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Research Article

Types and Distribution Characteristics of Callovian-Oxfordian Reservoir on the Right Bank of Amu Darya River in Turkmenistan

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Given the characteristics of significant or enormous resources, a wide range, many reservoir types, and challenging exploration on the right bank of the Amu Darya River, we systematically studied the characteristics of its reservoirs. Based on the core description, thin sections in combination with logging and seismic facies characteristics as well as regional tectonic-sedimentary background, the Callovian-Oxfordian platform and the gentle slope sedimentary system in the Amu Darya Basin of Turkmenistan were summarized. Sedimentary subfacies such as evaporation platform, restricted platform, open platform, and platform margin reef are developed in block A and its west. In contrast, the upper slope, lower slope, and basin sedimentary subfacies are developed in the east of block A. On this basis, the main reservoir types on the right bank of the Amu Darya River are summarized, namely, porous reservoir, vuggy reservoir, fractured-porous reservoir, and fractured-vuggy reservoir. After describing the characteristics of various reservoirs in detail, the main controlling factors, development patterns, and distribution rules of the development of different reservoirs are summarized. Specifically, based on the platform reef, the porous reservoir and vuggy reservoirs are developed mainly on the concealed palaeouplift in the study area and are greatly influenced by atmospheric freshwater leaching and buried dissolution. Based on the dominant sedimentary facies, the fractured-porous reservoirs are mainly developed in the central areas on the right bank of the Amu Darya River. In the later period, hydrothermal fluid and hydrocarbon-generating acidic fluid can dissolve the reservoir through strike-slip faults and their associated fractures. Diagenetic fluid enters the reef through faults and associated fractures to form dissolved reservoir bodies of a certain scale. The fractured-vuggy reservoirs are mainly controlled by faults and dissolution and are mainly developed near the eastern thrust fault on the right bank of the Amu Darya River, effectively guiding the direction for further exploration and development in this area.

1. Introduction

The Amu Darya Basin in Turkmenistan is an important oil-gas-bearing basin in the world [1–4], in which the middle-upper Jurassic Callovian-Oxfordian limestone is a key oil-gas-bearing reservoir [5, 6], with proven gas reserves of about 22 trillion cubic meters and remaining gas resources of about 20 trillion cubic meters. Thus, how to effectively explore and develop these oil and gas resources has become a crucial target of oil geologists worldwide. In the early stage, Turkmenistan focused on the development of oil and gas resources in the Amu Darya Basin but failed to conduct basic geological research. In addition, due to a lack of data and a poor understanding of the characteristics of the Callovian-Oxfordian carbonate reservoir in the whole block, the exploration and development are not productive. In recent years, with increasingly rich data in this area, many scholars have conducted in-depth research on the characteristics and evolution laws of its sedimentary facies and reservoirs [7–13], but most research was still theoretical. Therefore, it is difficult to efficiently guide oil and gas exploration and development in the whole area, even the whole basin, by exploring the types and distribution laws of reservoirs in the relatively small-scale structural zone. Therefore, this paper takes the right bank of the Amu Darya River, with its rich data, wide areas, and many types of facies, as the target area to explore the type of its Callovian-Oxfordian carbonate reservoir. It is easy to improve the effects of exploration and development in the Amu Darya Basin by studying the laws of different reservoir types. Furthermore, it will surely guarantee the process of oil and gas development by alleviating the international energy crisis.

2. Method

The materials and interpretations presented in this study are based on 36 well-drilled cores from the Callovian-Oxfordian strata in 28 gas fields located in the Amu Darya Basin. The 36 studied wells are Ilj-21, EIlj-21, Gad-21, NGad-21, Kish-21, WKish-21, Nfar-21, Sam-53-1, Sam-45-1, Sam-44, Aga-21, Met-21, Met-22, Ber-21, Ber-22, Pir-21, Pir-22, Oja-21, Uzy-21, Cha-21, Cha-22, San-21, etc.

Petrographic studies were based on approximately more than 1800 thin sections stained with Alizarin Red S and potassium ferricyanide solution. All the thin sections were described under the microscope using the modified Dunham (1962) textural classification of Wright (1992). These samples were utilized for thin section, porosity-permeability, and mercury injection analyses.

Conventional logging sequences and imaging logging data are used in the study. All collected data were logged in detail according to lithology, texture, components, sedimentary structures, and paleontology. Conventional logging data include gamma ray, spontaneous potential, sonic, neutron, density, and resistivity logs.

A total of 55 samples were selected for the mercury injection experiment. Physical properties and mercury injection tests were conducted on cylinder-shaped samples (25 mm long and 25 mm in diameter) with the CMS-30 tester for testing porosity and permeability under overburden pressure.

3. Regional Geological Characteristics

The Amu Darya Basin, which spans Uzbekistan, Turkmenistan, and Afghanistan, is a sedimentary basin with a huge potential for oil and gas resources in Central Asia [14]. The Amu Darya Basin is tectonically located in the west of the Central Asian tectonic domain. The basin developed on the basement of the Tethys domain in the late Paleozoic and changed into an extensionally faulted basin after undergoing the Triassic rift period. It is also the largest petroliferous basin within the Turan Platform (Figure 1). The main body of the basin is NW–SE trending, steeper in the southwest and wider and slower in the northeast. The southwest wing is narrow and steep, while the northeast wing is wide and gentle. According to the basement undulation and cap rock structure, the basin can be divided into three first-level structural units: Kopetat piedmont depression in the southwest, Karakum uplift belt in the middle, and Amu Darya depression belt in the northeast [6]. In the basin, two sets of NW-trending and NE-trending faults are developed, which control the regional tectonic-sedimentary pattern and the distribution of petroleum source bed, reservoir, and cap rock [15–17]. The region on the right bank of the Amu Darya River in Turkmenistan is located on the Chardzhou terrace of the Amu Darya Basin, which is divided into four regions: western B block, A block, central B block, and eastern B block (Figure 2). According to the structural and lithological characteristics, the Amu Darya Basin can be divided into three structural strata, namely, basement, reservoir stratum, and cap rock. The basement is composed of Paleozoic, Permian, and Triassic igneous rocks, metamorphic rocks, and molasse-coarse clastic rocks, and their buried depths vary greatly. The depth of the Karakum uplift in the shallowest part is less than 2000 m, and that of the North Karabil depression in the deepest part is more than 14000 m. On the basement, reservoir strata composed of Permian-Triassic terrigenous clastic rocks are widely developed. They thicken from north to south, and their maximum thickness at the Kopetat piedmont depression on the southern margin of the basin is up to 12000 m. The widely developed platform cap rocks are composed of Jurassic, Cretaceous, and Paleogene carbonates, evaporites, sandstones, mudstones, and coal seam interbeds. The Callovian-Oxfordian stage of the Middle-Upper Jurassic is the main oil-bearing reservoir. The lower Middle Jurassic is a set of coal-bearing clastic rock series of coastal plain-lagoon swamp facies, which is in overburden unconformity contact with the target strata. The Gordak Formation of the Upper Jurassic is a set of mudstone or a thick gypsum salt layer, which is in continuous sedimentary relationship with the target layer [18, 19]. Therefore, in terms of sedimentary sequence and lithofacies configuration relationship, there is a good combined configuration relationship among petroleum source bed, reservoir, and cap rock, and the closed trap accumulation conditions of petroleum source bed (lower)-reservoir (middle)-cap rock (lower) are available.

4. Characteristics of Callovian-Oxfordian Sedimentary Facies

There are many rift valleys controlled by basement faults in the Permian-Triassic basement in the block on the right bank of the Amu Darya River. After gap filling in the middle-lower Jurassic Series, the ancient landform was generally gentle before the Callovian-Oxfordian sedimentation. However, affected by the Chardzhou uplift and Kyzyl Kumu uplift in the northwest, the areas on the right bank are high in the northwest and low in the southeast in terms of the structural pattern [20–22]. Based on the characteristics of the tectonic setting and regional sedimentary facies, the right bank of the Amu Darya River can be divided into a carbonate platform depositional system and a front slope depositional system according to the petrological characteristics, paleontological markers, and logging facies markers [23–25]. The carbonate platform is subdivided into such subfacies as evaporation platform, restricted platform, open platform, and platform margin, while the foreslope sedimentary facies are divided into such subfacies as upper slope and lower slope and further divided into 9 microfacies [26, 27] (Table 1). The plane distribution

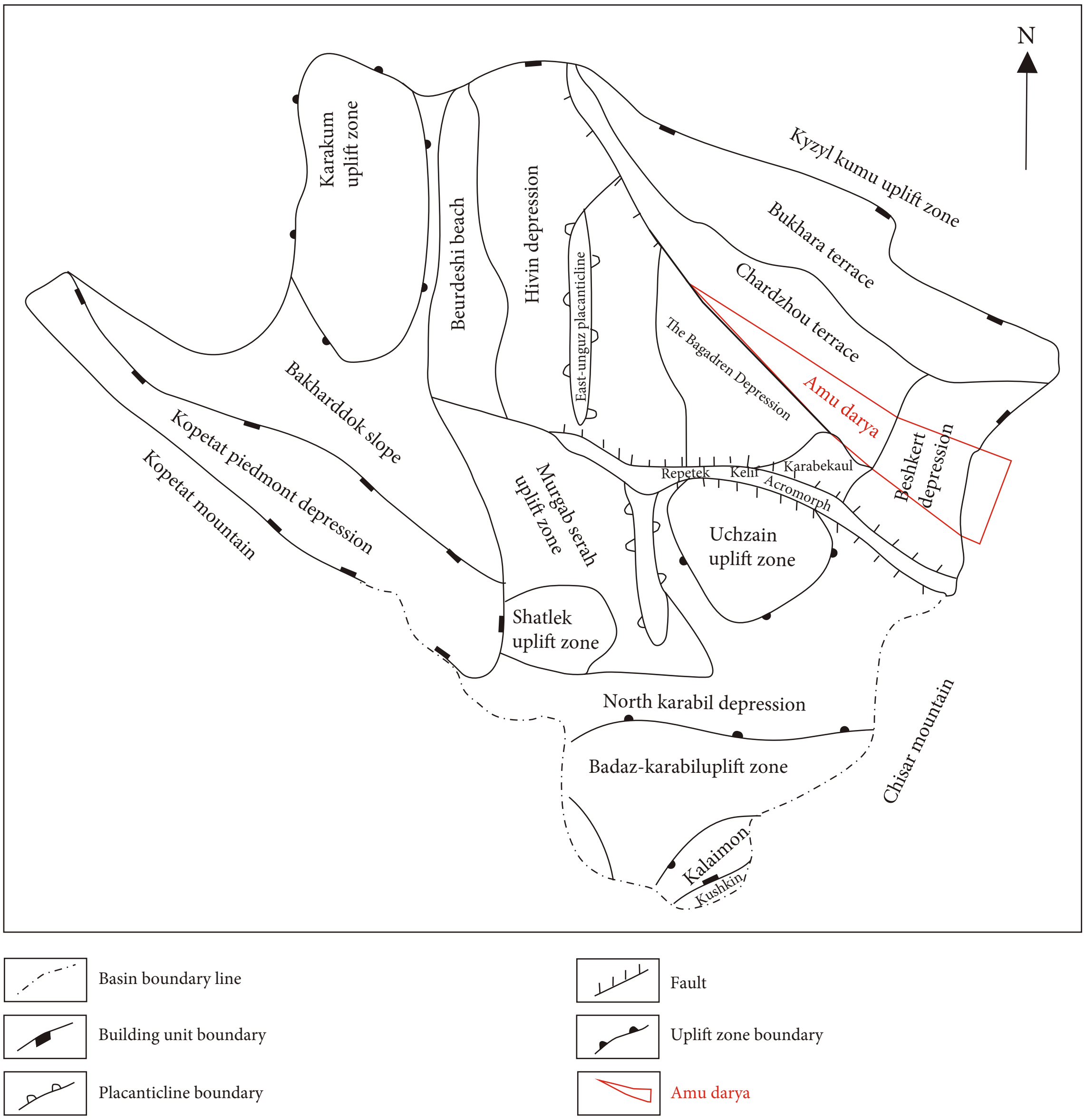

Figure 1: Structural location map of areas on the right bank of the Amu Darya River.

characteristics of Callovian-Oxfordian sedimentary facies on the right bank of the Amu Darya River are further analyzed and determined based on the stratum thickness, granular rock thickness, single-well facies characteristics, and well-connected sedimentary facies profile (Figure 2).

5. Types and Characteristics of Reservoirs

The Callovian-Oxfordian carbonate reservoir spaces on the right bank of the Amu Darya River are composed of pore, karst vug, and fracture. Different combinations and proportions of porous, vuggy, and fractured reservoirs lead to the complexity of reservoir spaces. According to the different characteristics of reservoir space and with reference to reservoir lithology and sedimentary microfacies, carbonate reservoirs on the right bank are divided into 4 categories, namely porous, vuggy, fractured-porous, and fractured-vuggy ones (Table 2).

5.1. Characteristics of Porous Reservoir. The porous reservoir is generally developed at sparite bioclastic limestone, calcarenite, oolitic limestone, and microsparite granular limestone. The reservoir spaces are mainly pores, and needle-shaped dissolved pores can be seen locally on the core. The reservoir space under the microscope mainly consists of remaining primary intergranular pores, intergranular dissolved pores, and intragranular dissolved pores. The pore throat structure of this type of reservoir is generally good. According to the analysis of mercury injection and casting thin section, the reservoir mainly has a medium-small throat (Table 2). According to image logging, there are many black low-resistance strips caused by porous limestones in the reservoir section, which indicates that dissolved pores are developed

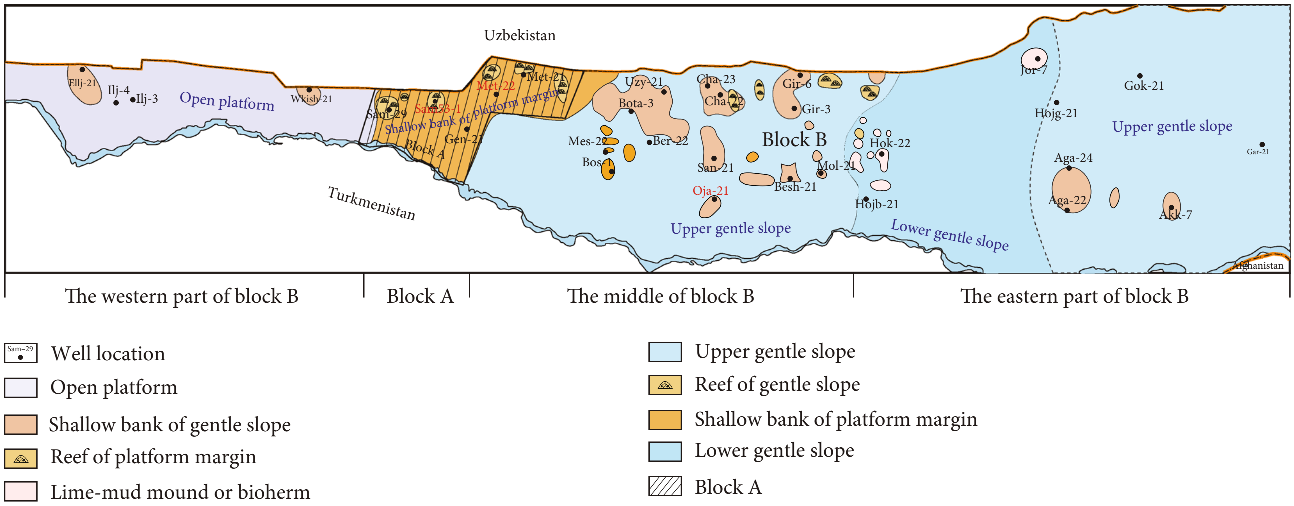

FIGURE 2: Paleographical sketch of Callovian-Oxfordian lithofacies on the right bank of the Amu Darya River.

TABLE 1: Characteristics of sedimentary facies on the right bank of the Amu Darya River.

Facies	Subfacies	Microfacies	Lithology description
Carbonate platform	Evaporation platform	Supratidal flat and evaporation lake	Argillaceous limestone and anhydrite
	Restricted platform	Intertidal flat and lagoon	Dark gray granular microcrystalline limestone and dolomite
	Open platform	Platform grain and grain shoal	Gray bioclastic limestone and granular limestone
		Intershoal flat	Gray microcrystalline limestone with a small amount of bioclastic
	Platform margin	Barrier reef	Gray reef limestone intercalated with sparite bioclastic limestone
		Interreef shoal (flat)	Dark gray bioclastic limestone intercalated with argillaceous limestone
Foreslope	Upper slope	Forereef slope	Dark gray crystal powder limestone, crystal powder-containing bioclastic limestone
		Point reef	Gray crystal powder-containing bioclastic limestone, crystal powder-containing bioclastic limestone
	Lower slope	Deep gentle slope	Grayish black muddy microcrystalline limestone and argillaceous limestone

and fractures are not developed (Figure 3(a)). This type of reservoir is medium-thin in thickness, with a single layer thickness of 0.5 m-8 m, mainly distributed at 2 m-4 m, with obvious vertical stratification characteristics. As shown by physical property analysis, the reservoir porosity is 3%-24.2%, mainly 3%-15%, with 10% on average. The permeability is 0.001 mD-1162 mD, mainly 0.01 mD-1 mD, and 0.132 mD on average (Figure 4(a)). As shown by the core analysis of this type of reservoir, except for the low-porosity section, the relationship between porosity and permeability is linear on a whole; however, the distribution range is relatively wide (Figure 4(a)), which indicates the wide range of throat distribution of the reservoir. In the low-porosity section, there are high-permeability samples, greatly affected by fractures in the dense limestone section.

5.2. Characteristics of Vuggy Reservoir. The vuggy reservoir is generally developed at biolithite limestone, sparite bioclastic limestone, and sparite reef limestone. Karst vugs and pores are well developed in the reservoir space (Table 2), and dissolved pores can be seen on the core (Figure 3(b)). The core observation of the XVm stratum in Sam-53-1 well shows there are up to 5.84 large karst vugs with a diameter of greater than 10 mm per meter. Under a microscope, the remaining primary intergranular pores, intergranular pores, and intragranular pores were well developed. The pore throat structure of this type of reservoir is generally good. The results of the mercury injection experiment are consistent with the understanding of thin section analysis, and the reservoir type is coarse pore-large throat type. According to imaging logging, the reservoir segment developed with

Table 2: Types and characteristics of carbonate reservoirs on the right bank of the Amu Darya River.

Reservoir type		Porous	Vuggy	Fractured-porous	Fractured-vuggy
Sedimentary environment		Low-energy shoal of carbonate platform	High-energy shoal of carbonate platform	High-energy shoal of gentle slope or reef shoal	Near NE-trending thrust fault
Lithological characteristics		Sparite bioclastic limestone, calcarenite, oolitic limestone, microsparite crystal granular limestone	Biosparitic bioclastic limestone, reef limestone	Microcrystal bioclastic calcarenite, bonded limestone, bioclastic gravel limestone, tuff limestone, and bioclastic tuff limestone	Microcrystal, microsparite tuff limestone, bioclastic limestone, and angular limestone
Reservoir space		Intergranular pore, intergranular dissolved pore, and intragranular dissolved pore	Intergranular dissolved vug, intergranular dissolved vug, intragranular dissolved vug, intrafossil vug, and dissolved vug	Mold pore, intergranular pore, intragranular dissolved pore, micropore, and fracture	Fracture, dissolved pore along the fracture, and irregular dissolved pore
Petrophysical characteristics	Permeability (mD)	0.001 ~ 1162/0.132	0.013 ~ 3155/8.6	0.001 ~ 2935/0.091	0.001 ~ 4848/0.117
	Porosity (%)	3.01 ~ 24.2/10	3.1 ~ 24.9/13.2	3 ~ 16.2/7.03	3 ~ 27.7/6.53
Matrix throat characteristics		Mainly medium-small throat	Mainly coarse pore-large throat	Mainly fine-microthroat	Mainly medium-fine throat
Thickness characteristics		Moderately thick-thin	Moderately thick-thick	Moderately thick	Various thickness
Distribution area		West of block B	Sam area	Middle of block B in the west of Yanguy fault	Near the Yanguy fault and NE-trending thrust fault in the east of block B
Main control factors for reservoir development		Jointly controlled by the distribution of low-energy carbonate shoal and sedimentary cycle	Mainly controlled by the distribution of high-energy carbonate shoal and diagenetic dissolution	Mainly controlled by the distribution of gentle carbonate slope and buried dissolution	Mainly controlled by the distribution of NE-trending fault and late buried dissolution

holes is characterized by black low-resistivity bands and black patches, which are smooth in appearance and infested with oil and gas. In terms of appearance, they are smooth and obviously invaded, which indicates that pores or vugs are developed. As shown by physical property analysis, the reservoir porosity is 3%-24.9%, mainly 9%-18%, and 13.2% on average. The permeability is 0.013-3155 mD, mainly 1-100 mD, and 8.6 mD on average (Figure 4(b)). The linear correlation between porosity and permeability in this type of reservoir is good, and its distribution range is narrow (Figure 4(b)), indicating that the reservoir throat is relatively uniform.

5.3. Characteristics of Fractured-Porous Reservoir. The fractured-porous reservoir is mainly distributed in the low-energy reef shoal in the medium or gentle slope facies belt. The main reservoir rocks include microsparite calcarenite, microsparite bioclastic limestone, bonded limestone, bioclastic gravelly limestone, bioclastic pelleted limestone, tuff limestone, and bioclastic tuff limestone. For this type of reservoir, the reservoir spaces include various dissolved pores. Needle-shaped pores can be seen on the core, while mold pores, intergranular dissolved pores, intragranular dissolved pores, micropores, and fractures can only be seen in the casting thin section (Table 2). The throat structure of this type of reservoir is medium or poor. According to the analysis of mercury injection and casting thin section, the reservoir mainly has a small throat. According to imaging logging, the pores appear as black bands with low resistance, while the fractures appear as irregular dark bands with wide changes (Figure 3(c)). Generally, there are also fractures developed in the pore section. As shown by physical property analysis, the reservoir porosity is 3%-16.2%, mainly 3%-9%, and 7.03% on average. The permeability is 0.001 mD-2935 mD, mainly 0.001 mD-1 mD, and 0.91 mD on average (Figure 4(c)). The relationship between porosity and permeability in this type of reservoir is very messy (Figure 4(c)), indicating that the fractures are seriously affected. The main characteristics of medium porosity and low permeability are consistent with the results of mercury injection analysis, namely, fine matrix throat. It is difficult to achieve high production capacity only by the pore throat. Because the fractures in this reservoir are very well developed, it has good commercial productivity.

5.4. Characteristics of Fractured-Vuggy Reservoir. The fractured-vuggy reservoir is mainly in microlite tuff limestone, microlite bioclastic limestone, microsparite breccia limestone, and micrite limestone. The holes are generally developed along the cracks, and the karst caves along the cracks can be seen on the core. Under the thin section are mainly irregular dissolved pores, body cavity pores, and

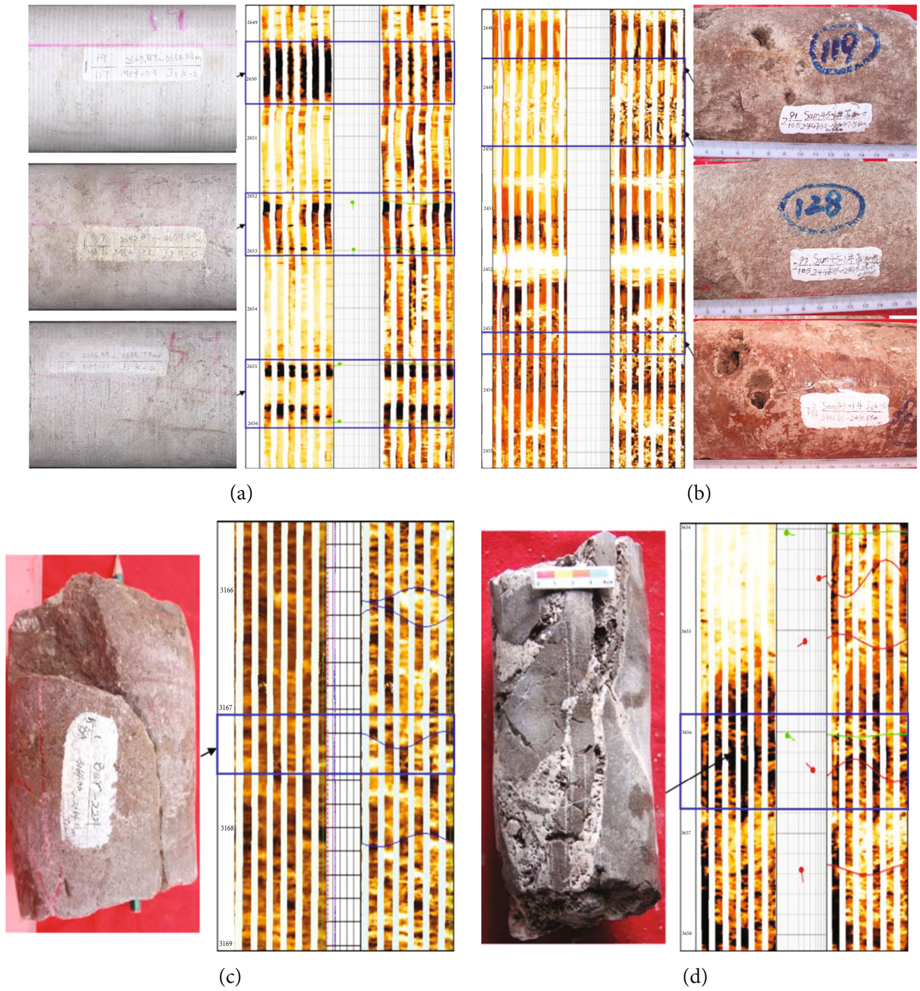

Figure 3: Core images and imaging logging characteristics of different types of reservoirs. (a) Porous reservoir: in the Met-22 well, the XVp stratum has a porosity of 5%-11% and a reservoir thickness of 2 m-4 m. The reservoir has many black, low-resistance strips caused by porous limestones. The dissolved pores are developed, and fractures are not developed. No dissolved pore has been seen on the core. (b) Vuggy reservoir: at the XVm stratum in the Sam-45-1 well, the reservoir has many black, low-resistance strips caused by high-porosity limestones and black patches with high conductivity. In terms of appearance, they are smooth and obviously invaded, which indicates that dissolved pores are developed and fractures are not developed. No karst cave has been seen on the core. The reservoir is thick and lumpy. (c) Fractured-porous reservoir: at the XVhp stratum in Ber-22 well, the reservoir is dominated by pores, and there are many black low-resistance strips caused by porous limestones, as well as some irregular fractures characterized by dark strips and varying greatly in width at the same time. (d) Fractured-vuggy reservoir: at the XVhp stratum in the San-21 well, the reservoir has irregular fractures characterized by dark strips and varying greatly in width. Meanwhile, due to dissolution, pores and caves with black patches of abnormally high conductivity are developed along the cracks. In terms of appearance, they are smooth and obviously invaded, allowing integration between fractures and caves.

mold pores (Table 2). According to the mercury injection analysis and the study on casting thin section, the pore throat of this type of reservoir is fine, mainly showing the pore throat characteristics of matrix limestone. As shown by physical property analysis, the reservoir porosity is 3%-27.7%, mainly 3%-15%, and 6.53% on average. The permeability is 0.001 mD-4848 mD, mainly 0.01 mD-10 mD, and 0.117 mD on average (Figure 4(d)). The relationship between porosity and permeability in this type of reservoir is very messy (Figure 4(d)). In the section with a porosity of more than 15%, the permeability is only 0.1 mD, which indicates that there is a poorly connected vuggy reservoir, while the high permeability in the low-porosity section just shows the existence of fractures, which indicates that the main seepage flow channels of this type of reservoir are fractures. Of course, in some sections with developed pores or vugs, porous (vuggy) throats are also important seepage channels.

6. Main Development Control Factors and Development Models of Different Reservoirs

There are many main development control factors of reservoirs. For the J_2k-J_3o carbonate reservoir on the right bank of the Amu Darya River, sedimentation and diagenesis are important control factors. The development control factors of different types of reservoirs are analyzed below.

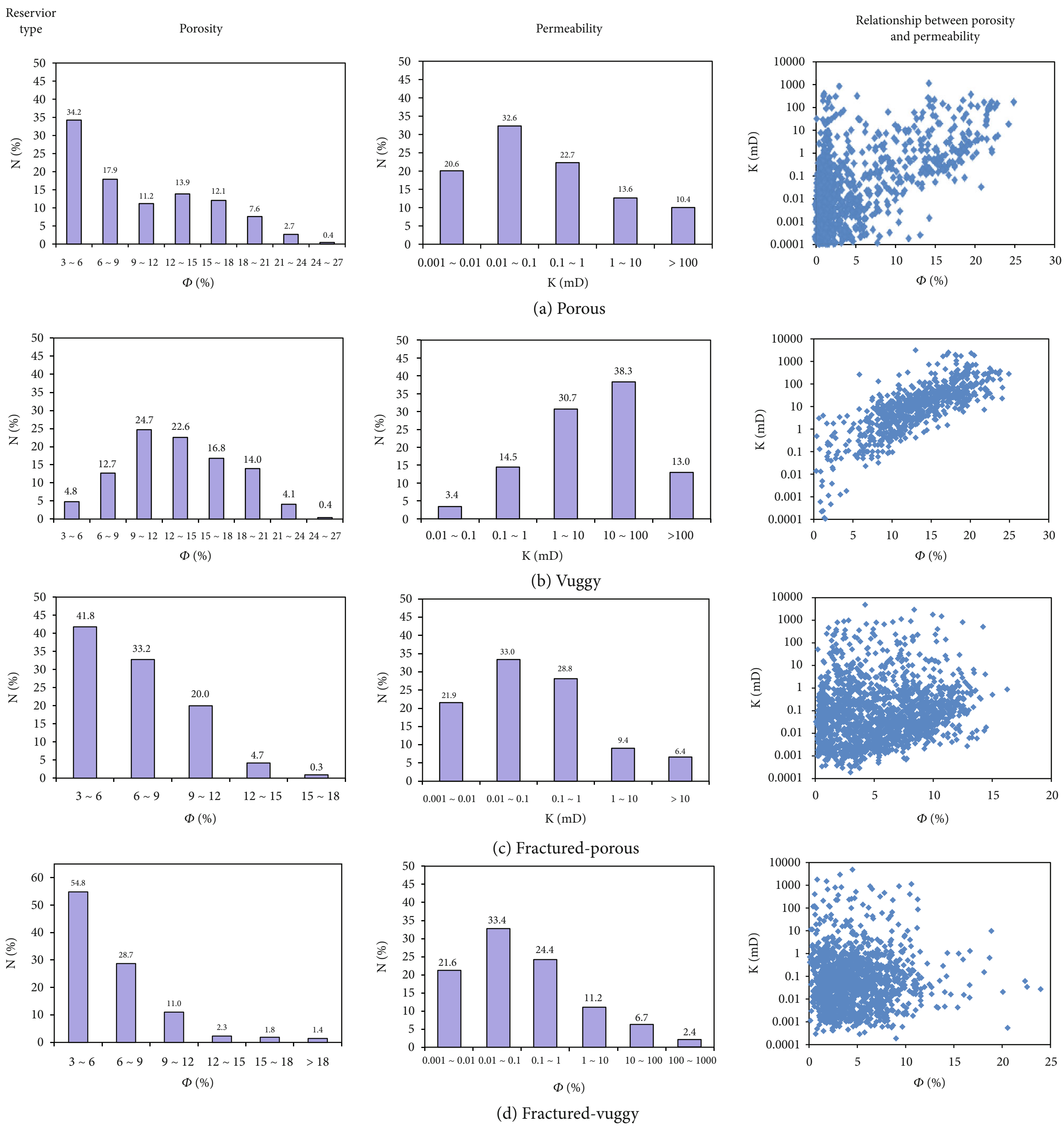

Figure 4: Porosity and permeability distribution histogram of different types of reservoirs.

6.1. Main Development Control Factors and Development Models of Porous/Vuggy Reservoir. For the carbonate reservoir, the reservoir spaces are generally controlled by the original sedimentary facies belt, without exception for the porous reservoir of the low-energy thin intraplatform shoal, which is mainly controlled by the low-energy shoal developed in the sedimentary period of the carbonate platform.

It is just the intergranular pore in the original shoal that provides a fluid percolation channel for the later diagenetic transformation, ensuring continuous diagenesis such as dissolution. The high degree of dissolution causes vuggy reservoirs, while the slightly lower degree of dissolution causes porous reservoirs. The dissolution includes the freshwater leaching and dissolution of carbonate rocks in the deposition period and the buried dissolution in the middle and later diagenesis periods. Freshwater leaching and dissolution mainly occur in the near-surface environment, and the platform reef shoal is affected by high-frequency sea-level fluctuation. In the later period of the highstand systems tract, the carbonate reef shoal is intermittently exposed to the

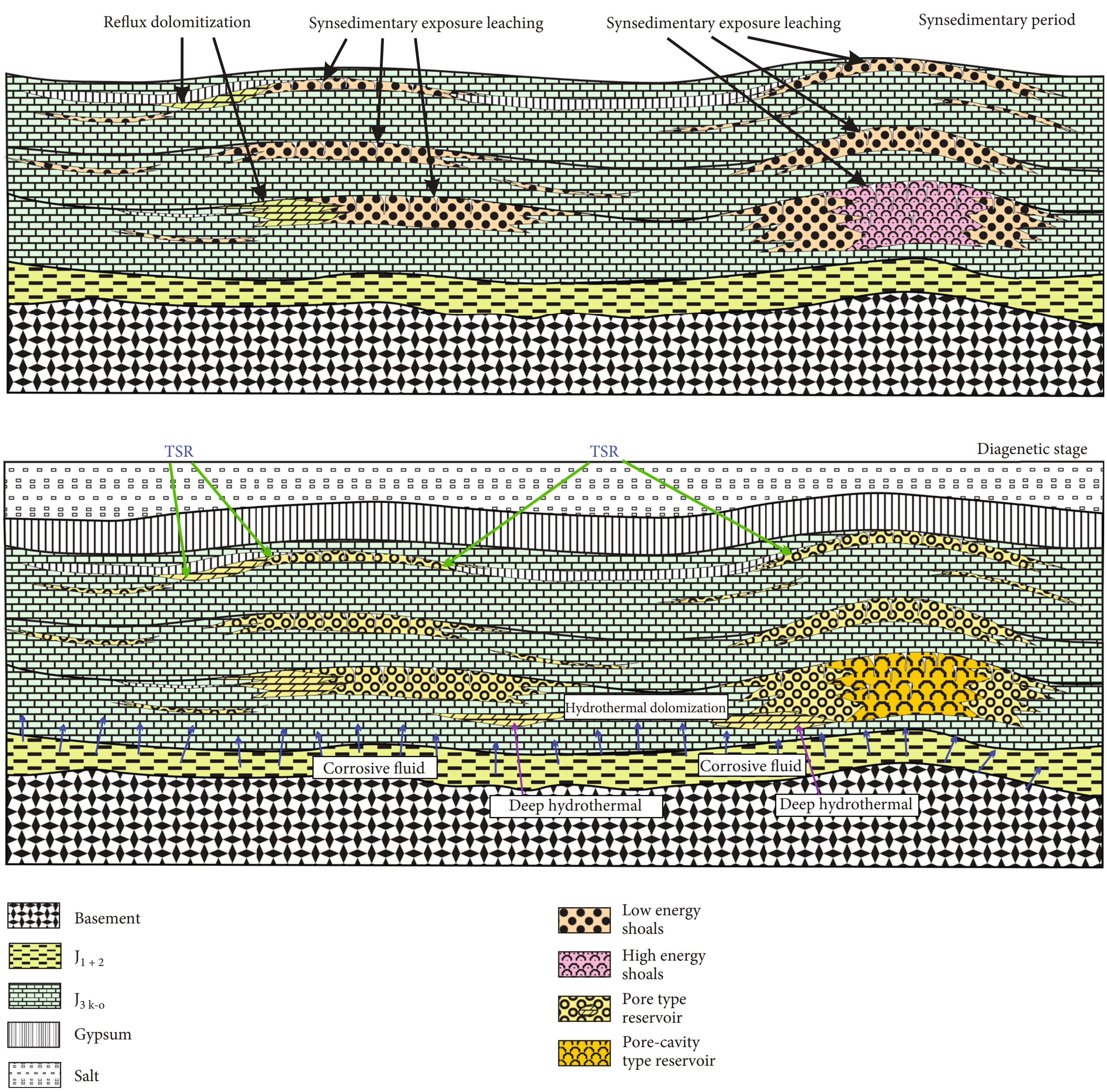

Figure 5: Development pattern of the porous (vuggy) reservoir on the platform area of the right bank of the Amu Darya River.

atmospheric environment. Due to freshwater leaching, obvious selective dissolution occurs. The reservoir in the later stage is also mainly developed in the late highstand period of the high-frequency cycle (Figure 5). TSR also contributes greatly to reservoir dissolution. H_2S generated during TSR dissolution dissolves in water, forming hydrogen sulfuric acid that dissolves carbonate, enlarging the pores or vugs. In the platform on the right bank, the top of the J_2k-J_3o stage is an interbed between limestone and gypsum, which provides a favorable place for hydrocarbons to contact with sulfate. In the later period, incoming hydrocarbons, as well as gypsum and pyrite existing there provide material conditions for the thermochemical sulfate reaction. At present, the reservoir temperature on the right bank area of the Amu Darya River is generally about 100°C, but the reservoir paleogeotemperature has reached 120-140°C (J_2k-J_3o stage was buried deeply, and it was obviously lifted during the Neo-Alpine orogenesis). This provides a temperature condition for the thermochemical sulfate reaction. On the right bank of the Amu Darya River, the content of carbon dioxide in natural gas is higher than that of hydrogen sulfide, which is the result of carbonate dissolution by hydrosulfuric acid. The results of the X-ray diffraction experiment also show that pyrite is associated with the strata at a well depth of more than 2400 m in the Samandepe gas reservoir, which indirectly proves the thermochemical sulfate reaction.

6.2. Main Development Control Factors and Development Models of Vuggy Reservoir. Both the high-energy thick intraplatform vuggy reservoirs and the porous reservoirs of the low-energy thin intraplatform shoal are distributed in carbonate platform facies areas, where the sedimentary environments are similar. The difference between them is that the water energy in high-energy shoal areas is higher, and the shoals spread more widely.

Unlike the porous reservoirs of the low-energy thin intraplatform shoal, high-energy shoal reservoirs are mainly distributed in the middle of the Callovian-Oxfordian stage and are more affected by atmospheric freshwater leaching and buried dissolution. This is due to the thick strata and large area of the high-energy flat. Meanwhile, the sedimentary surface is often near sea level, so it is easily and frequently exposed to the water surface. The high-energy beach facies is repeatedly scoured and leached by atmospheric precipitation to produce dissolution. During the diagenetic period, the acid generated during the hydrocarbon generation process of the burial process continuously dissolves and transforms the beach. Firstly, various easily soluble biological bone fragments such as coral, foraminifera, bryozoa, and red algae were selectively dissolved, thus forming intragranular dissolved pores and mold pores, while the spinous and brachiopod organisms were well preserved. As a result, the porosity and permeability of various dissolved shoal limestones are greatly improved, and the reservoirs are developed. In the middle and late diagenetic periods, due to the influence of neotectonic movement, faults and folds occurred. Deep thermal fluid seeped into the shoal along the cracks. At the same time, the hydrosulfuric acid formed by TSR will also penetrate into the shoal body and further dissolve the shoal limestone, resulting in the common development of various secondary pores, vugs, and fractures. So, in the Samandepe Gas Field, vuggy high-energy shoal reservoirs dominated by secondary pores or caves and supplemented by remaining primary pores are formed of the XVm stratum at Callovian-Oxfordian (Figure 5).

6.3. Main Development Control Factors and Development Models of Fractured-Porous Reservoir. The difference in the genesis of the fracture-pore reservoir and the mesa facies derived from the evolution of gently sloping reef flats lies first in the facies. These reservoirs are mainly distributed in the gentle low-energy reef (mound) shoal area in the middle of the right bank, with deep water (relative to the platform area). Therefore, they are little affected by freshwater leaching in the depositional period, but there is still buried dissolution. Meanwhile, they can also be dissolved by hydrocarbon-generating acidic water and deep hydrothermal fluid.

The structural study shows that many faults and fractures occurred in the middle of the right bank during the Late Jurassic period and neotectonic movement. In the later period, hydrothermal fluid and hydrocarbon-generating acidic fluid can penetrate the coarse-structured, soluble reef shoal limestone reservoirs such as reef (mound) limestone and granular limestone through strike-slip faults and their associated fractures and pressolutional fractures for dissolution. This area's development of fractures or stylolite pores or vugs is an example.

Four sedimentary microfacies such as bioherm (biogenic reef), lime-mud mound, slope shoal, and slope marl are mainly developed in the J_2k-J_3o stage of the gentle slope facies belt. As shown by core analysis, the porosity characteristics of different sedimentary microfacies are different, and the porosity of the reef (mound) limestone reservoir is 5.61%-9.81% and 7.04% on average. The average porosity is 6.34% for bioherm limestone, 5.44% for slope shoal microfacies, 5.30% for lime-mud mound microfacies, and only 1.79% for slope marl microfacies. According to these, on the whole, the gentle slope reef-shoal belt is also a favorable reservoir development belt [28–30].

The paleontological content of limestones in the slope facies is less than that of the limestones in the inner shoal facies because the burial depth is deeper and the lack of hydrogen sulfide dissolution, so the development degree of the pores is far less than that of the inner shoal facies. Fortunately, this area is subject to high extrusion stress from the east, resulting in more faults and fractures than those in the platform area. This improves reservoir performance and constitutes a typical fractured-porous reservoir. This type of reservoir is formed based on the sedimentary facies belt, focusing on the fault. From this, the development model of the fractured-porous reservoir in the gentle slope reef shoal can be summarized (Figure 6).

6.4. Main Development Control Factors and Development Models of Fractured-Vuggy Reservoir. Fractured-vuggy carbonate reservoir mainly refers to a reservoir formed by pores or vugs caused by the dissolution of diagenetic fluids such as acidic fluid and deep hydrothermal fluid in the later period along the fractures, which results from the rupture of the NE-trending fault. As this type of reservoir is little affected by sedimentary facies but mainly controlled by extrusion-stress-caused faults and their associated fractures, the dissolved pores or vugs are generally developed near the hanging wall of the thrust fault. The development degree of reservoirs decreases in turn as they are far from the thrust fault.

When a low-energy reef shoal connects with the thrust fault, the diagenetic fluid can smoothly enter the reef shoal through the fault and its associated fractures, and the dissolution rapidly exacerbates along the reef shoal so that large, high-quality reservoirs can be finally formed. For example, Yanguy belongs to a favorable reservoir distribution area formed by matching and superimposing faults and reef shoals. From this, the development model of the fractured-vuggy reservoir on the right bank can be summarized (Figure 7).

7. Distribution Prediction of Different Types of Reservoir Bodies

There are four types of reservoirs on the right bank of the Amu Darya River. Comprehensively considered, the reservoirs can be divided into three types of reservoirs of a certain scale, namely, intraplatform shoal reservoir body, gentle slope reef shoal reservoir body, and fractured-vuggy carbonate reservoir body. Among them, there are porous and vuggy reservoirs developed in the intraplatform shoal, fractured-porous reservoirs developed in the gentle slope reef shoal, and fractured-vuggy reservoirs developed in the fractured-vuggy carbonate.

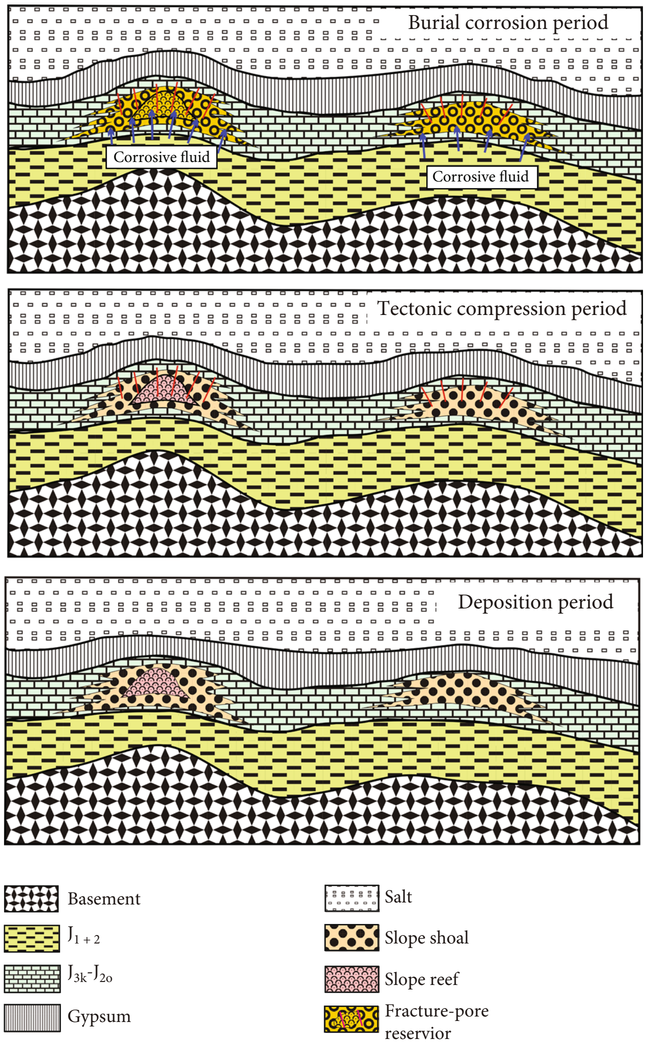

Figure 6: Development pattern of the fractured-porous reservoir on the middle gentle slope of the right bank of the Amu Darya River.

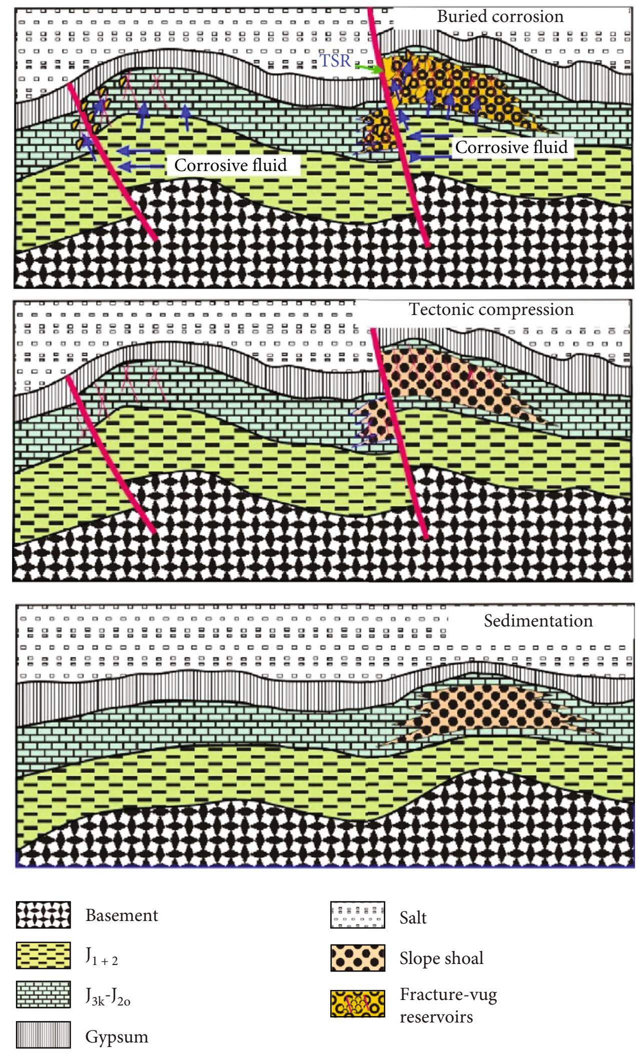

Figure 7: Development pattern of the fractured-vuggy reservoir on the eastern part of the right bank of the Amu Darya River.

7.1. Prediction of Intraplatform Shoal Reservoir Bodies of a Certain Scale. The main development control factors for intraplatform shoal reservoir bodies include the sedimentary environment, early freshwater leaching, dolomitization, dissolution of hydrocarbon-generating acidic water, and dissolution of TSR-caused H_2S. According to the comprehensive analysis of these aspects, geological prediction can be conducted on this type of reservoir body on a certain scale. It can be inferred that various intraplatform shoal bodies of a certain scale can be formed at the high palaeogeomorphological positions on the concealed paleouplift on the right bank of the Amu Darya River, e.g., Samandepe and Gadyn. These beaches are subjected to freshwater leaching during the sedimentary period, allowing the original pores of the reservoir to be preserved. Meanwhile, they are covered with gypsum-limestone interbeds, so they are also the key areas of TSR reaction in the later period. When these shoals are located at the high positions of the structural trap, the buried dissolution during oil and gas migration and accumulation is also the most intensive, so these areas are favorable positions for the development of intraplatform reservoir bodies. The actual drilling data show that the effective thickness of the shoal reservoir in the Samandepe Gas Field is more than 130 m and more than 90 m on average. On the plane, these shoals are widely distributed, and the continuous distribution area can exceed 100 km^2.

7.2. Prediction of Gentle Slope Reef Shoal Reservoir Bodies of a Certain Scale. In addition to sedimentary facies type and dissolution, the fault is also a greatly important factor in controlling fractured-porous reservoirs. To sum up, the sedimentary facies in the middle of block B belongs to gentle slope sedimentation, and there are patches of reef shoals based on the inherited paleouplift. They are bases for the development of reservoir bodies of a certain scale. In addition to early development strike-slip faults, late development extrusion formed by thrust faults is accompanied by more cracks. Faults and fractures provide percolation channels for dissolved fluids and hydrothermal fluids from the deep crust to enable such fluid to enter the reef shoals, which causes dissolved pores on dissolved carbonate to form reservoirs of a certain scale. These dissolved pores and fault fractures constitute fractured-porous reservoirs. Therefore, the gentle slope reef shoal near the fault in the middle of block B is in a favorable position for the development of fractured-porous reservoirs of a certain scale. According to the actual drilling data, the single reef shoal reservoirs developed in the Bereketli-Pirguyy area are 0.5 m-30 m thick, but multiple shoals are vertically overlapped, with an overlapped thickness of more than 100 m. These shoals are distributed in patches, but their sizes vary from several square kilometers to ten square kilometers. Of course, fractured-porous reservoirs can be formed if the dissolution is particularly intensive in these areas.

7.3. Prediction of Fractured-Vuggy Reservoir Bodies of a Certain Scale. Fractured-vuggy reservoir bodies of a certain scale are mainly controlled by faults and dissolution. In the east of block B, due to intensive compression, the faults are well-developed, and their development degree is higher when their locations are closer to the east. In this area, multiple sets of faults were developed, which provide migration channels for dissolved fluid. In addition to the dissolution near the fault zone that forms a fracture hole, in the area where the fault matches the reef beach, the large amount of diagenetic dissolution fluid provided by the fault causes substantial dissolution of the reef beach. As a result, a large area of dissolution pores is formed, and a high-quality fracture-hole type reservoir is formed. Examples are the Hojagurluk-Agayry anticline belt and the Joramergen-Dugoba structural belt, etc. According to the actual drilling data, in the matching area between the reef shoal and the thrust fault, the thicknesses of single fractured-vuggy reservoirs range from several meters to more than 40 meters, with a large plane distribution area of approximately 100 km^2. But in the area where reef shoals are underdeveloped but only thrust faults are developed, single single-well reservoirs are generally several meters in thickness and only a few more than 10 meters in thickness.

8. Conclusions

(1) The areas on the right bank of the Amu Darya River are divided into carbonate platforms and foreslope sedimentary facies. The carbonate platform is subdivided into such subfacies as evaporation platform, restricted platform, open platform, and platform margin, while the foreslope sedimentary facies are divided into such subfacies as upper slope and lower slope. The platform and gentle slope are further divided into nine microfacies. From the perspective of sedimentary evolution, every layer on the right bank of the Amu Darya River has inherited the early sedimentary pattern. The platform depositional system is developed in the west of area A, and the thin platform bank is randomly distributed, while the gentle slope depositional system is maintained in the east of area A

(2) The carbonate reservoirs on the right bank of the Amu Darya River are divided into 4 categories, namely, porous, vuggy, fractured-porous, and fractured-vuggy ones. The porosity and permeability of the porous reservoir range from 3.01% to 24.2% and from 0.001 mD to 1162 mD. The porosity of the cavity reservoir is 3.1%~24.9%, and the permeability is 0.013 mD~3155 mD. The porosity and permeability of the fracture-pore reservoir are 3%-16.2% and 0.001 mD~2935 mD. Fracture-cavity reservoir is 3%~27.7%, permeability is 0.001 mD~4848 mD

(3) The porous and vuggy reservoirs are mainly developed based on the intraplatform reef shoals in the late highstand period of the high-frequency cycle. However, different from porous reservoirs, vuggy reservoirs are mainly distributed in the middle of the Callovian-Oxfordian Stage and are more affected by atmospheric freshwater leaching and buried dissolution. The fractured-porous reservoirs are based on the dominant sedimentary facies, and in the later period, hydrothermal fluid and hydrocarbon-generating acidic fluid can be dissolved through strike-slip faults and their associated fractures to develop fractured-porous reservoirs of gentle slope reef shoal. Due to the connection between the thrust fault and high-quality reservoir, the diagenetic fluid can smoothly enter the reef shoal through the fault and its associated fractures, and the dissolution rapidly exacerbates along the reef shoal, so fractured-vuggy reservoirs are formed

(4) The intraplatform shoal reservoirs are mainly developed on the concealed paleouplift on the right bank of the Amu Darya River. Among them, Samandepe and Gadyn are the most favorable development areas. The gentle slope reef shoal reservoir bodies are mainly developed in the middle of the right bank of the Amu Darya River. Among them, Bereketli is the most typical. Due to the influence of concealed paleouplift and a high-frequency cycle, patches of reef shoals have developed on the inherited paleouplift, and the gentle slope reef shoal reservoirs have been formed by multiple structural destructions and buried dissolutions. The fracture-vuggy reservoirs of a certain scale are not closely related to sedimentary facies but are mainly controlled by faults and dissolution associated with faults

Data Availability

The author works at the Institute of Geological Exploration and Development of CNPC Chuanqing Drilling Engineering Co., Ltd. The paper is a partial achievement of the national demonstration project "Demonstration Project of Natural Gas Development in the Middle Area of the Right Bank of the Amu Darya River". All information is available from the agency.

Conflicts of Interest

The author declares no conflicts of interest.

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