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Characterisation of Shale Gas Reservoirs in the Uralik Formation, Western Margin of the Ordos Basin

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Abstract: The Lower Paleozoic Ordovician at the western margin of the Ordos Basin is rich in natural gas resources, and the results of the gas test show that the mud shale and greywacke sections of the Uralik Formation have good oil and gas shows. Therefore, the study of reservoir characteristics and controlling factors of the Uralik Formation is of great significance for the exploration of natural gas in this formation. Based on the study of reservoir space type and physical characteristics of mud shale and greywacke in the Uralik Formation, this paper further investigates the reservoir control factors. The results show that the reservoir space of the Uralik Formation is mainly developed with cracks, pores and caves. The enrichment of shale gas requires the mud shale to have the dual properties of hydrocarbon production and storage, and the study of reservoir characteristics is to lay the foundation for the next step of enrichment and reservoir formation.

Keywords: Uralik Formation; Reservoir Characteristics; Porosity; Ordos Basin; Shale.

1. Introduction

Ordos Basin is one of the important oil and gas basins in China, with the continuous exploration of oil and gas resources in the Ordos Basin, unconventional oil and gas resources have gradually become the focus of exploration, shale gas and greywacke tight gas are mainly stored in the free state in the nanoscale micropores and microcracks of mud shale and greywacke. In recent years, the exploration of marine shale gas in the Ordos Basin has gained significant breakthroughs (represented by Zhongping 1 and Zhong4 wells), confirming that the Uralik Formation in the western part of the basin has favourable geological conditions for marine shale gas. Ordos Basin is one of the important oil and gas basins in China, with the continuous exploration of oil and gas resources in the Ordos Basin, unconventional oil and gas resources have gradually become the focus of exploration, shale gas and greywacke tight gas are mainly stored in the free state in the nanoscale micropores and microcracks of mud shale and greywacke. Among them, the tight greystone gas reservoir at the top and the shale gas reservoir at the bottom of the Uralik Formation have the conditions of integrated source-reserve formation, indicating that the Uralik Formation has good exploration prospects. Therefore, on the basis of objective understanding of the geological features of shale gas in the Uralik Formation in the western part of the Ordos Basin, the analysis of the characteristics of greywacke and mud shale reservoirs in the Ordovician Uralik Formation at the western margin of the Ordos Basin is crucial for the greywacke tight gas and shale gas in the Uralik Formation.

2. Regional Geological Features

The study area is mainly located between the Tianhuan depression in the western margin of the Ordos Basin and the alluvial zone in the western margin of the basin, and also covers a small area in the western part of the Yimeng uplift, where three major tectonic systems are mainly distributed, namely the Liupanshan alluvial tectonic system, the Hetao-Yinchuan extensional tectonic system, and the Shigouyi-Pingliang slip-transform tectonic system. The main three tectonic systems in this block are the Liupanshan alluvial system, the Hetao-Yinchuan extensional tectonic system, and the Shigouyi-Pingliang strike-slip tectonic system. The linear tectonics of the basin mainly spreads in east-west, north-south, north-east, north-north-east, and north-west directions, but there are differences in different tectonics and depths, for example, the linear tectonics of the western rim of the masked tectonic zone is in the north-south direction. The tectonics of the western part of the Ordos Basin is relatively complex and zoned, with relatively strong tectonic activities in the western margin of the alluvial fault zone and relatively stable Tianhuan depression. The west edge of the Ordos Basin is extremely developed, the main tectonic features are: the development of a number of large north-south spreading thrust faults and nearly east-west translational faults, the basic tectonic pattern of the overall thrust faults from west to east, while the large north-south thrust faults are separated into a number of small tectonic zones by east-west faults, the east-west faults are mostly manifested as a right strike-slip characteristics, with the nature of the regulating faults. The east-west faults mostly show right-track slip characteristics and have the nature of regulating faults.

3. Reservoir Characteristics

3.1. Mineral Composition and Lithology

3.1.1. Mineral Composition

The mud shales of the Uralik Formation in the western Ordos Basin have higher carbonate mineral contents and higher brittle mineral contents relative to the mud shales in China and abroad. In this study, 55 whole-rock X-ray diffraction experiments were carried out to analyse the rock samples of the Ulalik Formation from five key wells, including Zhongping 1 well and Yu Tan 1 well, in the western margin of the Ordos Basin. The experimental results reveal that the mineral composition of the rock samples from the Uralik Formation is dominated by feldspathic minerals, followed by carbonate minerals and clay minerals, with small amounts of hard gypsum, pyrite and rhodochrosite. The mudstone has a clay content of 10-30 percent, a carbonate mineral content of 10-20 percent and a feldspathic content of

20-70 percent. The grey mudstone has a clay content of 10 to 30 percent, a carbonate mineral content of 30 to 50 percent, and a feldspathic content of 20 to 50 percent. Chert has a clay content of 0-5 percent, a carbonate mineral content of 70-100 percent and a feldspathic content of 0-30 percent. The total brittle mineral content is generally 71.1% to 79.5%, with an average of 75.3%, which is significantly higher than that of the brittle mineral content of Longmaxi Formation mud shale (58.7%) in the Sichuan Basin, which is more conducive to fracture modification of the reservoir in the later stage.

The results of clay X-ray diffraction experimental tests and analyses of the Uralik Formation rock samples show that the clay minerals are dominated by illite and ilmenite and ilmenite/montmorillonite interlayers, followed by chlorite and kaolinite, and no montmorillonite is present, while the shales of the Wufeng Formation and Longmaxi Formation of the Sichuan Basin do not contain kaolinite. The clay minerals in the rocks of the Wulalik Formation increase in illite content and decrease in illite/montmorillonite interlayer content with the increase of burial depth, revealing that montmorillonite is transformed to illite under geothermal temperature and diagenesis due to the high degree of diagenetic evolution of the rocks of the Wulalik Formation.

3.1.2. Lithology

Core observation shows that greenish grey shale, dark grey and greyish black shale are mainly developed in the Uralik Formation in the study area. In terms of mineral composition, greenish grey shale and part of dark grey shale have similar distribution ranges, but there are large differences in their development layers, TOC, reservoir properties and gas content. Based on the information of field profiles and drilling shale samples, using petrographic grading nomenclature, the following six petrographic phases are identified to be mainly developed in the Wulalik Formation at the western margin of the Ordos Basin: siliceous shale, clay-rich siliceous shale, calcium-rich siliceous shale, mixed shale, calcareous shale phase, and clay-rich mixed shale.

3.2. Reservoir Characteristics

The porosity and permeability of the reservoir are important parameters reflecting the storage and connectivity of shale gas and greywacke tight gas in the Uralik Formation, the porosity reflects the size of the reservoir space, and the permeability reflects the size of the seepage capacity of the reservoir. Marine shale is a matrix pore and fracture double pore medium, in which matrix pore type shale storage space is the main body, and fracture pore type shale gas enrichment and high yield of high quality storage and seepage space. The main matrix pores are clay mineral intergranular pores, organic matter pores and brittle mineral internal pores, of which the first two account for more than 73%. Fissure pore type shale is open in the shape of high-angle joints, laminar joints, microcracks and the length of a few microns to tens of microns, good connectivity of intergranular pores, in the shale fissure pore development section, the permeability of the rock is better, the permeability is generally in the 0.01mD or more than 2 to 4 orders of magnitude higher than the substrate permeability.

3.2.1. Types and Characteristics of Storage Space

Shale reservoirs differ from conventional shale gas formations in that shale gas is mainly adsorbed on the inner surface of microporous spaces and exists in a free state in the pores and fissures of the shale. The mud shale of the Uralik Formation at the western margin of the basin is very dense, mainly developing nanoscale pores, and the pore types include four categories: intergranular pores (intergranular pores), interlayer seams of clay minerals, dissolution pores, and organic matter pores. In addition to matrix pores, microfractures and cracks are also more developed.

1. Pore space

The intergranular pores in the Uralik Formation mainly develop pyrite strawberry body intergranular pores, feldspar or carbonate dissolution pores, and clay mineral intergranular pores. The pyrite strawberry intergranular pores have flat edges, and the pore diameters are mainly less than 80 nm. More interlayer nanoscale pore seams are also developed between clay minerals, mainly dominated by micropores between illite. The intergranular pores of clay minerals mostly show a thin and elongated shape, with the length of the long axis up to several micrometres and the length of the short axis mostly tens of nanometres. The intergranular pores of the Uralik Formation mostly exhibit triangular or polygonal shapes with flat edges, are fewer in number, but have larger pore diameters, mainly between tens of nanometres and several micrometres.

The mud shale of Wulalik Group is rich in carbonates and quartz and other minerals, and the dissolution of soluble minerals such as dolomite, calcite, feldspar and quartz can form mineral dissolution holes. Dissolution holes are closely related to the organic acids released during the thermal evolution of organic matter, and the diameter of the holes is generally less than 50nm, mostly round and oval, with smooth edges.

The organic matter pores of the Uralik Formation are not developed, and only sporadic observation of organic matter pores developed in the organic matter endowed with interlayers of clay minerals and intergranular pores such as pyrite, and the pore diameter (pore diameter) is generally small, with ＜50 nm as the dominant one, and the shape of the organic matter pores is mainly circular, elliptical, or irregular. The organic matter pores mainly contain two kinds of asphalt pores and solid cheese root pores. The organic matter pores of mud shale of the Uralik Formation are mainly elliptical or irregular, and most of them are mesopores. The overall development of organic matter pores is low, obviously different from other mud shales at home and abroad, which is mainly caused by the following two reasons: firstly, the low organic carbon content of mud shale in the Uralik Formation; secondly, the Ro of mud shale in the Uralik Formation is 1.8%-2.0%, and the organic matter pores are in the closed stage during the stage of hyperthermal evolution, which is not conducive to the development and preservation of organic matter pores. Organic matter pores are one of the important pore types in shale reservoirs and have a significant impact on shale gas storage and transport. They provide additional storage space and may increase the permeability of shale reservoirs. Meanwhile, the development degree and distribution characteristics of organic matter pores also affect the physical and chemical properties of shale reservoirs, which in turn affect the development effect of shale gas.

2. Cracks

The shale cracks of Uralik Formation at the western edge of the basin are extremely developed, mainly horizontal laminar joints, with the joint density between 40~133 joints/m, the joint width between 0.1~0.2mm, and the joint spacing generally between 0.5~2.5cm. The extreme development of microfractures and cracks is the biggest storage space advantage of the mud shale of the Wulalik Formation in the western Ordos Basin. A large number of fractures are visible on imaging logs and drill cores, dominated by interlayer and tectonic joints. Secondly, a large number of nanoscale microfractures are also visible under scanning electron microscope (SEM), which are mainly grain-edge joints, organic matter-edge joints, and clay-mineral interlayer joints. The development of different scales of fracture systems in the mud shale of the Wulalik Formation has greatly improved the reservoir properties of the Wulalik Formation in the western part of the basin on the one hand; on the other hand, it is also conducive to the resolution of adsorbed gas to free gas in the shale gas, which is favourable to the later stage of the drainage and recovery.

3.2.2. Physical Characteristics

The porosity of the mud shale of the Wulalik Formation in the western Ordos Basin generally ranges from 1% to 3%, with an average of 1.82%; the permeability generally ranges from 0.01 to 0.1 mD, with an average of 0.07 mD; and the porosity of the mud shale of the Longmaxi Formation in the Sichuan Basin ranges from 4% to 7%, with an average permeability of 0.0002 mD. It can be seen that the porosity of mud shale of Uralik Formation in the western part of Ordos Basin is relatively low, and the permeability is higher, which is mainly due to the extreme development of microfracture and horizontal laminations in the Uralik Formation in the western part of the basin. On the plane, the main distribution range of contour is 0.5-3.5, and the average value is 2.0, and the high value area is distributed near wells E102 and Ren17.

3.3. Research on Factors Controlling Reservoir Development

3.3.1. Control of Reservoirs by Tectonic Activity

The western margin of the Ordos Basin was successively affected by the Caledonian, Hercynian, Indo-Chinese, Yanshanian and Himalayan movements, and has gone through many phases of tectonics such as tensile, extrusion and re-tensile. Frequent tectonic activities and the development of faults have led to the formation of tectonic cracks, which increase the reservoir space and permeability of mud shale and greywacke in the study area, and are of great significance in improving the physical characteristics of the reservoirs in the Wulalik Formation. A large number of seam-hole systems are easily developed at the connection of tectonic cracks and pores, resulting in the development of tectonic cracks in the study area, which increases the reservoir capacity of shale and greywacke in the Uralik Formation and provides space for oil and gas reservoirs.

3.3.2. Control of Reservoirs by Diagenesis

The reservoirs of Ordos Basin western margin Ordovician Wulalik Formation have complex diagenesis, which is mainly affected by various diagenetic effects, such as compaction, cementation, account, dissolution, etc. The reservoirs of Ordos Basin western margin Ordovician Wulalik Formation have complex diagenesis. Compaction is a common diagenetic effect in the diagenesis of greywacke and mud shale, which mainly occurs after the first stage of cementation, and is easy to lead to the narrowing of primary pores, which is destructive to the primary reservoir space in the diagenetic process. Pressure-solution action is easy to lead to the generation of sutures, a large number of sutures are common in the casting of thin section, and the sutures are easy to be filled with black asphalt and organic. Dissolution is an important factor in the mud shale and greywacke reservoirs of the Uralik Formation, and dissolution porosity is more developed in the study area.

3.3.3. Petrographic Palaeogeographic Controls on Reservoirs

The depositional environment of the Uralik Formation in the study area has an important influence on the development of reservoirs. During the depositional period of the Uralik Formation, with the rise of the sedimentary water body, the whole Uralik Formation was in a deep-water basin area, which is located below the storm wave basement, and under the long-term hydrostatic and anoxic reducing environment, the reducing effect is obvious, and a large number of black penstock mud shale and greywacke have been formed. The organic matter is relatively rich, forming a good set of hydrocarbon source rocks, reservoirs and cap layers.

Petrographic paleogeography can reflect the depositional environment at that time, and favourable petrographic and sedimentary zones are the basis for reservoir development. The paleogeography of the Uralik sedimentary period underwent a major change, with the entire central and eastern part of the basin being uplifted and becoming a denudation area, while the western part of the basin was deeper, and the western sea area developed the peneplankton shale basin phase, the greyish mudstone open land-shelf phase, the marl-bearing land-shelf phase, and the marl land-shelf phase was developed in the low-lying area close to the paleouplift. The favourable zones for gas reservoirs are predicted to be mainly in the open grey mudstone shelf zone, the marl-bearing shelf zone, and the muddy tuff shelf zone close to the central paleouplift. The development of grey cracks and dissolution pore space in the grey mudstone and marl provides storage space for natural gas. The grey mudstone can be used as a hydrocarbon source rock to generate hydrocarbons and provide oil and gas sources for itself and for the marl and marl-bearing limestone, meanwhile, the organic pore space and microfractures contained in the grey mudstone also have storage space.

3.3.4. Effective Reservoir Spreading

In this study, through the comprehensive analysis of shale thickness, greywacke thickness, reservoir thickness and effective reservoir planar distribution law of the Uralik Formation, the results show that the shale thickness at the bottom of the Uralik Formation has a high degree of superposition and matching with the reservoir thickness and effective reservoir thickness, while the greywacke thickness at the top of the Uralik Formation has a high degree of correlation with the reservoir thickness and effective reservoir thickness, which reflects the characteristics of shale gas reservoir at the bottom and tight greywacke gas reservoir at the top of the study horizon. This reflects that shale gas reservoirs are dominated at the bottom of the study horizon and tight gas reservoirs are dominated by greywacke at the top of the study horizon.

Combining the above views with the comprehensive analysis of gas layer thickness and petrographic paleogeography, the overall effective reservoir spread of the Uralik Formation is superimposed, and a favourable prediction map of the Uralik Formation is drawn. The favourable zones are classified into three categories, with the best favourable zone in category I, the second favourable zone in category II and the less favourable zone in category III. The main body of the western edge of Ordos Basin is spreading in the north-south direction, and its favourable zones are also spreading in the north-south direction.

4. Collection Patterns

The organic matter pores of the mud shale of the Uralik Formation are mainly elliptical or irregular, and are mostly dominated by mesopores. The overall development degree of organic matter pores is low, which is obviously different from other mud shales at home and abroad, which is mainly caused by the following two reasons: Firstly, the organic carbon content of mud shale of Uralik Formation is low; secondly, the Ro of mud shale of Uralik Formation is 1.8%-2.0%, and the organic matter pores are in the closed stage during the stage of high thermal evolution, which is not conducive to the development and preservation of organic matter pores.

In addition, the extreme development of microfractures and fractures is the biggest reservoir space advantage of the mud shale of the Uralik Formation in the western Ordos Basin. A large number of cracks can be seen on the imaging logs and drilling cores, with interlayer and tectonic joints as the main ones. Because the lithology of the Uralik Formation in the western part of the basin is a combination of mud shale and muddy greywacke, which has experienced a number of tectonic movements in the later part of Indo-Chinese-Himalayan period, it is easy to form interlayer joints and tectonic joints.

The mud shale of Uralik Formation in Ordos Basin is mainly of "self-generated and self-storage" type, and the mud shale in the study area is both a good hydrocarbon source rock and a good reservoir; the mud shale layer is used as a hydrocarbon source rock, and the hydrocarbons can be transported to the greywacke reservoir. Through the comprehensive analysis of gas test data and reservoir characteristics of Uralik Formation at the western margin of Ordos Basin Ordovician, it is found that there are two types of unconventional natural gas reservoirs within the Uralik Formation, through the comprehensive analysis of gas test data and reservoir characteristics of Uralik Formation at the western margin of Ordos Basin Ordovician, and establishment of the Uralik Formation reservoir model map, it is found that there are two types of unconventional natural gas reservoirs within the Uralik Formation. The study found that there are two types of unconventional gas reservoirs in the Wulalik Formation, namely the shale gas reservoir in the middle and lower part of the Wulalik Formation and the grey rock tight gas reservoir in the middle and upper part of the Wulalik Formation. Shale gas is the main type of gas reservoir in the Uralik Formation, and the reservoir type is dominated by micro- and nano-scale pores in mud shale, and tight gas in greywacke is distributed in the upper part of the Uralik, and the reservoir type is dominated by karsts (pore seams).

5. Summary

(1) The macroscopic reservoir space types of Ordovician Uralik Formation at the western edge of Ordos Basin mainly include cracks and pores. The microcosmic reservoir space types are mainly soluble pores, organic matter pores, mineral intergranular pores and microcracks; the microcosmic reservoir space types of greywacke are mainly cracks and soluble pores; both are micro- and nanoporous reservoirs. The physical characteristics are mainly low porosity and low permeability.

(2) The mud shale of the Wulalik Formation in the study area has higher carbonate mineral content and higher brittle mineral content than those of mud shales at home and abroad, which is significantly higher than that of the Longmaxi Formation mud shale in the Sichuan Basin, and is more favourable to the fracturing and modification of the reservoir at a later stage. Controlled by the sedimentary phase, six lithological phases are mainly developed: siliceous shale, clay-rich siliceous shale, calcium-rich siliceous shale, mixed shale, calcareous shale and clay-rich mixed shale.

(3) The controlling factors of reservoir development mainly include tectonics, diagenesis, and phase paleogeography; tectonic activity makes tectonic cracks develop in the study area, which provides space for oil and gas storage in the study area; dissolution provides dissolution porosity for the reservoir in the study area; favourable lithofacies and sedimentary zones play an important role in reservoir development, and the greyish mudstone open land-shelf zone, the marl-bearing land-shelf zone, and the muddy greyish land-shelf zone are the favourable reservoir zones, and the favourable zones are divided into three categories, with the best type I favourable zone, the second type II favourable zone, and the less type III favourable zone. In the study area, the grey mudstone open shelf zone, mud limestone shelf zone and mud limestone shelf zone are the favourable reservoir zones, and the favourable zones are divided into three categories, with the best favourable zone in category I, the second favourable zone in category II, and the less favourable zone in category III, and the overall spreading is in the direction of north-south.

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