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“Tri-in-One” Accumulation Model of Lithologic Reservoirs in Continental Downfaulted Basins: A Case Study of the Lithologic Reservoir of Nantun Formation in Tanan Sag, Mongolia

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Abstract: This article analyzes the key controlling factors and hydrocarbon distribution rules of lithologic reservoirs in a continental downfaulted basin according to the structural features, sedimentary evolution, types of sedimentary facies, source rock features, diagenesis evolution, reservoir features, hydrocarbon formation mechanisms, exploration status, and hydrocarbon resource potential. The results show that three major controlling factors (sandbody types, effective source rocks, and effective reservoirs) and one coupled factor (fractures that act as a tie) influence hydrocarbon accumulation in the lithologic traps in the Nantun Formation in Tanan Sag. With the increase in depth, sufficient hydrocarbon is generated in the source rock with thermal evolution. When the depth threshold is reached and critical conditions of hydrocarbon supply are met, hydrocarbon generation and expulsion are more intensive. Traps that are surrounded or contacted by source rock or connected by faults are able to form reservoirs. As the buried depth increases, the intensity of hydrocarbon generation–expulsion grows, and the trap is more petroliferous. Hydrocarbon accumulation and reservoir formation are also controlled by sandbody accumulation conditions. When the critical conditions for hydrocarbon generation are met and concrete oil and gas are charged in, the better physical properties of the sandbody will always indicate more hydrocarbon accumulation in the trap. The allocation of sand type, effective source rock, and an effective reservoir is optimized under the effect of fractures and the coupled hydrocarbon reservoir with these three elements.

Keywords: Mongolia; Tanan sag; downfaulted basin lithologic reservoir; fracturing; hydrocarbon accumulation mode; distribution of oil reservoirs

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1. Introduction

After years of exploration in the continental downfaulted basin in eastern China, a set of continental petroleum geology theories represented by “continental petroleum generation theory” and “source control theory” have been formed. From the early exploration of anticline reservoirs to the current subtle reservoir exploration, the “source control theory” of oil/gas generation and distribution in the continental downfaulted basin in China was proposed after the discovery of the Daqing oilfield (1960s~1970s). Based on the exploration achievements of the continental downfaulted basin represented by the Bohai Bay basin, the “composite oil/gas accumulation zone theory” was formed (1980s). The “Accumulation of petroleum in oil-bearing belt” theory was concluded by geologists working on the Shengli Oilfield during the exploration process in Dongying Sag (1990s). In the study of the formation and distribution characteristics of subtle reservoirs in the Erlian basin, the "Complementarity" Feature (2003), the "Theory of Advantage" Feature (2005) and the concept of "Multi-factor Controlling and Key Factor Entrapping" (2006) were proposed. These new understandings and concepts function not only as important guidelines in oil and gas exploration in continental downfaulted basins in China, but also greatly enrich the Continental Petroleum Generation Theory [1–4]. In the past decade, major breakthroughs have been made in lithologic oil reservoirs in continental downfaulted basins, which have become important fields of oil and gas exploration. However, there is no clear statement on the main controlling factors and reservoir-forming models of their oil and gas, and single-factor analysis is mainly carried out around structural characteristics, fault characteristics, sedimentary characteristics, reservoir characteristics, source rock development characteristics, etc. [5–30].

Based on geological theories and technical research, combined with years of related work experience, the writer proposes a "Tri-in-one" accumulation model, in which fractures act as ties, together with the trinity of lithosome, effective source rock, and effective reservoir physical properties, in the formation of lithologic reservoirs in continental downfaulted basins. Multi-factor combination model analysis provides support for the subsequent identification of high-quality reservoirs and gold target selection.

2. Connotations of the "Tri-in-One" Hydrocarbon Accumulation Model

Among all factors, there must be one factor in a domain that influences subsequent developments. Perhaps, in the six controllers of "source, reservoir, cap, migration, trap and preservation", there lies one key factor controlling the others. The controlling factors and accumulation process of the lithologic reservoirs of the Nantun Formation in the Tanan Sag continental downfaulted basin were studied, and the results indicate that fractures and their combination mode control reservoir distribution, and are closely related to the development of source rocks, as well as their position and trap distribution. By recovering fault development and the processes of hydrocarbon generation, migration, accumulation, and dissipation, comparison and analysis were undertaken in both time and space domains. The results show an evident correlation between fault development and hydrocarbon accumulation in terms of the degree of development, time synchronism, and spatial matching. They either show mutual growth or decline, or are consistent with each other. The better the matching in time and space, the richer the hydrocarbons that are accumulated [31–35]. The allocation of sand type, effective source rock, and effective reservoir are optimized under the effect of fractures, and the hydrocarbon reservoirs are coupled with these three elements. Thus, the author builds up the "Tri-in-one" hydrocarbon accumulation model for lithologic reservoirs in continental downfaulted basins (Figure 1).

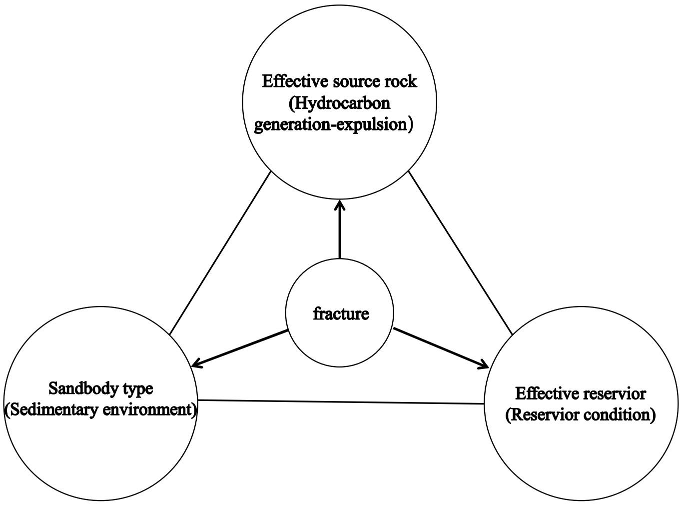

Figure 1. "Tri-in-one" hydrocarbon accumulation model of lithologic reservoirs in continental downfaulted basins.

2.1. Connotation of "Fracture Set"

Fracture set combination morphology is a reflection of fault kinematic characteristics. Different types of fracture exhibit different motions, which will cause different complex faults. Continental downfaulted basins are caused by the extension and subsidence of costal continental areas after the collision and subduction of oceanic plates. An asymmetric "half-graben structure" forms in continental downfaulted basins due to the special genetic mechanism of the basin [36,37]. Fault-screened reservoirs comprise a large proportion in eastern China, and over 90% of reservoirs are fault-controlled or -related [38,39]. Through study, it was concluded that fracture sets mainly have four effects in the hydrocarbon accumulation of continental downfaulted basins.

(1) Bridge function—Fractures function as bridges in the construction of the spatial allocation of lithologic bodies, source rocks, and reservoir physical properties.

Practices in hydrocarbon exploration have proven that fractures are very important in hydrocarbon accumulation. There is no doubt that they act as barriers and channels in hydrocarbon accumulation and migration, respectively. However, the role that fractures play in hydrocarbon accumulation has been studied limitedly within one basin or sag, with no consideration of the influences that may be caused by the different spatial allocation of these fractures in the basin or sag. The spatial relationships between fracture, source rock, and reservoir are different when the fracture's position changes in the basin or sag [40]. Although fractures still control petroleum accumulation and reservoir formation, they work differently and the effects vary considerably.

(2) Properties of sand control, hydrocarbon control, and reservoir quality control—Syngenetic fractures are very developed in ① continental downfaulted lake basins. These syndepositional fractures and their allocations generate the characteristics of "gully source control, fault-break sand control" in basining. Fractures control sandbody spatial distribution. Configuration in the plane controls sand dispersal systems through conducting, confining, separating, and adjusting activities. ② Fractures can affect source rock in two aspects, one of which is source rock spatial distribution. Downfaulted lake basin features include deep depression, a high division degree, and diversity depositional systems and types. Generally, several depocenters are contemporaneously developed due to regional tectonic elevating movements. The depocenter of a lake basin often shifts considerably in different geological periods, resulting in the generation of many hydrocarbon centers, which consist of different layer systems, complementary in spatial distribution, and characterized by "overlapped and connected sandbodies". A good environment for "Sag-wide Oil-Bearing" is created this way and sources for hydrocarbon generation in different zones and various traps are also provided; thus, a foundation for complementary hydrocarbon distribution is laid. The other aspect is that source rocks may form a low-mature reservoir [41] under the effects of fractures in the low-mature stage before the major oil generation period. Compared with mature source rock, it is often hard for low-mature source rock to reach hydrocarbon expulsion threshold of oil saturation. However, as long as fractures are developed in the area, it is possible for the primary migration and generation of a productive reservoir. ③ Control in physical properties presents as improvements in reservoir permeability caused by micro fracture or "reservoir petrophysical fracture". Usually they control the distribution of high-permeability zones, and the reservoir physical fault system that consists of these fractures is in control of the "dessert" area distribution in basin [42].

(3) Conducting effect—Fault zones act as key channels for hydrocarbon migration in continental downfaulted basins, in which synsedimentary faults are well developed. The conducting systems mainly present as a tridimensional fault complex that differ in scale or property. There is one thing in common, that one or more inherited regional faults must exist to provide channels; thus, oil and gas can migrate along these fractures from source bed on the bottom to reservoir bed on the top, and finally form a petroleum accumulation. The distribution of deep fractures and secondary fractures, especially those developed inside a lake basin with an extension ranging from several kilometers to tens

of kilometers, is always in control of the orientation of sags or subsags, as well as the formation development degree and sedimentary facies distribution. Moreover, sets of similar secondary faults and minor faults are derived, constructing combinations and relative conducting networks in "fault-steeped type", "ladder-shaped", "grid-type", and "chair-type" in space [43].

(4) Sealing effect—Fault sealing is the major determinant of the hydrocarbon enrichment degree in a fault screened reservoir. It is commonly accepted that fractures are in the main control of reservoir formation and destruction. Researchers such as Jones (1974), Price (1980), and Weker (1975) have considered that faults are conductors in oil and gas migration [31], whereas some claim that faults function as barriers [41] (Rerkkins, 1961; Smith, 1980; and Fowler 1971). Others have proposed the concept that faults play both roles of channel and barrier [44] (Seebarger, 1981; Chapmaw, 1981, Hooker, 1991; and Losh et al., 1999). The breakup of a sealing fault is good for further petroleum migration and accumulation, and fault sealing is the primary cause of variation in oil and gas aboundance in fault trap. Therefore, fault sealing analysis was highlighted in the study of fracture influences on hydrocarbon migration and reservoir accumulation. It is considered that as long as the time for unsealing and sealing is clear, the hydrocarbon enrichment degree in this fault trap can be evaluated.

2.2. Connotation of "Tri"

"Tri" here refers to the three fundamental geological elements of "sandstone type", "effective source rock", and "effective reservoir".

(1) Sandstone types are influenced by sedimentary environments and lithofacies paleogeography. The sedimentary environment controls reservoir distribution and development, and also has a considerable effect on reservoir lithology and physical property [42]. Structure factors and depositional environments affect petroleum accumulation and reservoir formation. Controlled by sedimentation in certain geological conditions, hydrocarbon accumulation is relatively rich, although only in traps with a specific sand type. Although lithologic reservoirs may develop in many sedimentary environments [45] (river channel, delta, coastal sand bar, and various kinds of turbidite fan), hydrocarbon potentials are not the same in different sandbodies formed in different sedimentary environments. During primary hydrocarbon expulsion, oil and gas mainly migrate upward or laterally toward basin margin. A reservoir itself is a good pathway without the influence of faults. Reservoirs themselves are good channels for hydrocarbon migration, without the effects of faults, in that oil and gas enter the reservoirs directly from source rocks through sandbodies, which means that turbidite sandstones surrounded by source rocks exhibit advantaged superiority for hydrocarbon accumulation [46].

(2) As source rock is buried deeper, abundant hydrocarbon is generated by thermal evolution. Only when it reaches the threshold depth, and after various hydrocarbon-involved actions such as self-adsorption, interstitial water solution, oil dissolution (gas), and capillary sealing have taken place, will free oil and gas begin massive migration or expulsion. Traps that are surrounded or contacted by source rock, or communicated by faults, are able to form reservoirs. As the buried depth increases, the intensity of hydrocarbon generation–expulsion grows and the trap is more petroliferous.

(3) Sandbody poro-perm characteristics and grain size sorting properties (differential) are also controlling factors of oil and gas charging in lithological trap. Only when sandbody porosity and permeability reach critical values can the sandbody be able to keep hydrocarbons coming from outside. Better physical properties mean that the trap has higher potential. Through experiments, researchers have found that sandbodies with larger grain sizes are petroliferous, while smaller grain sizes may indicate no oil or gas accumulation. Experiments on the reservoir formation of lithologic sandbodies have also proven that oil and gas cannot be accumulated to form lithological reservoirs unless the grain size of the sandbody reaches a certain level [47–50].

The type of sandbody indicates a sedimentary environment. Burier depth and hydrocarbon expulsion intensity are employed to describe the hydrocarbon generation and expulsion conditions of wall rock. Physical properties demonstrate the accumulation conditions of this sandbody. The trap can perform accumulation when all these three elements are in certain conditions, and the better the conditions are, the higher hydrocarbon potential the trap has (Table 1).

Table 1. Basic information of the "Tri-in-one" reservoir formation model.

Category		Mechanism of Action
The Meaning of One	Fracture combination	Bonding effect; control effect; conducting effect; sealing effect
The Meaning of Three	Sandstone	Oil and gas enrichment; oil and gas migration; effective source rock
	Effective source rock	Oil and gas accumulation; oil and gas migration
	Effective reservoir	Oil and gas storage

3. Control of Fault Combination, Sandbody Type, Effective Source Rock, and Effective Reservoir on Oil and Gas

3.1. Sandstone–Mudstone Combination Optimization and Lithologic Reservoir Distribution Controlled by Fracture Set

The configuration of sand type, effective source rock, and effective reservoir is optimized under the effect of fractures, and coupled reservoirs with these three elements. Tanan sag is a typical continental downfaulted lake basin with greatly developed syngenetic fractures. These synsedimentary faults and their configuration have caused basining features of "gully source control, fault-break sand control" in Tanan sag. Fractures are in control of sandbody spatial distribution; moreover, micro fractures have greatly improved physical properties of low-porosity and low-permeability reservoirs. On the hanging wall and foot wall, dark mudstone and sandstone are connected within the hydrocarbon expulsion threshold; thus, a "three in one" configuration is formed within the lithosome, source rock, and reservoir.

Based on known reservoir type, distribution and reservoir-forming features, combined with formations such as the geologic configuration of subsags and fault slope type in the Tamtsag exploration area, four hydrocarbon accumulation modes in Tanan sag are concluded as follows: terrace fault steep-slope break mode; terrace fault gentle-slope break mode; fault scrap steep-slope break mode; and intrabasinal slope break mode (Figure 2). As shown in Figure 2, lithologic reservoirs all developed along fractures in different tectonic units of Tanan sag. Sandstone–mudstone contact relationships vary in different positions of fracture. Thus, a lithologic reservoir is likely to form under such conditions: the basin shape is controlled by first-order faults on basin margins, while the spatial distribution of sand rock and source rock is controlled by syndepositional faults; sand disperse systems are conducted, confined, separated, or adjusted by fractures developed in accommodation zones and transfer zones; and distal sublacustrine fans or subaqueous turbidite fans, which are developed on the thrown side of faults, exist on the slope break of the basin, and make full contact with sublacustrine dark mudstone.

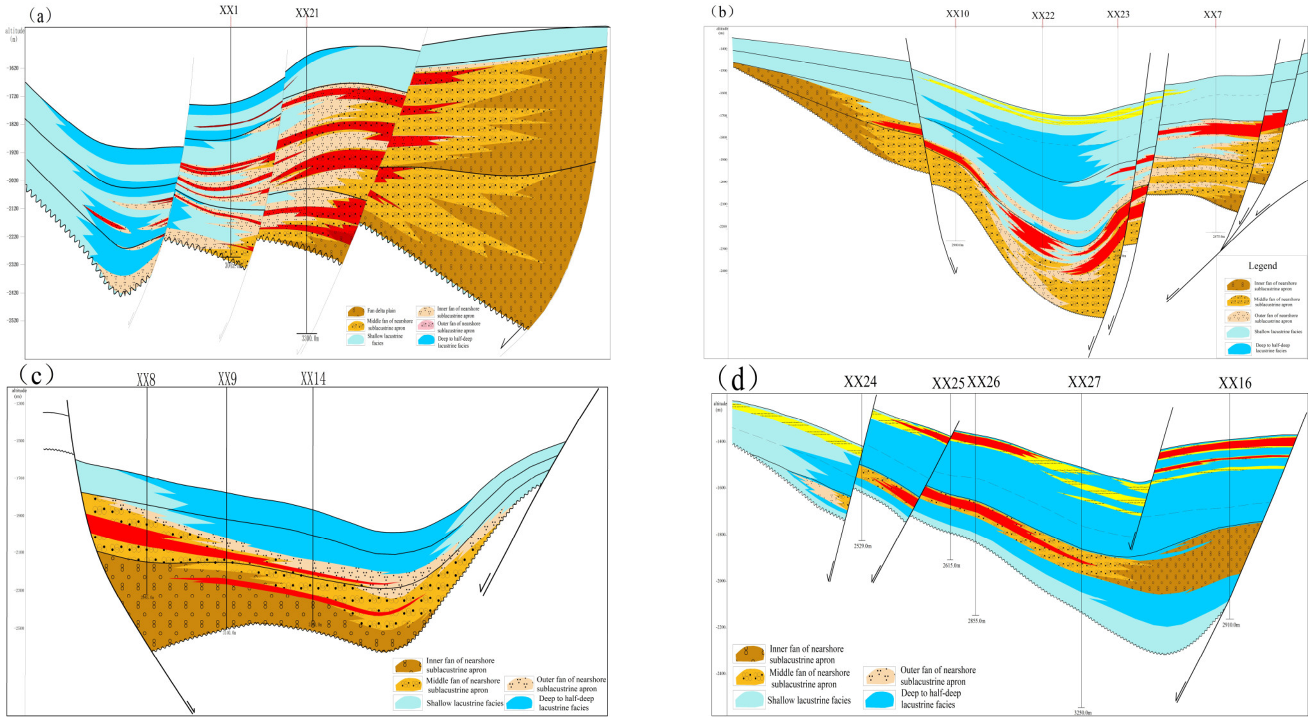

Figure 2. Typical reservoir forming modes in Tanan sag ((**a**–**d**) are in represent of terrace fault steep-slope break mode, terrace fault gentle-slope break mode, fault scrap steep-slope break mode, intrabasinal slope break mode, respectively).

3.2. Lithologic Reservoir Distribution Controlled by Sandbody Type

(1) Sand-control effects of basin margin gully and fault slope.

Paleostructural and paleogeomorphologic features are in direct control of sequence development. As a key tectonic unit, sedimentary slope controls the development of main stratigraphic sequences in basin, and sequence types that generated on slopes with different paleogeomorphologic features varies greatly. As the most typical paleogeomorphologic units, "gully" and "fault-slope zone" are in control of favorable reservoir sandbody distribution. Researches on sequence stratigraphy in Tanan sag indicate that only the position of fan is determined by basin margin gully, while its scale and thickness are determined by sandbody types that controlled by different syndepositional structure fault-slopes. Thus, the type of lithologic reservoir is further controlled (Figure 3).

Basin margin gullies on steep or gentle slopes in Tanan sag are lake inlets of rivers. Parallel (terrace fault) slope break zones, cross fault slope break zones, brush fault slope break zones, and comb fault slope break zones control sandbody thickness, and their strikes influence sandbody distribution. Thick lowstand sandbodies are developed in major structural slope break zones of sag; in addition, excellent lake transgression source rocks and highstand source rocks are developed in this area. These high-quality source rocks developed on lowstand sandbodies can function as cap rocks, as well as hydrocarbon generators, and make up a good combination of "source, reservoir and cap". Meanwhile, active slope break fractures can serve as conducting system for hydrocarbon migration and communicate source bed with sandbodies, which are developed at both sides of the slope break. Slope break fractures act as reservoir caps during their stable periods; therefore, hydrocarbon-enriched zones of lithologic reservoirs are developed at where structural slope break zones, lowstand sandbodies, and lake transgression source rocks are effectively configurated at Tanan sag.

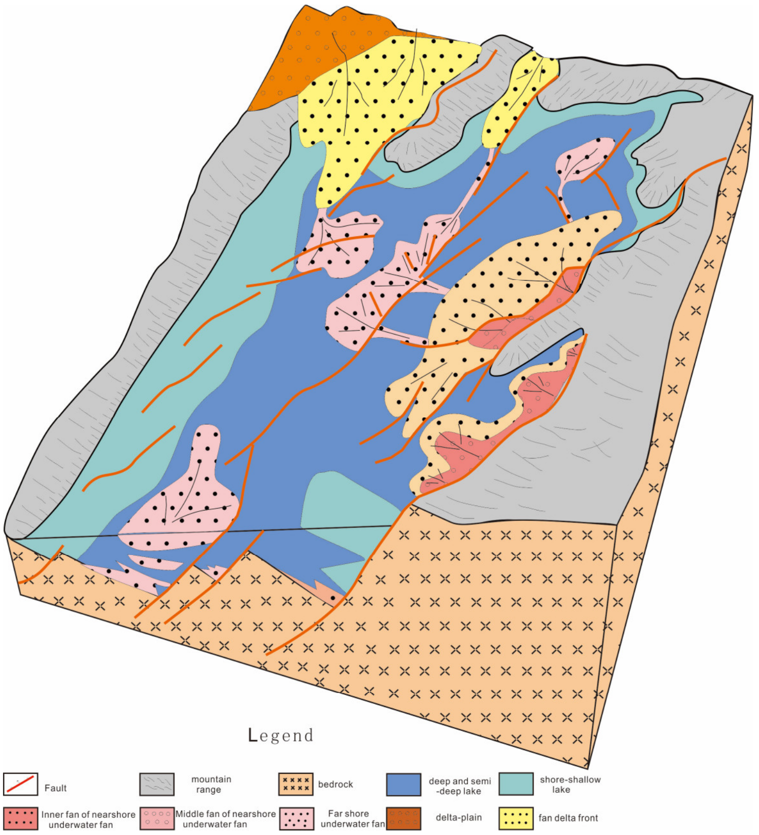

Figure 3. Paleostructure background and sedimentation model, Nantun Formation of Tanan sag.

(2) The Control Effect of Sandstone Types on Lithological Oil Reservoirs.

For lithologic reservoirs and structural–lithologic reservoirs of the Nantun Formation of Tanan sag, sandbodies are mostly developed in places such as nearshore subaqueous middle-fan, distal subaqueous fan, fan-delta front, and delta front, which are controlled by boundary faults and sag-controlled faults (Figure 4). Rock types are mainly glutenite, fine sandstone, and siltstone. It has been found through exploration and development that the sandbody distribution is controlled by sedimentary facies. Lithologic sandbodies are developed with good hydrocarbon potential in places such as the nearshore subaqueous middle-fan of steep slope zones, the fan-delta front of gental slope zones, and the delta front, followed by nearshore outer-fan and distal subaqueous fan (Table 2).

Table 2. Major sedimentary microfacies and rock types in the Tamtsag exploration area.

Block	Structural Type	Oil-Bearing Area	Number of Wells	Reservoir Thickness	Reservoir Lithology	Sedimentary Facies	Hydrocarbon Filling Degree
		km^2		m			%
XX1	Lithologic reservoir	7.33	4	30	Glutenite, siltstone	Nearshore subaqueous middle-fan	24.43
XX2	Lithologic reservoir	2.32	3	96	Siltstone, grit stone, glutenite	Nearshore subaqueous middle-fan	2.42
XX3	Lithologic reservoir	3.12	2	200	Fine sandstone, siltstone, glutenite	Nearshore subaqueous middle-fan	1.56
XX4	Lithologic reservoir	1.09	1	15	Fine sandstone, siltstone	Nearshore subaqueous outer-fan	7.27
XX5	Lithologic reservoir	3.32	3	80	Siltstone, fine sandstone	Nearshore subaqueous middle-fan	4.15

Table 2. *Cont.*

Block	Structural Type	Oil-Bearing Area	Number of Wells	Reservoir Thickness	Reservoir Lithology	Sedimentary Facies	Hydrocarbon Filling Degree
		km^2		m			%
XX6	Structural–lithologic reservoir	1.32	1	400	Glutenite, fine sandstone	Nearshore subaqueous middle-fan	0.30
XX7	Structural–lithologic reservoir	7.26	6	60	Fine sandstone	Nearshore subaqueous middle-fan	9.44
XX8	Structural–lithologic reservoir	4.72	5	50	Siltstone	Nearshore subaqueous outer-fan	7.59
XX9	Structural–lithologic reservoir	11.38	10	150	Glutenite, fine sandstone	Nearshore subaqueous middle-fan	3.92
XX10	Structural–lithologic reservoir	0.98	1	25	Glutenite, fine sandstone	Nearshore subaqueous inner/middle-fan	1.50
XX11	Structural–lithologic reservoir	0.60	1	40	Siltstone	Nearshore subaqueous outer-fan	2.76
XX12	Structural–lithologic reservoir	1.93	1	70	Fine sandstone	Distal subaqueous fan	3.97
XX13	Structural–lithologic reservoir	3.97	21	100	Siltstone, fine sandstone	Distal subaqueous fan	1.33
XX14	Structural–lithologic reservoir	0.60	1	45	Fine sandstone, glutenite	Nearshore subaqueous middle-fan	0.33

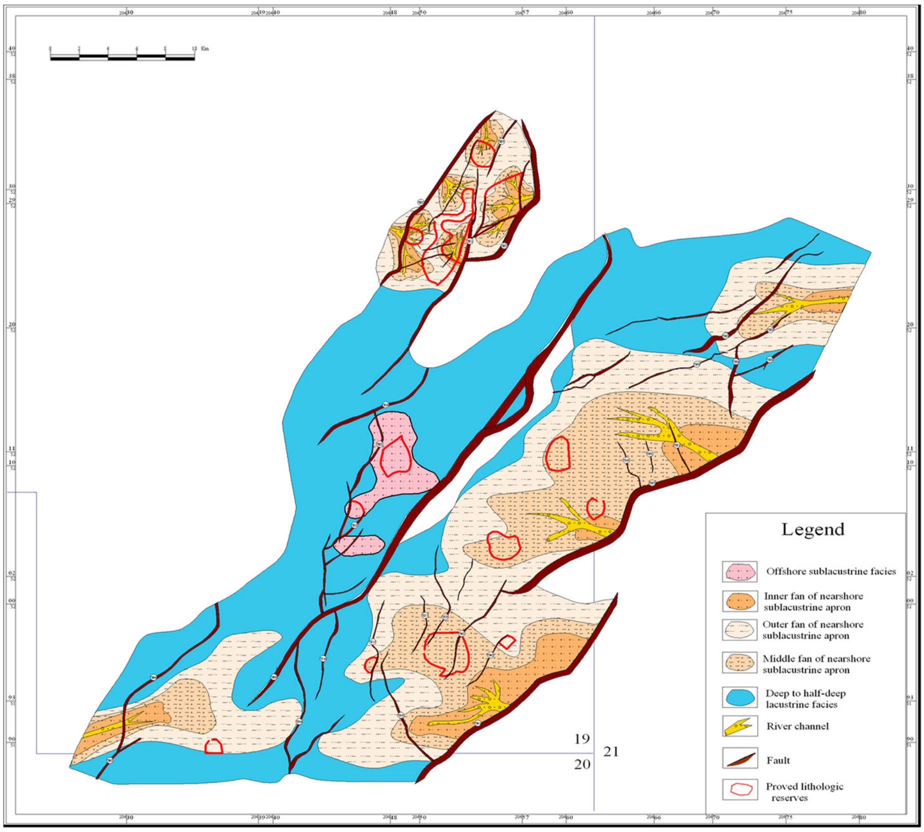

Figure 4. Overlay map of sedimentary facies, sag-controlled faults, and lithologic reservoir distribution.

3.3. Lithologic Reservoir Size Is Controlled by Effective Source Rock

Judging from the current research results, the distribution of effective source rock is apparently related to the lithologic reservoir formation. Four types of position relationships between effective source rocks and lithologic reservoirs can be concluded as follows:

(1) lithologic reservoir inside source rock; (2) lithologic reservoir outside source rock; (3) lithologic reservoir over source rock; and (4) lithologic reservoir under source rock

As source rock is buried deeper, abundant hydrocarbon is generated by thermal evolution. Only when it reaches threshold depth, and after various hydrocarbon-related actions such as self-adsorption, interstitial water solution, oil dissolution (gas), and capillary sealing have taken place, will free oil and gas begin mass migration or expulsion. With the increase in the intensity of hydrocarbon generation and expulsion, the trap is more petroliferous near oil and gas generation–expulsion centers. In Tanan sag, oil-bearing characters in the vertical and horizontal planes are controlled by effective source rocks and hydrocarbon expulsion peaks (Figure 5). The hydrocarbon expulsion threshold depth is around 2500 m in the Nantun Formation of Tanan sag (Figure 6), and hydrocarbon expulsion peak appears between 2600 and 3000 m; thus, the lithologic reservoirs of Tanan sag are mainly developed at depth ranging from 2500 m to 3000 m. As the burial depth increases, oil shows interval of this productive lithologic reservoir first increases and then decreases (Figure 5). Judging from the positions between traps and expulsion counters of effective source rocks, all isolated sandstone lithologic reservoirs are discovered within hydrocarbon expulsion scope or on the hydrocarbon expulsion boundary of effective source rocks, for example, lithologic reservoirs and structural–lithologic reservoirs in XX2, XX10, XX7, XX8, and XX9 blocks in the north trough of west subsag and XX3, XX5, XX1, and XX11 blocks in east subsag, as well as lithologic reservoirs in XX4 block in the south trough of middle subsag (Figure 7). However, structural reservoirs in XX15, XX16, XX17, and XX18 blocks, which are conducted by fractures in the highstand of Nantun Formation, are exceptions in this case. Traps that form in the center and are surrounded by source rocks in the Nantun Formation are more petroliferous than those laterally connected to source rocks. The closer to the center, the more oil and gas are accumulated in the trap (Figure 8). In other words, lithologic reservoirs are usually high-quality, where hydrocarbon expulsion is intensive, and vice versa. Figure 8 shows the relationship between the trap filling degree and the hydrocarbon expulsion intensity in lithologic reservoirs and structural reservoirs. Judging from this picture, the trap filling degree is closely related to the expulsion intensity in lithologic reservoirs; however, it is less affected by oil abundance in structural reservoirs in the Nantun Formation. This means that hydrocarbon has to migrate a long way before accumulating in a structural trap, while lithologic traps are usually close to the oil sources.

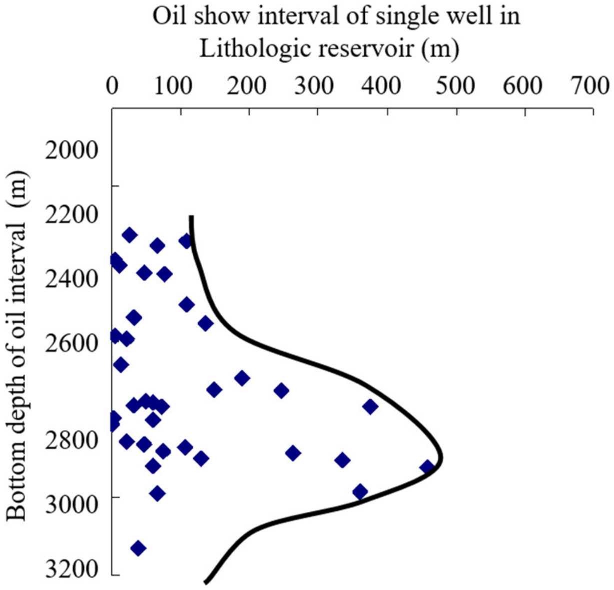

Figure 5. Relationship between oil shows the interval and depth in the lithologic reservoir in the Nantun Formation of Tanan sag.

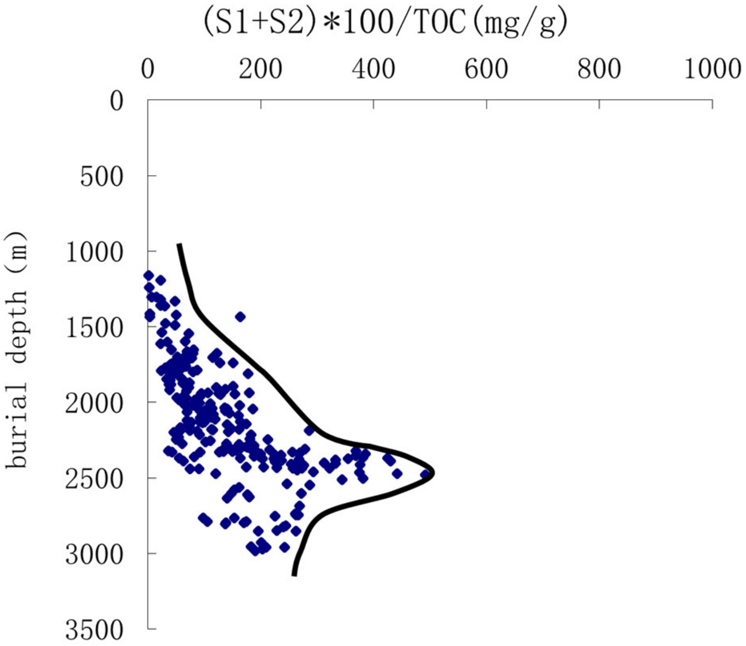

Figure 6. Hydrocarbon expulsion threshold of source rock in the Nantun Formation of Tanan.

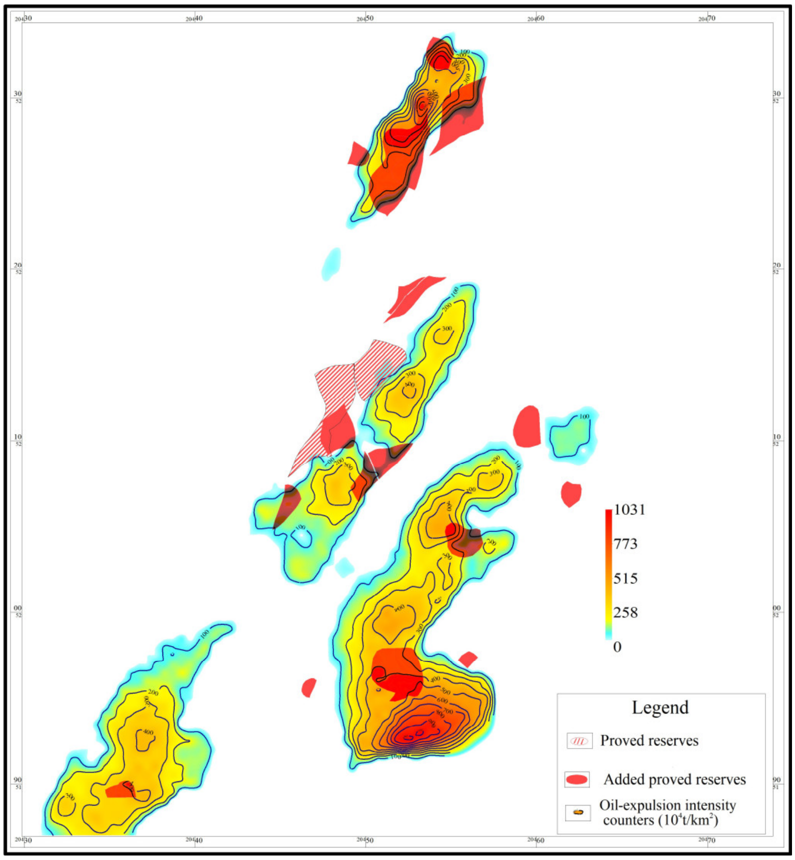

Figure 7. Overlay maps of the oil-expulsion intensity and oil-bearing area (1P) in the Nantun Formation of Tanan sag.

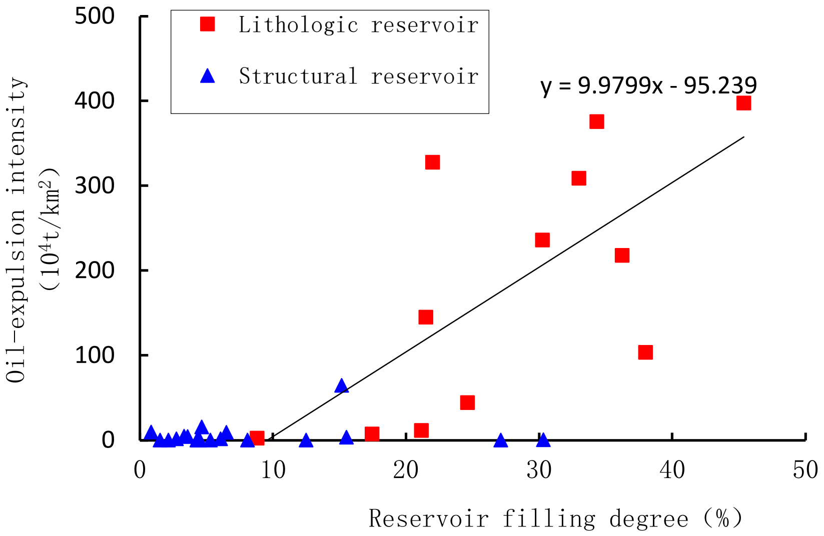

Figure 8. Relationship between the trap filling degree and hydrocarbon expulsion intensity in Tanan sag.

3.4. Hydrocarbon Enrichment Degree Controlled by Effective Reservoirs

(1) Impacts of reservoir physical properties on lithologic reservoir accumulation.

In addition to exterior sedimentary conditions and resource rocks, gas and oil in lithologic reservoirs are controlled by reservoir conditions of the sand rocks themselves. In the process of burial compaction, pore throat radiuses between rock particles decrease as the burial depth increases. Compactions between sand rocks and mud stones differ from each other under the same burial conditions. Compaction for mud stones is greater than that of sand rocks, resulting in different throat radiis. Due to the different radii, the difference between pore throat capillary pressures becomes a cause of lens reservoirs. In the deep trough zones, because of deep burial depth, high temperature, and great pressure, organics are highly evolved and the phase state of crude oil changes with the evolution. As the burial depth increases in trough zones, crude oil changes from medium oil into light oil, and eventually become condensate gas, and phase state of oil transmits from single state into gas-oil mixed state and eventually becomes gas. For example, the reservoir revealed at 2896–2905 m by the XX1 Well in Tanan Sag of Tamtsag Basin is a nearly condensate gas reservoir, with a density of crude oil of 0.76 g/cm. In addition, for the same Tanan Sag, revealed by wells such as XX19, XX20, etc., the oil and gas phase state at the burial depth has evolved into a gas–oil mixed state. As a result of the changes in crude oil and phase states, the oil density and viscosity of the deep buried tight layers decrease, physical properties of the layers are suitable for low-density and low-viscosity gas and oil to form industrial reservoirs (Figure 9). These lead to broadened enrichment and an accumulation of oil and gas in trough zones.

The burial depth of the industrial reservoir in Tanan Sag is between 1600 m and 3200 m and average porosity at 3200 m is about 5%. Statistics between porosity and permeability show that, under the current fracturing technology, gas and oil in the lithologic reservoir accumulate in sandbodies with a porosity higher than 4.5% and permeability higher than 0.01 mD (Figure 10). It is generally concluded from the data of unbroken cores that, under the current fracturing technology, the low limits of porosity and permeability for lithologic reservoirs are 5% and 0.01 mD, respectively; oil bearing and space filling factors increase with the physical properties of the reservoir. It is obvious in Figure 10 that, for the NanTun groups in Tanan Sag, average oil saturation is directly proportional to the average porosity. Consequently, better physical properties of the sands are suitable for hydrocarbon expulsion, accumulation, and reservoir formation of exterior resource rocks into the sands.

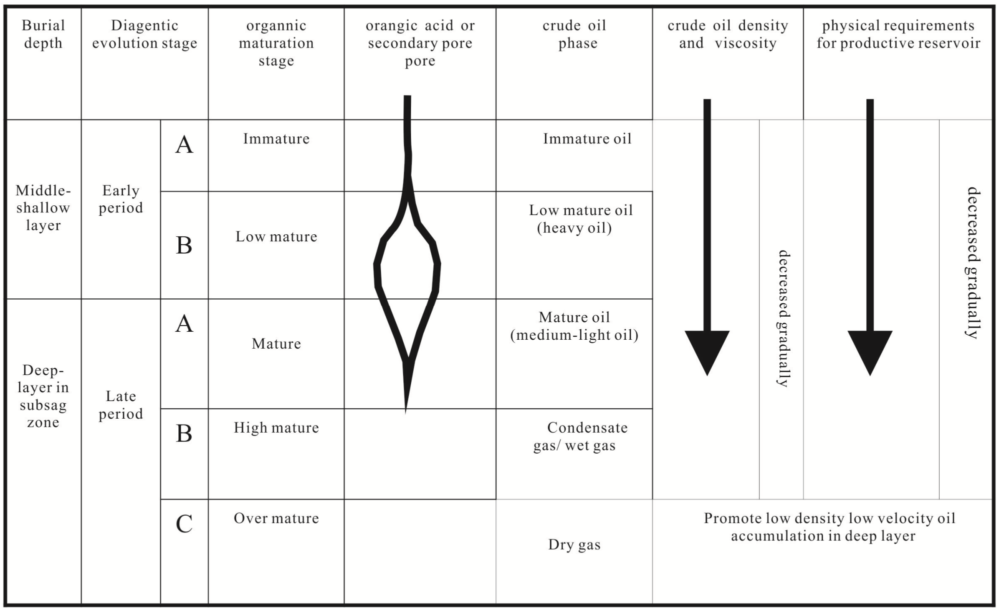

Figure 9. Diagenetic evolution, hydrocarbon phase change, and their requirements for reservoir quality [32].

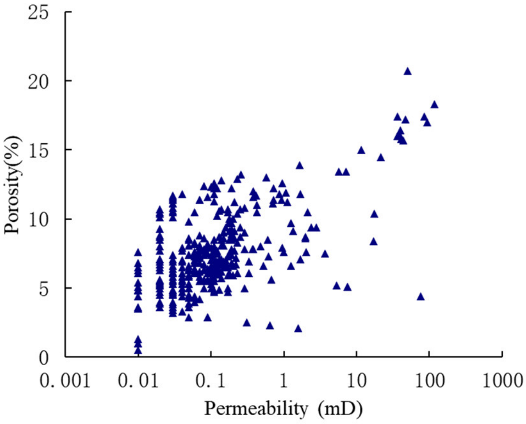

Figure 10. Poro-perm relationship in the lithologic reservoir in the Nantun Formation of Tanan sag.

(2) Impacts of reservoir shale content on lithologic reservoir accumulation.

Certain minerals in the reservoir react with water to cause lattice expansion, dispersion, or fragmentation, resulting in blocked pores, throats, and decreased permeability. These are called water-sensitive minerals and have a great capacity for cation exchange. Clays are normal water-sensitive minerals; typical examples are smectite and illite–smectite. In addition, kaolinite, illite and chlorite are also strongly water-sensitive. Due to the strong hydratability of sodium ions and weak gravitational forces between crystal layers, crystal layers of smectite hydrate and expand with outer water molecules. The expanded smectite further disperses and migrates with flow liquid, causing water sensitivity damage and velocity sensitivity damage to the oil layers. These eventually lead to hard reservior development and have a certain influence on research on the distribution of lithologic reservoirs.

Research has been performed on lithologic reservoirs in Tanan sag, where tuffaceous sandstones (conglomerates) are well developed; the results show relatively high degrees of water sensitivity and acid sensitivity in this area, strong evidence that correlations exist between reservoir sensitivity and rock type. Argillaceous fractions such as clay minerals are responsible for the reservoir sensitivity in Tanan sag. A positive correlation exists between clay mineral and reservoir water-/velocity-sensitive damages.

The Nantun Formation of Tanan sag mainly formed in the early–middle peak period of rifting; nearshore subaqeous fans are the major sedimentary system in this area, dominating by turbidite deposit. Thus, reservoirs are poorly situated with relatively high shale contents. Figure 11 depicts an average shale content histogram of reservoirs in the lowstand of the north trough of east/west subsag of the Nantun Formation. The overall shale content in reservoirs of the Nantun Formation of Tanan sag is relatively high, with an average value of 32.8%. Large-scale conglomerates are developed in lowstand sandbodies in the north trough of west subsag, with relatively low shale contents of 20% on average, which is main reason for the subsag-wide oil-bearing capability in this area. However, in east subsag where source rock and reservoir bed are both developed, high shale contents may result in water sensitivity during fracture treatment, and ultimately cause difficulties in production. Figure 12 shows the relationship between shale content and reservoir output in the Nantun Formation of Tanan sag. When the production rate is over 5 t/d, there is a negative relationship between the production rate and shale content, which indicates that reservoir output is strongly constrained by the shale content.

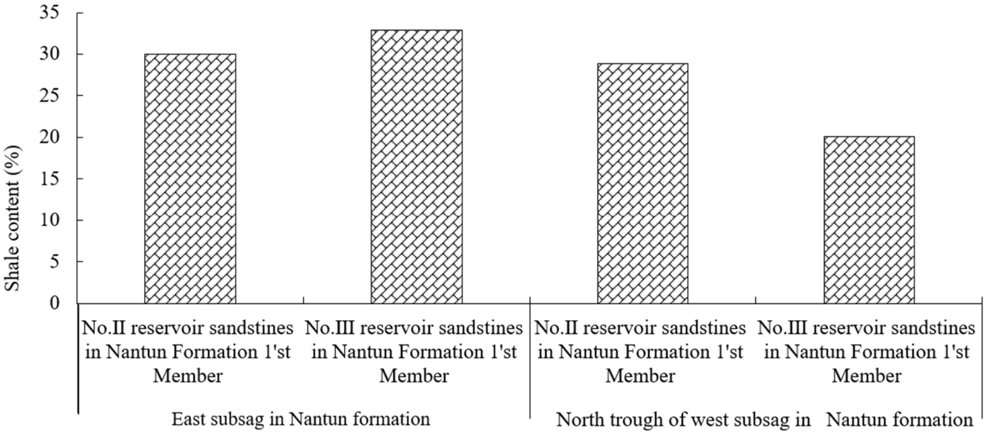

Figure 11. Average shale content histogram of the reservoir in the Nantun Formation of Tanan sag.

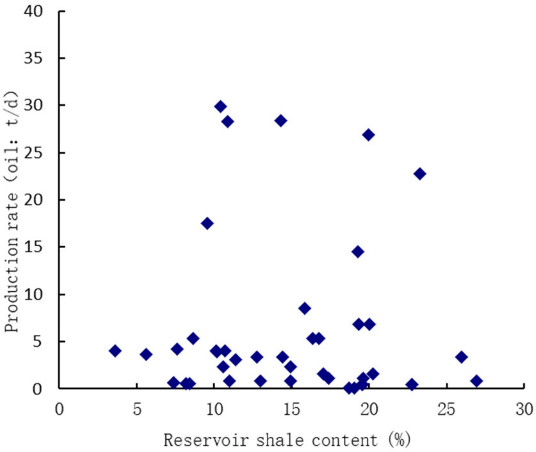

Figure 12. Relationship between the shale content and reservoir output in the Nantun Formation of Tanan sag.

4. Discussion

The reservoir formation model summarized in this article is based on the establishment of lithologic oil reservoirs in continental downfaulted basins, which exhibit good adaptability [51]; through detailed analysis of fault characteristics, sedimentary facies characteristics, source rock characteristics, and reservoir characteristics of lithologic reservoirs in the Nantun Formation of the Tanan Sag, a continental fault depression basin, the author has summarized three main controlling factors of sandbody type, effective source rock, and effective reservoir, as well as the “Tri-in-one” reservoir forming model of a coupling factor, which has certain theoretical basis and scientific role [52–54]. There are differences in specific parameters between effective source rocks and effective reservoirs [55–57]: for fault basins, faults are generally contemporaneous, with a high probability of sand and mud docking between the two layers of sandstone and mudstone. The lateral sealing ability is good, and it is easy to form lithological oil and gas reservoirs formed by fault sealing; in sandstone, the main types are dominant sandbody combinations distributed near faults. Different blocks may have different types of favorable sandbody combinations. For the Tanan Depression, it has been found through exploration and development that the sandbody distribution is controlled by sedimentary facies. Lithologic sandbodies are developed with good hydrocarbon potential in places such as the nearshore subaqueous middle-fan of steep slope zones, the fan-delta front of gental slope zones, and the delta front, followed by nearshore outer-fan and distal subaqueous fan; lithologic reservoirs are generally near source reservoirs. Therefore, effective source rock mainly refers to mature source rock below the hydrocarbon expulsion threshold. The hydrocarbon expulsion threshold of source rock varies greatly in different blocks. The hydrocarbon expulsion threshold depth is around 2500 m in the Nantun Formation of Tanan sag and the hydrocarbon expulsion peak appears between 2600 and 3000 m; thus, lithologic reservoirs of Tanan sag are mainly developed at depths ranging from 2500 m to 3000 m. For high-quality reservoirs with effective reservoir performance above the lower limit of reservoir physical properties, and lithological reservoirs, sandstone is relatively dense and the physical reservoir properties are generally small. Through comprehensive research on the lower limit of porosity and permeability of industrial reservoirs in the Tanan Depression, the low limits of porosity and permeability for lithologic reservoir are 5% and 0.01 mD, respectively. Oil bearing and space filling factors increase with the physical properties of the reservoir.

5. Conclusions

(1) Through detailed analysis of structural characteristics, sedimentary evolution, sedimentary facies type, source rock characteristics, and reservoir characteristics of lithologic reservoirs in the Nantun Formation of the Tanan Sag, combined with years of work experience, three main controlling factors of sandbody type, effective source rock, and effective reservoir, as well as a “Tri-in-one” reservoir forming model of coupling factors, are summarized. Fractures and their combinations not only control reservoir distribution, but are also closely related to source rock development and lithologic trap distribution. When time–space relationships between fault development and reservoir formation processes are good, oil and gas accumulation is abundant. Under the effect of fractures, the best spatial relationship constitutes sandbodies, dark mudstones, effective reservoirs, and coupled hydrocarbon reservoirs. As a typical continental downfaulted lake basin, Tanan sag has many contemporaneous fractures, as well as the “gully source control, fault-break sand control” basining characters, which are determined by synsedimentary fractures and their configurations. These fractures control of sandbody distribution. On the hanging wall and foot wall, dark mudstone and sandstone are connected within the hydrocarbon expulsion threshold; thus, a “Tri-in-one” configuration is formed among lithosome, source rock, and reservoir.

(2) Structural factors and sedimentary environment of lithologic reservoir can influence hydrocarbon accumulation and reservoir formation. Affected by sedimentary actions, abundant hydrocarbons only accumulate in traps formed by certain sandbody types under particular geological conditions. Lower parts of various slope break zones, nearshore subaqueous fans, fan delta sandbodies, and turbidite sandbodies in Tanan sag have good chances of forming lithologic traps.

(3) With the increase in depth, sufficient hydrocarbon is generated in source rock under thermal evolution. Hydrocarbon generation and expulsion are more intensive when it comes to the depth threshold and critical conditions of hydrocarbon supplying are

met. Traps that are surrounded or are in contact with source rock, or communicated by faults, can form reservoirs. As the buried depth increases, the intensity of hydrocarbon generation–expulsion grows and the trap is more petroliferous.

(4) Hydrocarbon accumulation and reservoir formation are also controlled by sandbody accumulation conditions. When the critical conditions of hydrocarbon generation and concrete are met, oil and gas are charged in; better physical properties of the sandbody always indicate more hydrocarbon accumulation in the trap.

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References

1. Liu, Z.; Chen, Y.P.; Zhao, Y.; Hao, Q.; Xu, X.M.; Chang, M. Distribution and controlling factors of hydrocarbon reservoirs in continental downfaulted basins. *Lithol. Reserv.* **2007**, *19*, 121–127. (In Chinese)
2. Li, P.L. Zonary distribution of hydrocarbon in oil enriched rifted basins and exploration direction in the Huimin sag. *Pet. Exp. Geol.* **2001**, *23*, 146–148. (In Chinese)
3. Zhang, Y.F. Modelling Experiments of Lithologic Reservoirs Formation in Source Rocks and Its Accumulation Mechanism Analysis. *Lab. Res. Explor.* **2001**, *20*, 103–106. (In Chinese)
4. Zhao, W.Z.; He, D.F.; Chi, Y.L.; Lei, Z.Y.; Qu, H. Major characteristics and exploration technology of muti-source petroleum systems in China. *J. Pet.* **2001**, *22*, 6–13. (In Chinese)
5. Gao, X. Analysis of ridge fault circle coupling reservoir control in Huizhou Sag of the Pearl River Mouth Basin. *Contemp. Chem. Res.* **2023**, *6*, 55–57. (In Chinese) [CrossRef]
6. Tang, Y.; Ji, J.; Guo, W.J.; Chen, H.; Li, Y.Y.; Dong, F. Structural characteristics and reservoir control of Middle/Upper Permian unconformity in the east of Fukang Sag, the Junggar Basin. *Pet. Geophys. Explor.* **2022**, *57*, 1138–1147+1005. (In Chinese) [CrossRef]
7. Chen, S.G.; Zhu, Q.Z.; Zhang, R.F.; Liu, X.H.; Wang, S.C.; Tian, N.; Zhang, X.M.; Wang, J.G.; Liang, Q.J. Formation, evolution, and reservoir control of the Jilantai tectonic belt in the Hetao Basin. *J. Chengdu Univ. Technol. Nat. Sci. Ed.* **2022**, *49*, 533–541. (In Chinese)
8. Bao, H.P.; He, D.F.; Wang, Q.P.; Zhang, L.; Zhang, J.W.; Yan, T.; Yan, W. Four main palettes evolution in Ordos Basin and their differences in significance of oil and gas reserve control. *J. Paleogeogr.* **2022**, *24*, 951–969. (In Chinese)
9. Sun, X.D.; Xiao, W.H.; Bai, J.; Zhang, Y.C.; Yuan, Y.C.; Chen, S. Characteristics and reservoir-controlling effect of the Kulongshan buried structure. *Pet. Geophys. Explor.* **2022**, *57*, 236–242+19. (In Chinese)
10. Wang, X. Characteristics of the strike-slip faults in Jinghe Chang 8 reservoir and their influence on hydrocarbon accumulation. *Petrochem. Appl.* **2021**, *40*, 101–105. (In Chinese)
11. Liu, L. Study on the Deformation Mechanism of Strike Slip Oblique Extension Faults and Their Control on Oil and Gas Accumulation in Penglai 25–31 Block in the Bohai Sea. Ph.D. Thesis, Northeast Petroleum University, Daqing, China, 2022. (In Chinese) [CrossRef]
12. Martirosyan, A.V.; Martirosyan, K.V.; Mir-Amal, A.M.; Chernyshev, A.B. Assessment of a Hydrogeological Object's Distributed Control System Stability. In Proceedings of the 2022 Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus), Saint Petersburg, Russia, 25–28 January 2022; pp. 768–771. [CrossRef]
13. Guo, H.Y. The Control of the Qinan Fault on the Formation of Oil and Gas Reservoirs in the Lower Shale Formation. Ph.D. Thesis, Northeast Petroleum University, Daqing, China, 2021. (In Chinese)
14. Du, X.D.; Peng, G.R.; Wu, J.; Zhang, Z.W.; Xu, X.M.; Zhu, D.W. Characteristics of Yangjiang East Depression Fault in the Pearl River Mouth Basin and Its Impact on Oil and Gas Accumulation. *Xinjiang Pet. Geol.* **2020**, *41*, 414–421. (In Chinese)
15. Ma, Z.Z. Study on the Characteristics and Main Controlling factors of Oil and Gas Accumulation in the Kong2 Member of the Cangdong Depression. Ph.D. Thesis, China University of Petroleum (Beijing), Beijing, China, 2020. (In Chinese) [CrossRef]
16. Wang, Y.F. Source Control of Oil and Gas Accumulation in Qikou Depression. Ph.D. Thesis, China University of Petroleum (Beijing), Beijing, China, 2020. (In Chinese) [CrossRef]

17. Luo, Q.; Hong, L.; Gao, Y.; Deng, Y.; Li, Y.Y.; Wang, S.C.; Ma, W.Y.; Xu, Q. Differential enrichment mechanism and reservoir control model of tight oil source reservoir associations: A case study of Qingxi Depression in Jiuquan Basin. *Pet. Exp. Geol.* **2023**, *45*, 1–10+19. (In Chinese)
18. Jia, X.L.; Yao, Z.S.; Xu, X.J. Analysis of Controlling factors for Jurassic Tight Sandstone Gas Reservoirs in Qiudong Depression. In Proceedings of the 2022 International Conference on Oil and Gas Field Exploration and Development III, Urumqi, China, 16–18 August 2022; pp. 404–413. (In Chinese)
19. Zhao, Z.L.; Zhao, J.Z.; Er, C. A Method for Judging the Control of Transportation and Reservoir by Combining Fault Sand Cover Elements. CN114624786A, 14 June 2022. (In Chinese)
20. Wang, Q.H.; Chen, Y.Q.P.; Hu, F.J. Lower Paleozoic carbonate cap rocks and their reservoir control in the Tarim Basin: A case study of the Tarim Platform. *Nat. Gas Geosci.* **2023**, *34*, 1–14. (In Chinese)
21. Zhang, W.G. Study on reservoir characteristics and main controlling factors of reservoir formation in the middle and lower part of the Yanchang Formation in the southeastern Tiebiancheng Block of Jiyuan Oilfield. Ph.D. Thesis, Northwest University, Xi'an, China, 2020. (In Chinese) [CrossRef]
22. Dong, C.Y.; Liu, Z.; Liu, Q.D.; Luo, B.W.; Li, C.H.; Wang, W.J. Study on the Fault Lithological Reservoir Formation System and Main Controlling factors of the Dainan Formation in Gaoyou Depression. *Pet. Exp. Geol.* **2013**, *35*, 395–400. (In Chinese)
23. Li, Q.; Miao, H.; Li, L.; Wang, L. Gas accumulation characteristics and main controlling factors of deep clastic rock in Changling fault depression in southern Songliao Basin. *China Pet. Explor.* **2009**, *14*, 34–39+9. (In Chinese)
24. Yang, Y. High yield law of shale oil enrichment in Jiyang continental downfaulted basin. *Oil Gas Geol. Recovery* **2023**, *30*, 1–20. (In Chinese) [CrossRef]
25. Zhang, S.C.; Wang, X.J.; Wang, X.H.; Zhu, R.F.; Qiu, Y.B. Differences and characterization of reservoir forming fluid dynamics in continental downfaulted basins. *Pet. Exp. Geol.* **2022**, *44*, 941–949. (In Chinese)
26. Zhou, Q. Characteristics and classification of tight oil reservoirs in continental downfaulted basins. *Geol. Resour.* **2019**, *28*, 30–34. (In Chinese) [CrossRef]
27. Sun, X.D.; Wu, C.L.; Sui, Z.Q.; Mao, X.P. Simulation of oil and gas migration and accumulation based on continental downfaulted basins. *J. Xi'an Pet. Univ. Nat. Sci. Ed.* **2015**, *30*, 1–6+112. (In Chinese)
28. Cao, Y.C.; Chen, L.; Kang, X.W.; Gao, Z.S. Slope break zone theory and exploration overview of subtle oil and gas reservoirs in continental downfaulted basins. *Shaanxi Coal* **2014**, *33*, 47–50+28. (In Chinese)
29. Song, L.; Zhang, Y.G.; Mou, M.; Wang, N.; Zhang, X.J.; Zhang, E. Oil and gas migration and accumulation under overpressure systems in continental downfaulted basins: Taking the Chexi area of Chezhen depression as an example. *Oil Gas Geol. Recovery Rate* **2014**, *21*, 28–32+112–113. (In Chinese) [CrossRef]
30. Martirosyan, A.V.; Ilyushin, Y.V. Modeling of the Natural Objects' Temperature Field Distribution Using a Supercomputer. *Informatics* **2022**, *9*, 62. [CrossRef]
31. Di, L.J. Controlling of petrophysical fractures on extra-low permeability oil and gas reservoirs in Ordos Basin. *Pet. Explor. Dev.* **2006**, *33*, 667–670. (In Chinese)
32. Luo, Q. Concept, principle, model and significance of the fault controlling hydrocarbon theory. *Pet. Explor. Dev.* **2010**, *37*, 316–328. (In Chinese)
33. Tong, C.G. Some characteristics of petroleum geology of the rift systemin eastern China. *Acta Pet. Sin.* **1980**, *1*, 44–49. (In Chinese)
34. Luo, Z.L.; Liu, S.G. *Plate Tectonics and Petroliferous Basins in China*; China University of Geosciences Press: Wuhan, China, 1989; pp. 15–54. (In Chinese)
35. Zhang, J.F.; Lan, C.L. Fractures and faults distribution and its effect on gas enrichment areas in Ordos Basin. *Pet. Explor. Dev.* **2006**, *33*, 172–177. (In Chinese)
36. Dong, Y.X.; Wang, Z.C.; Zheng, H.J.; Xu, A.N. Control of strike-slip faulting on reservoir formation of oil and gas in Nanpusag. *Pet. Explor. Dev.* **2008**, *35*, 424–430. (In Chinese) [CrossRef]
37. Li, J.M. Fault System and Its Control on Oil-Water Relationship of Development Block in Haita Basin. Ph.D. Thesis, Northeast Petroleum University, Daqing, China, 2010; pp. 49–50. (In Chinese)
38. Gu, S.S.; Xu, W. Discussion on the article of "Application of fault control hydrocarbon theory to realize a greatbreakthrough of petroleum exploration in Qaidam Basin". *Acta Pet. Sin.* **2003**, *24*, 107–108. (In Chinese)
39. Luo, Q. Fault Controlling Hydrocarbon Theory and It's Application in Baitang Depression in Bohai Gulf Coastal Basin and Qaidam Basin. Ph.D. Thesis, PetroChina Research Institute of Petroleum Exploration and Development, Beijing, China, 2001; pp. 9–11. (In Chinese)
40. Wang, Z.C.; Zhao, W.Z.; Li, Z.Y.; Jiang, X.F.; Li, J. Role of basement faults in gas accumulation of Xujiahe Formation, Sichuan Basin. *Pet. Explor. Dev.* **2008**, *35*, 541–547. (In Chinese) [CrossRef]
41. Fu, G.; Lei, L. Research on Differences of Controlling of Fault to Oil Accumulation in and outside Oil Source Area. *Geol. Rev.* **2010**, *56*, 719–725. (In Chinese)
42. Hooper, E. Fluid migration along growth fault in compacting sediments. *J. Pet. Gevlogg* **1991**, *14*, 160–190. [CrossRef]
43. Zhou, H.Y.; Lu, J.F. Faults: A key factor for expelling low mature oil. *J. Jian Han Pet. Inst.* **1998**, *20*, 27–33. (In Chinese)
44. Yi, S.W. ExPloration Theory and Practice of Lithologic and StratigraPhic Reservoirs in Erlian Basin. Ph.D. Thesis, Chengdu University of Technology, Chengdu, China, 2006; p. 53. (In Chinese)
45. Wang, J.Q. The chimney effects of hydrocarbon activity. *Exp. Pet. Geol.* **1997**, *19*, 193–199. (In Chinese)

46. Zeng, J.H.; Jin, Z.J. *Physical Modeling of Secondary Oil Migration and Accumulation*; Petroleum Industry Press: Beijing, China, 2000; pp. 121–179. (In Chinese)
47. Chen, D.X.; Pang, X.Q.; Weng, Q.P.; Jiang, Z.X.; Zhang, J. Discussion and preliminary application of ternary genetic mechanism of lithologic reservoir. *Oil Gas Geol.* **2003**, *24*, 228–232. (In Chinese)
48. Simnovich, B.B.; Liu, S.X.; Xu, S.B. *None-Anticline Reserviors*; Petroleum Industry Press: Beijing, China, 1986.
49. Zhao, C.L.; Zhang, S.W.; Yuan, J. *Depositional Reservoir and Hydrocarbon of Shengli oil Region*; Petroleum Industry Press: Beijing, China, 1999; pp. 95–96. (In Chinese)
50. Hao, F.; Zou, H.Y.; Jiang, J.Q. Dynamics of petroleum accumulation and its advances. *Earth Sci. Front.* **2000**, *7*, 11–21. (In Chinese)
51. Du, J.H. Analysis of Natural Gas Accumulation Conditions and Exploration Prospects in the Central Paleouplift Belt (North), Songliao Basin. *China Pet. Explor.* **2017**, *22*, 1–14.
52. Wu, L.; Zhang, J. Characteristics of effective source rocks of Paleogene in Jiyang Depression. *Geogr. Res. Bull.* **2022**, *1*, 56–62.
53. Zhong, S.H.; Yuan, L.; Zhang, R.X.; Yan, C.P.; Cao, Y.; He, T.T. Identification and effectiveness evaluation of fractures in calcareous sandstone reservoirs in Northeast Sichuan. *Complex Oil Gas Reserv.* **2022**, *15*, 23–29.
54. Sun, T.W.; Wang, F.; Wang, Y.G.; Li, J.H.; Hu, M.; Ouyang, J.T.; Li, M. Types of fault sand body assemblages and differential enrichment mechanisms of oil and gas in the Nantun Formation in the southwestern region of the Hailar Basin. *Daqing Pet. Geol. Dev.* **2023**, *42*, 40–49.
55. Li, G. Characteristics of the faul-sand configuration conducting system and their differences in the oil-gas control between sag area and slope area. *Pet. Geol. Oifield Dev. Daqing* **2022**, *41*, 36–42.
56. Cui, X.; Jiang, H.F.; Wang, Y.Z. Control factorsand accumulation modes of central uplift belt in Beier Sag, Hailar Basin. *Fault-Block Oil Gas Field* **2018**, *25*, 555–558.
57. LI, T.T.; Deng, H.; Zou, W.Q. Accumulation conditions and hydrocarbon enrichment laws of low-permeabilty oil reservoirs in complex rift basins A case study from the second member of Nantun Formation of Beizhong sub-sag in Beier Sag of Hailar Basin. *Pet. Geol. Ollfield Dev. Daqing* **2021**, *40*, 32–37.