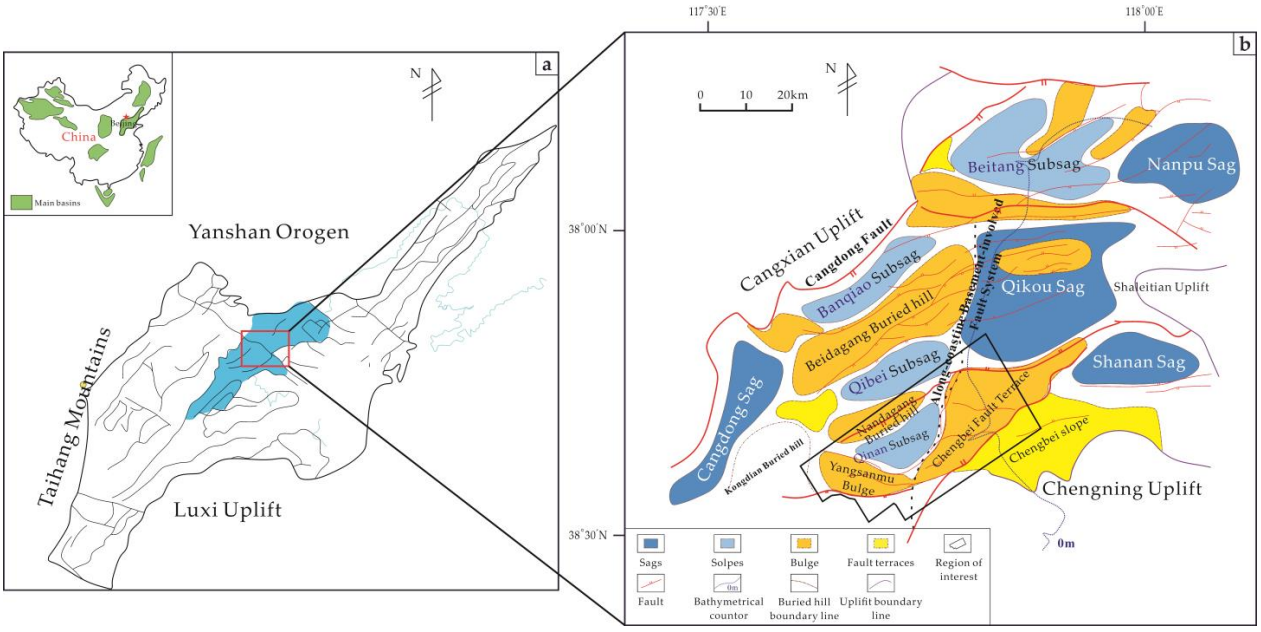

Figure 1. Regional geological map and structural framework of the Qikou Sag, Bohai Bay Basin, Eastern China (BBB-Bohai Bay Basin, modified from Ref. [22]); (**a**) tectonic position (**b**) tectonic features of the southern Qikou Sag.

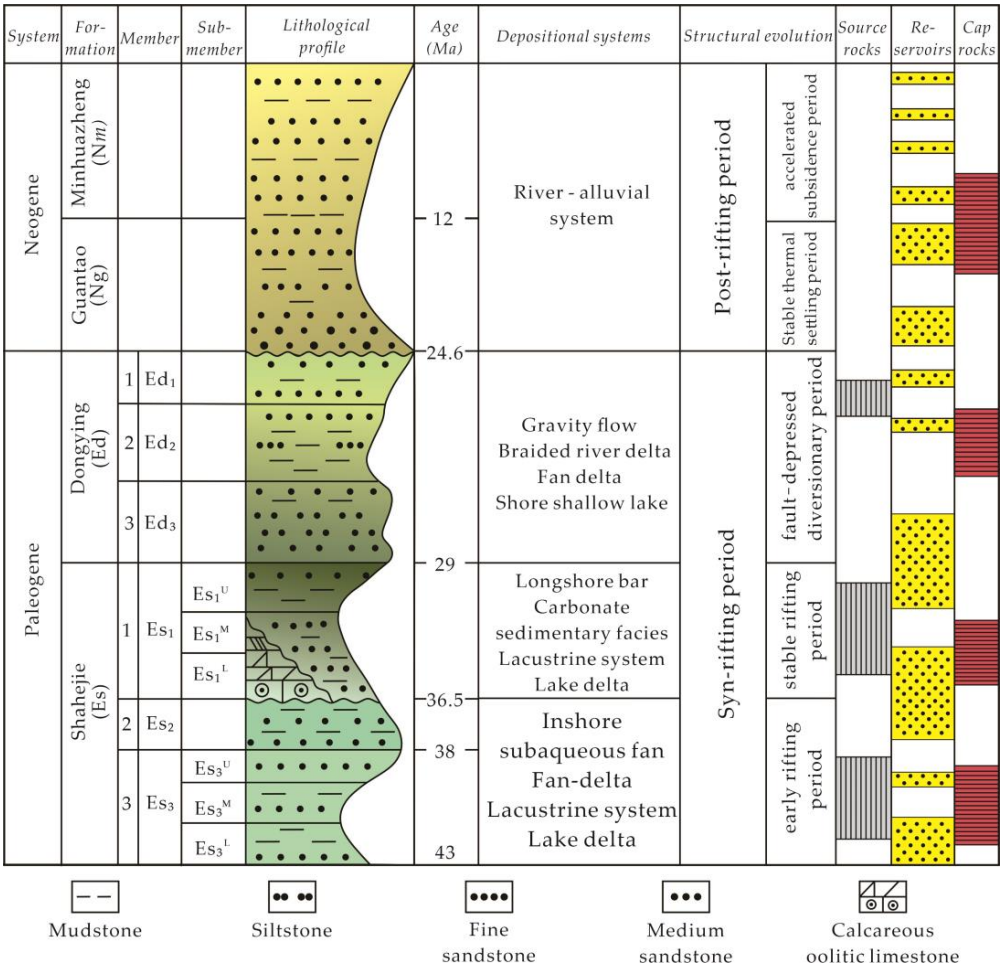

Figure 2. Basin filling evolution and columnar section (modified from Ref. [25]).

Oil and gas drilling results show that there are four sets of source–reservoir–cap assemblages in Qikou Sag: the first set is the self-generating and self-restoring source–reservoir–cap rock combination of the mudstone cap rock of Es_3 and its internal and lower reservoirs, and the oil and gas come from the source rock of Es_3; the second set is the lower-generating and upper-restoring source–reservoir–cap rock combination of the mudstone cap rock of $Es_1{}^M$ and the sandstone reservoirs of $Es_1{}^L$, and the oil and gas come from the source rock of Es_3; the third set is the lower-generating and upper-restoring source–reservoir–cap rock combination of the mudstone cap rock of Ed_2 and the sandstone reservoirs of Ed_3, and the oil and gas come from the source rock of Ed_1.

In this paper, the Qinan area (i.e., the study area) is located in the southern part of Qikou Sag, which consists of the following five tectonic zones: Nandagang Fault, the Qinan Slope area, Chengbei Fault terrace, Yangsanmu Bulge, and Yangerzhuang Fault (Figure 1), with an exploration area about 2300 km^2, and which is the leading oil-producing area with relatively intensive oil and gas exploration occurring in the whole sag [26]. $Es_1{}^L$ is the key layer studied in this paper; the oil and gas in this sub-member mainly come from the high-quality source rocks of Es_3 in the main Qikou sag in the south, which are mainly distributed in the northeast of the Qinan area, the eastern part of the Qinan Slope area, and the eastern part of Nandagang Fault. The regional mudstone cap rock developed over the oil layer of $Es_1{}^L$ is the regional cover layer of $Es_1{}^M$; the tectonic activity in the sedimentary period of $Es_1{}^L$ was relatively weak and the sedimentary environment is relatively stable. It deposited a set of deep/semi-deep lack facies with mudstone cover in the Qinan area, with the lithology being mainly sand mudstone.

3. Methods

3.1. The Effective Dominant Paths of Sand Bodies Transporting Oil and Gas and Their Distribution

The effectiveness of the dominant paths of sand bodies transporting oil and gas is determined by the spatial relationship between the studied paths and the hydrocarbon supply area of the oil source faults. Only when they are spatially connected will hydrocarbon be transported along the studied paths, which will become effective relative to the dominant paths of sand bodies transporting oil and gas; on the contrary, if they are spatially disconnected, there will be no oil and gas transported along the studied paths, and they will be ineffective relative to the dominant paths of sand bodies transporting oil and gas, as shown in Figure 3.

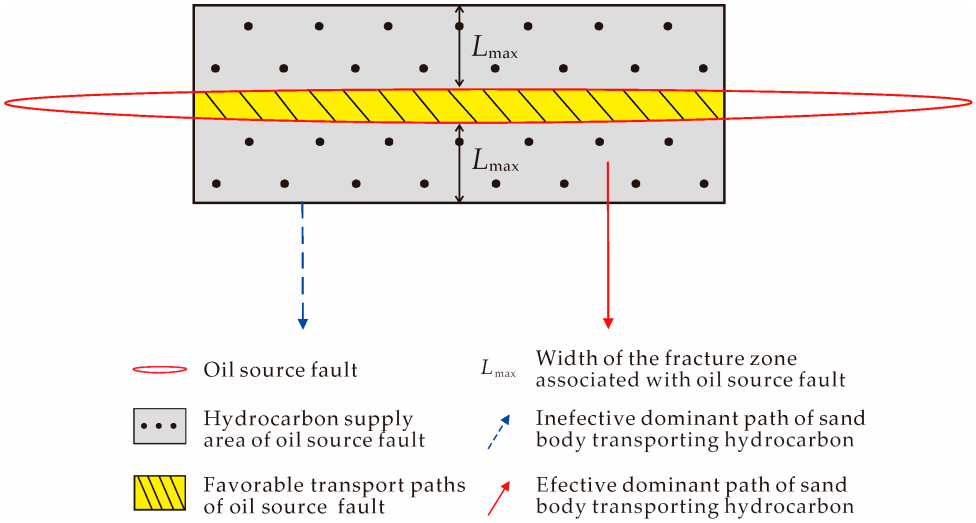

Figure 3. Schematic diagram of the effective dominant path of sand bodies transporting oil and gas.

To conclude, the distribution of effective dominant paths for sand bodies transporting oil and gas should be those dominant transport paths connected with the hydrocarbon supply area of the oil source fault.

3.2. The Prediction Method for the Distribution of the Effective Dominant Paths of Sand Bodies Transporting Oil and Gas

To predict the distribution of the effective dominant paths of sand bodies transporting oil and gas, we first need to determine the distribution of the dominant hydrocarbon transport paths of sand bodies and the hydrocarbon supply areas of oil source faults.

3.2.1. Determination Method for the Effective Dominant Paths of Sand Bodies Transporting Oil and Gas

The distribution of connected sand bodies and the location of a paleotectonic ridge at the top interface of the stratigraphic layer where the sand bodies are located is a prerequisite for determining the effective dominant paths of sand bodies transporting oil and gas. The sand-to-shale ratio is often used to identify the connectivity of sand bodies [27]. The sand-to-shale ratio of the studied stratigraphic layer containing sand bodies, and its associated planar distribution map, are often available from the drilling data. The minimum sand-to-shale ratio required for the sand bodies to communicate can be determined by adopting the method from the literature [28]. We can identify the contiguously distributed areas of sand bodies by delineating the areas where the sand-to-shale ratio of the studied stratigraphic layer is greater than or equal to the minimum sand-to-shale ratio required for the sand bodies to communicate (Figure 4).

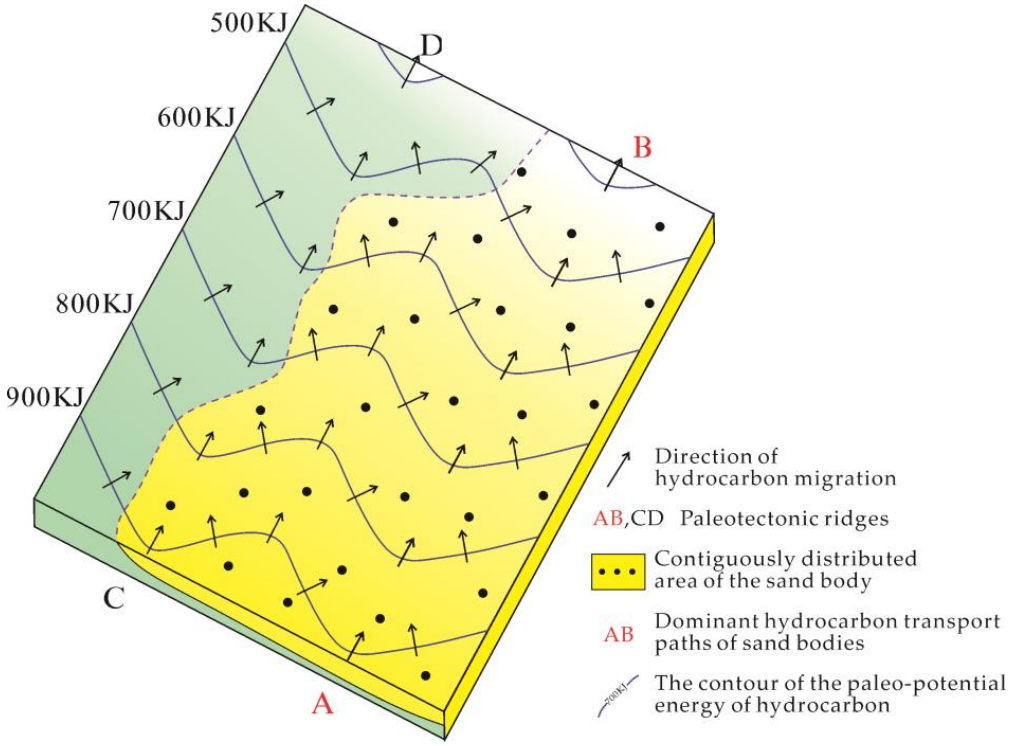

Figure 4. Determination of dominant hydrocarbon transport path of sand bodies.

The paleo-burial depth during the hydrocarbon accumulation period is recovered by a method from the literature [28], and the value of the hydrocarbon potential energy is derived by Equation (1). We can first obtain the present-day burial depth at the top interface of the studied stratigraphic layer based on 3D seismic data. Then, the paleo-burial depth during the hydrocarbon accumulation period can be recovered by applying the method from the literature. Afterwards, the value of the paleo-potential energy during the hydrocarbon accumulation period is calculated by Equation (1). Finally, we can delineate the distribution of paleotectonic ridges at the top interface of the studied strata containing

the sand bodies by identifying the normal convergence lines on the contour map of paleo-potential energy, as shown in Figure 4.

$$\Phi = gZ + \frac{p}{\rho} \quad (1)$$

where Φ—paleo hydrocarbon potential energy value, kJ; Z—paleo burial depth, m; p—fluid pressure, MPa (its magnitude is equal to $\rho_w Z$, where ρ_w is the density of formation water, g/cm^3); ρ—hydrocarbon density, g/cm^3; g—gravitational acceleration, m/s^2.

The dominant hydrocarbon transport paths of the sand bodies can be predicted by superimposing the distribution of the discovered zones with connected sand bodies and the distribution of paleotectonic ridges at the top interface of the strata containing the sand bodies, as illustrated in Figure 4.

3.2.2. Determination Method for the Hydrocarbon Supply Area of Oil Source Faults

To determine the hydrocarbon supply area of the oil source faults, we must determine the favorable transport paths of the faults and the width of the fracture zones. At first, we need to split the faults in the target layer into different types based on their seismic profiles, with those that connect the source rock and the studied sand bodies, and are active during the hydrocarbon accumulation period, being considered oil source faults. Afterward, the paleo-activity rates of oil source faults in the studied layer can be derived by dividing the paleo-fault throws by the fault activity period, where the paleo-fault throws are estimated by recovering the present-day fault throws to the hydrocarbon accumulation period using the maximum fault throw subtraction method [29,30]. We can obtain the minimum activity rate required for faults to transport by using the related method from the literature [31]. The areas with fault activity rates greater than or equal to the minimum value are grouped to locate the favorable transport paths of the oil source faults, as demonstrated in Figure 5.

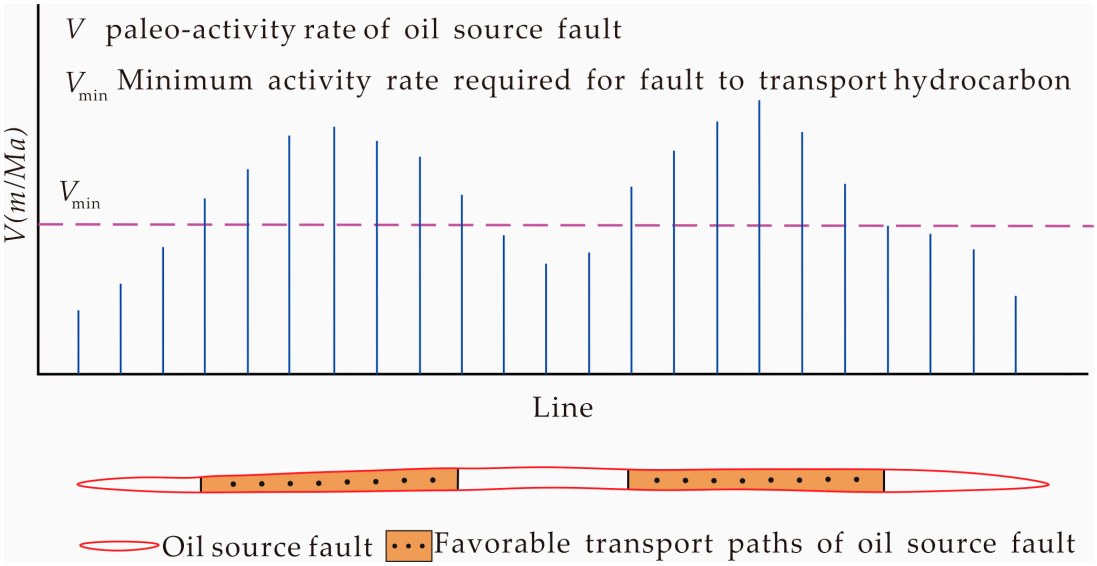

Figure 5. Determination of favorable transport path of oil source fault.

Due to current technological limits, it is impossible to directly measure the width of the fracture zones associated with oil source faults which developed during the formation period of hydrocarbon accumulation. However, it can be indirectly computed by sorting the distance between all wells in the Qinan area and their nearest favorable hydrocarbon transport paths for the oil source faults and identifying the maximum distance between the producing wells and the paths (Figure 6). The basis is that the formation of hydrocarbon accumulation is related to the occurrence of the associated fracture zone and the presence of the dominant hydrocarbon transport paths of oil source faults [18]. Therefore, the

maximum distance between the oil and gas well and the favorable hydrocarbon transport paths of oil source faults can indirectly indicate the width of the fracture zones associated with the oil source fault.

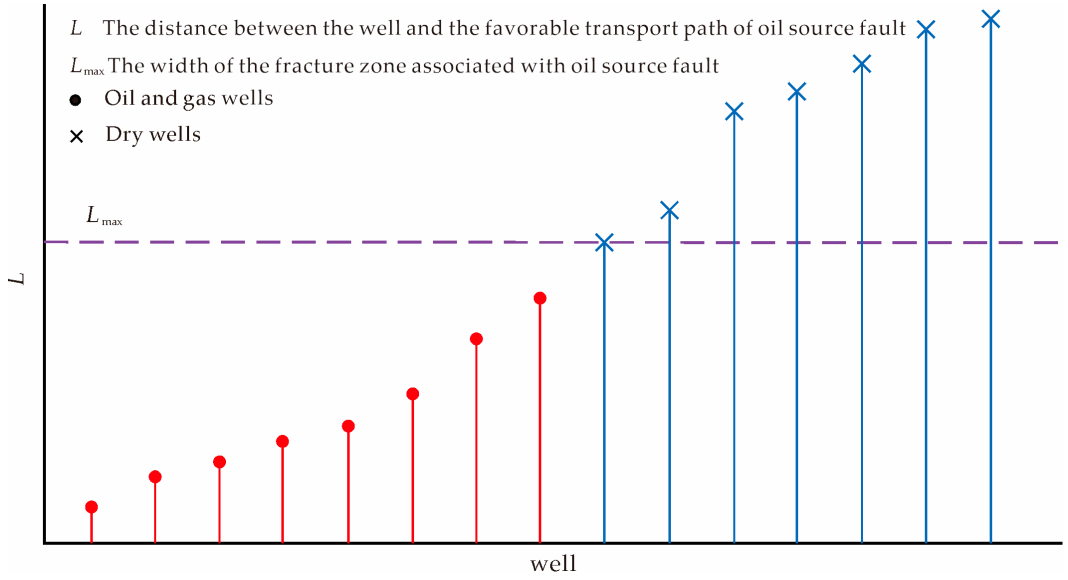

Figure 6. Schematic diagram for determining the width of the associated fracture zone of the oil source fault.

Combining the above-determined favorable hydrocarbon transport paths and the width of the associated fault zone, the effectiveness of the dominant paths of sand bodies transporting oil and gas can be obtained from the spatial relationship between the studied paths and the hydrocarbon supply area of the oil source faults in Figure 3.

3.2.3. Distribution of the Effective Dominant Paths of Sand Bodies Transporting Oil and Gas

Then, the distribution of the effective dominant path of sand bodies transporting oil and gas can be obtained by overlapping the hydrocarbon supply area of the oil source faults and the predicted dominant hydrocarbon transport path of sand discussed in the previous section.

4. Results and Discussion

Figure 7 demonstrates that hydrocarbons in the Es_1^L mainly exist in the western part of the Qinan area, with a small amount present in the southeast. This fact is related to the development of the structure traps, but more importantly, to the distribution of the effective dominant paths of sand bodies transporting oil and gas. Therefore, the key to its oil and gas exploration is to accurately predict the distribution of effective dominant paths of sand bodies transporting oil and gas in the Es_1^L of the Qinan area.

4.1. Determination of the Effective Dominant Paths of Sand Bodies Transporting Oil and Gas

After calculating the sand-to-shale ratio of the Es_1^L from the available drilling log data, we make a distribution map of the ratio (Figure 8). The minimum ratio for the Es_1^L of the Qikou Sag which would allow for oil and gas migration is about 15% (Figure 9). Using a 15% cutoff, we delineate the distribution of the connected sand bodies in the Qinan area (Figure 8). The map clearly shows that most parts of the study area have connected sand bodies, except for the southeast area and a small area in the west.

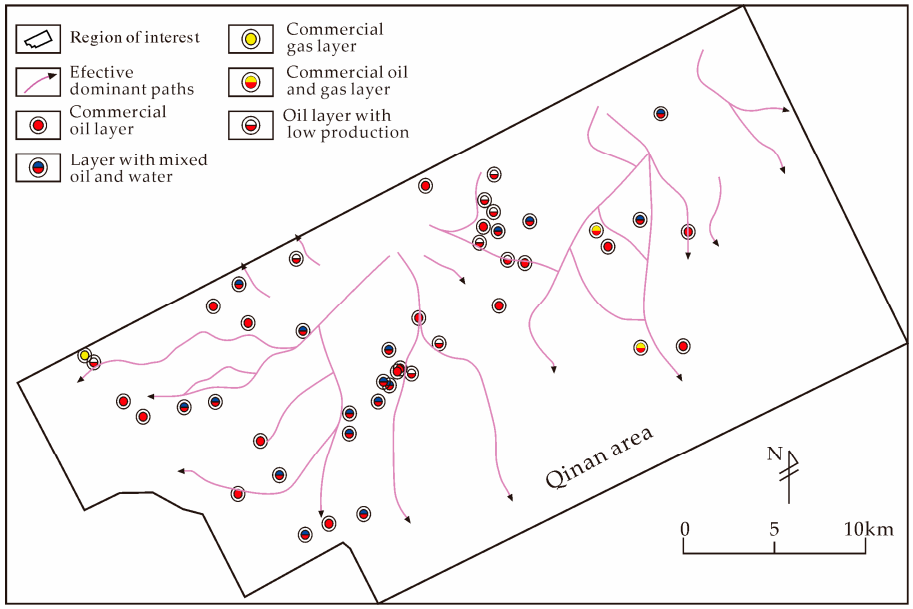

Figure 7. Relationship between the effective dominant path of sand bodies transporting oil and gas and oil and gas distribution in the Es_1^L in the Qinan area.

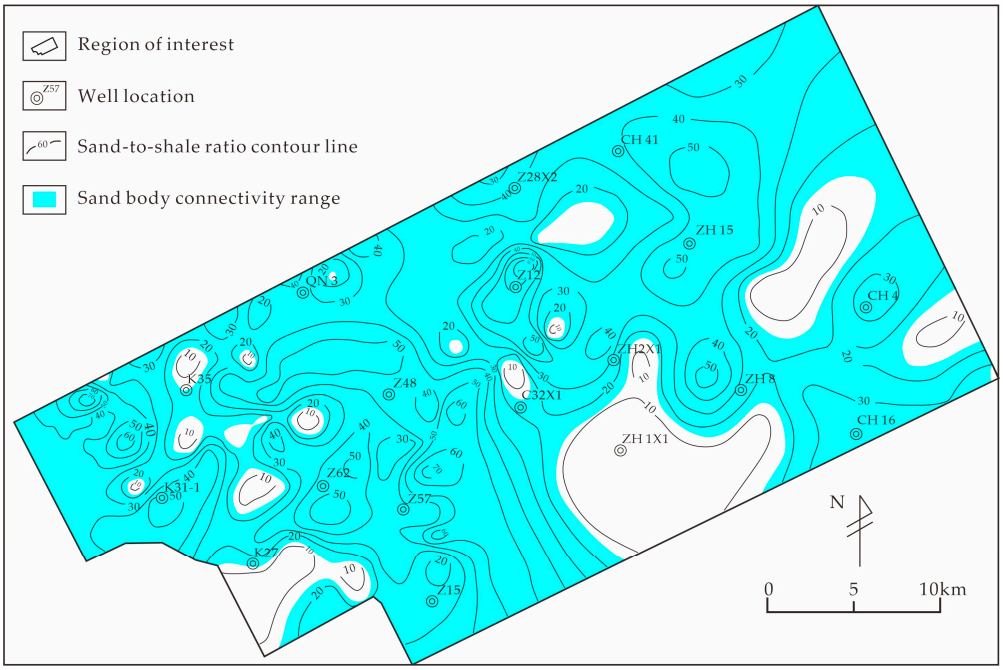

Figure 8. Distribution of connected sand bodies in the Es_1^L in the Qinan area.

The present-day burial depth of the top interface of the target layer in the Qinan area is determined based on 3D seismic data. The paleo-burial depth during the hydrocarbon accumulation period (i.e., the middle and late depositional period of the Nm [32]) is derived using the recovery method described in the literature [28]. Based on these results, the value of the paleo-potential energy is calculated by Equation (1). The distribution of paleotectonic ridges at the top of the target layer in the Qinan area is identified by mapping the normal convergence line of the paleo potential energy on its contour map. Figure 10 shows that the paleotectonic ridges in the Es_1^L are widely distributed in the Qinan area, where the eastern region is more developed and extends further in length than the western part.

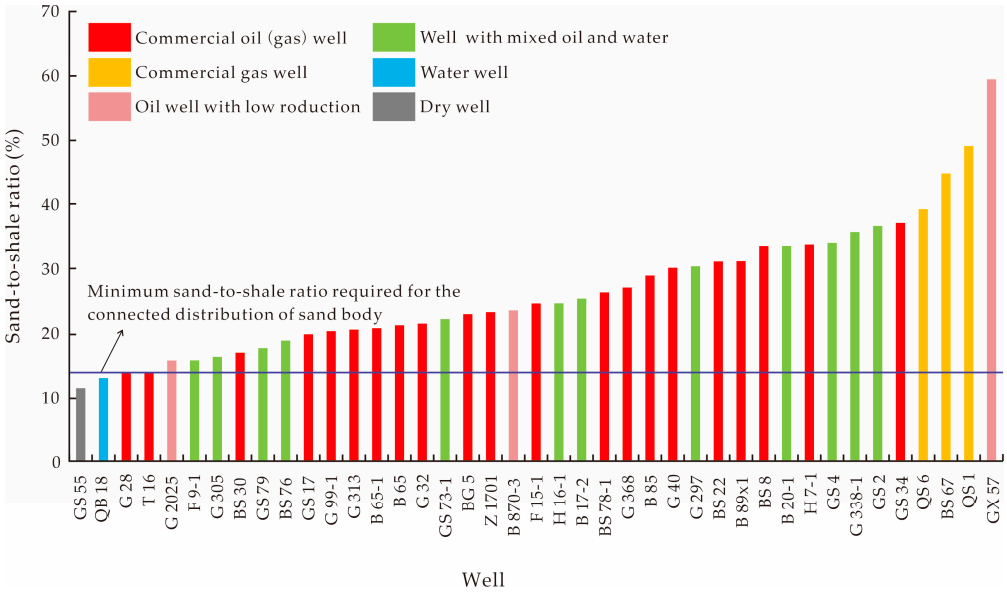

Figure 9. Determination of minimum sand-to-shale ratio required for connected distribution of sand bodies in Es_1^L in Qikou Sag.

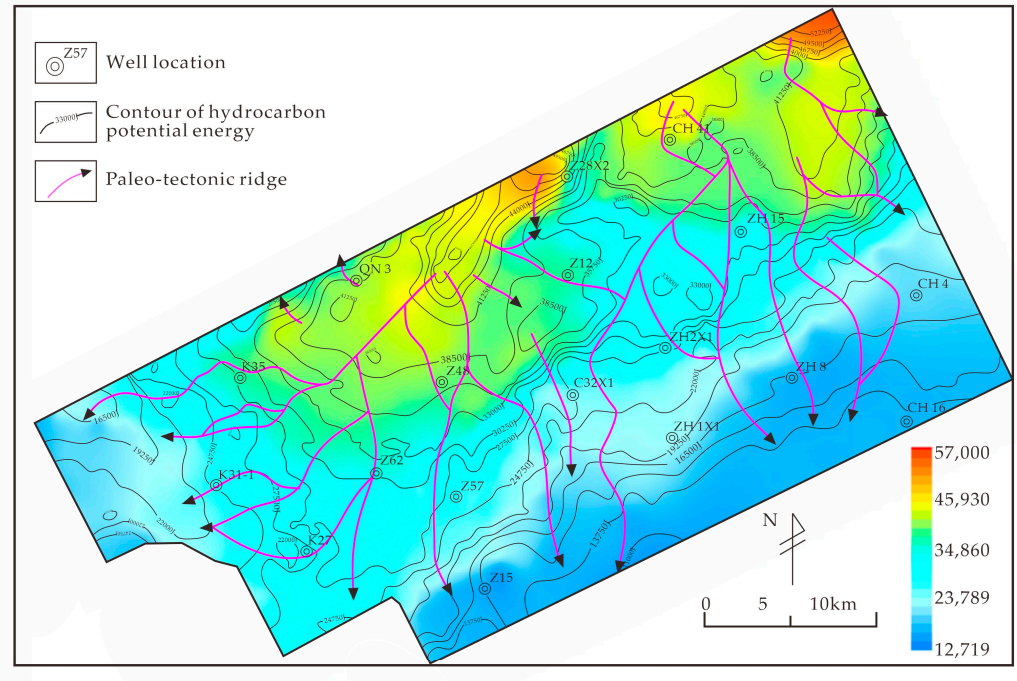

Figure 10. Distribution of paleotectonic ridges at the top of the Es_1^L in the Qinan area.

By superimposing the contiguously distributed areas of the sand bodies in the Es_1^L and the distribution of its paleotectonic ridges in the study area, we obtain the dominant hydrocarbon transport path of sand bodies of the target layer. Figure 11 shows that such favorable paths are developed and distributed throughout the region, with the western part being more developed than the eastern part. The dominant path in the eastern part extends north to south, while the dominant path in the western part extends from northeast to southwest.

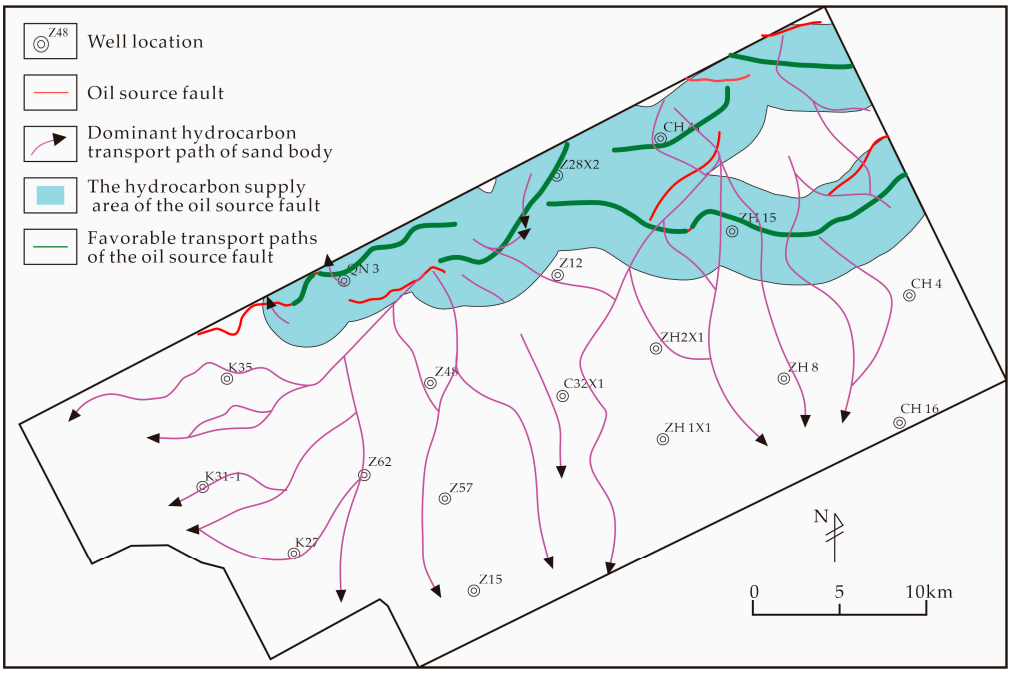

Figure 11. Distribution of the oil source faults and the dominant hydrocarbon transport paths of sand bodies in the Es_1^L in the Qinan area.

4.2. Determination of the Hydrocarbon Supply Area of Oil Source Faults

Next, we split the different types of faults developed in the Es_1^L in the Qinan area based on the dissecting strata observed on 3D seismic data. And its oil source faults are identified, based on the following rules: they must link the source rock in the Es_3 with the targeted Es_1^L, and they must be active during the formation period of hydrocarbon accumulation, which is the middle and late depositional period of Nm [32]. Figure 11 illustrates that the oil source faults in the Es_1^L in the Qinan area are poorly developed, and are only distributed in the northeast. We determine the present-day fault throw of the oil source faults in the Es_1^1 in the Qinan area from the 3D seismic data, and then obtain the paleo-fault throw during the formation time of hydrocarbon accumulation (i.e., the middle and late depositional period of the Nm [32]) using the maximum fault throw subtraction method [29,30]. Afterwards, we derive the paleo-activity rate of oil source faults in the Es_1^L in the Qinan area by dividing the paleo-fault throw by value for the fault activity period. Based on the value of the minimum activity rate required for faults to transport hydrocarbon in the Qikou Sag (i.e., 6 m/Ma, Figure 12), the distribution of the favorable transport paths of oil source faults in the Es_1^L in the Qinan area is obtained (Figure 11). These favorable transport paths are mainly distributed in the northeast.

By counting the distance between the dominant hydrocarbon transport path of sand bodies and the favorable transport path of oil source faults in the Es_1^L in the Qikou Sag, we estimate the width of the fracture zone associated with oil source faults in the area to be around 2.5 km (Figure 13). Based on this, we predict the oil and gas supply area of the Es_1^L in the Qinan area, mainly located on the northeastern side of the area.

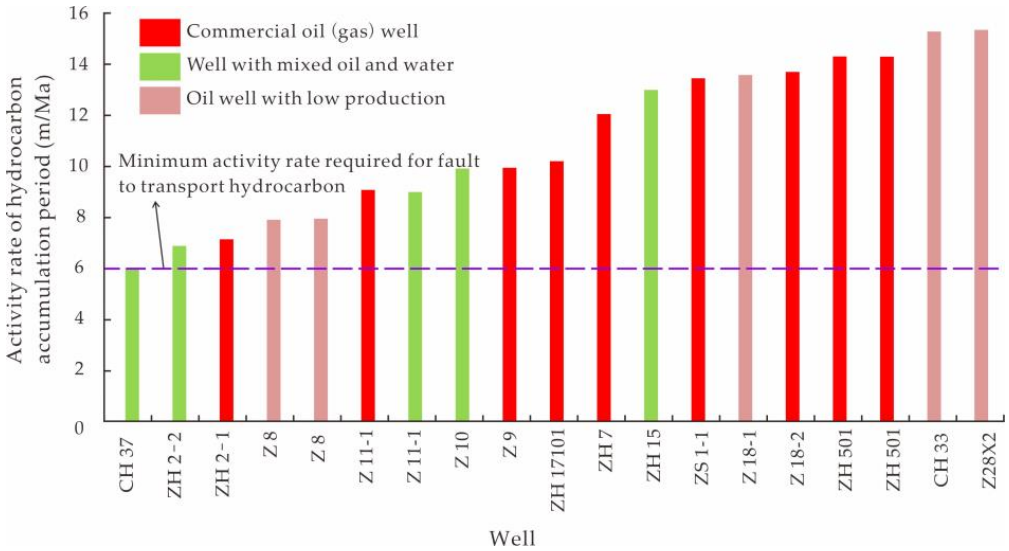

Figure 12. Determination diagram of minimum activity rate required for fault transportation of oil and gas in Qikou Sag.

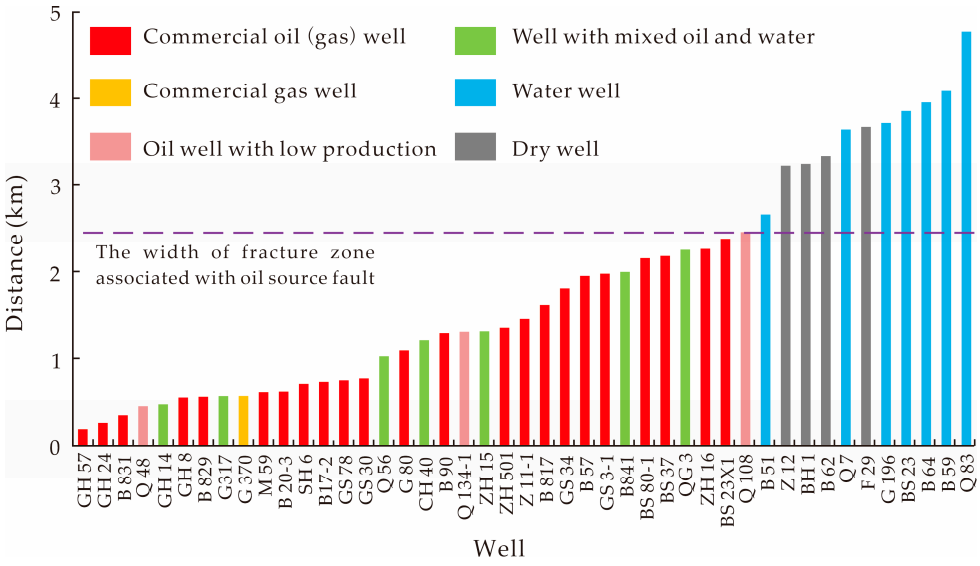

Figure 13. Determination of the width of the associated fracture zone of oil source fault in the Es_1^L in Qikou Sag.

4.3. Determination of Distribution of the Effective Dominant Paths of Sand Bodies Transporting Oil and Gas

By superimposing the distribution of the dominant hydrocarbon transport paths of sand bodies with the hydrocarbon supply areas of oil source faults, we obtain the effective dominant paths of sand bodies transporting oil and gas in the Es_1^L in the Qinan area. Figure 7 shows that the effective dominant paths of sand bodies transporting oil and gas in the Es_1^L are widely distributed in the Qinan area, with the western part being more developed than the eastern part. The dominant paths in the eastern part extend from the north to the south, while those in the western side extend from the northeast to the southwest.

4.4. The Relationship of the Effective Dominant Paths of Sand Bodies Transporting Oil and Gas and Their Distribution

Figure 7 shows that the oil and gas discovered in the Es_1^L are primarily located in the central and western sides of the Qinan area, with a slight amount in the southeast. The distribution of oil and gas agrees with the distribution of the effective dominant paths of sand bodies transporting oil and gas in the Es_1^L. It is reasonable as oil and gas can only migrate and accumulate in the Es_1^L in the study area through these effective migration paths to form hydrocarbon accumulation. The effective dominant paths are obtaining oil and gas sourced from the underlying source rock in the Es_3 member in the main depression of Qikou Sag from the hydrocarbon supply area of oil source faults by the dominant hydrocarbon transport paths of sand bodies. Therefore, oil and gas shows are often found near these dominant paths during exploration practice.

5. Conclusions

(1) The effective dominant paths of sand bodies transporting oil and gas are defined as the dominant transport paths of the sand bodies that connect with the hydrocarbon supply area of the oil source faults. Better development of such paths will lead to more convergence of oil and gas in the slope area and the formation of hydrocarbon accumulations.

(2) A method for predicting the distribution of effective dominant paths of sand bodies transporting oil and gas is established by superimposing the dominant hydrocarbon transport paths of sand bodies and the hydrocarbon supply areas of the oil source faults. The former is determined by the overlapping area of the connected sand bodies and the paleotectonic ridge at the top stratigraphic interface. The latter is determined by locating the favorable transport paths of the oil source faults and the widths of their associated fracture zones.

(3) The effective dominant paths of sand bodies transporting oil and gas in the Es1L are widely distributed in the Qinan area, with better development in the west than in the east. And the effective dominant paths in the eastern part extend from north to south, while those in the western part extend from northeast to southwest. These are favorable for the convergence of oil and gas generated from source rock in the Es3 in the main depression of Qikou Sag in the Es1L in the study area. It is consistent with the fact that a large amount of oil and gas discovered in the Es1L in Qinan area exists in the central and western parts of the study area and a tiny amount of oil and gas is distributed in the southeast region.

(4) This method is mainly applicable for the prediction of the distribution of effective dominant paths of sand bodies transporting oil and gas in sand–mudstone layers in a hydrocarbon-bearing basin.

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