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Analysis of the Coalbed Methane Reservoir Characteristics in the Ordos Basin

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ABSTRACT

Coalbed methane (CBM) broadly refers to all natural gas found in coal-bearing strata, while the more specific definition pertains to methane gas trapped within coal seams and the adjacent tight sandstone reservoirs. In China, there is significant potential for the "increase of reserves and production" of coalbed methane, which holds substantial strategic value for national energy security. However, the current resource discovery and utilization rates remain extremely low, revealing a significant disparity. This paper analyzes the six fundamental geological characteristics of coalbed methane, including its gas storage state, reservoir diversity with strong cyclicity, complex gas-water distribution within coal seams, variable relationships between source rocks and cap rocks, and the fragile dynamic equilibrium of overlapping gas-bearing systems. Using the northern and eastern parts of the Ordos Basin, particularly the Linxing and Ma-4 segments, as case studies, this paper examines the characteristics of coalbed methane accumulation, source rock conditions, reservoir conditions, and fracture development. The findings provide insights into the coalbed methane accumulation characteristics of the Ordos Basin and offer valuable reference for future CBM exploration and exploitation in China.

KEYWORDS

Coalbed methane; gas storage characteristics; accumulation characteristics; Ordos Basin.

1. INTRODUCTION

Coalbed methane (CBM) broadly refers to all types of natural gas found in coal-bearing strata. It is a mineral resource classification based on reservoir genesis or geological carriers. Coalbed methane primarily consists of endogenous humic-type gas within coal seams, with gas accumulation either in the same strata (source-reservoir co-location) or in adjacent strata (source-reservoir separation). These can be categorized into two basic types: endogenous self-contained gas and endogenous gas in other strata, which include coal seam gas, coalbed sandstone gas, and shale gas. Preliminary predictions from experts and organizations indicate that, in certain basins of China, the geological resources of CBM are distributed as follows: 36.61% coal seam gas, 23.53% tight sandstone gas, and 39.86% shale gas[1-2]. Research on coal seam gas mainly focuses on its genesis, accumulation types, and accumulation dynamics[3-4], as well as the reservoir properties, adsorption characteristics, and transformability of deep coal seam gas reservoirs[5]. For shale gas, studies primarily address reservoir characteristics, accumulation mechanisms, and resource evaluation. Research on tight sandstone gas typically concentrates on reservoir features, gas reservoir types, and accumulation mechanisms[6].

Geological processes in coal formation involve the transformation of primary organic matter under the influence of geothermal heat, tectonic stress, and other factors, leading to coalification. During this process, the organic matter evolves from peat into lignite, sub-bituminous coal, bituminous coal, coking coal, anthracite, and ultimately, methane-rich gas, with significant changes in composition, structure, and physical properties. Concurrently, large amounts of methane and other hydrocarbons and non-hydrocarbons are released. According to artificial thermal evolution experiments on coalbed methane, approximately 60 m3 of methane is produced per ton of lignite, 330 m3 per ton of bituminous coal, and 400 m3 per ton of anthracite[7]. However, the quantity and production patterns of coalbed methane in geological formations are controlled by a variety of geological and geochemical conditions. The study of coalbed methane geology specifically investigates the composition, quantity, and migration-accumulation patterns of methane produced from different coal materials under various geochemical conditions throughout geological history. Research into the genesis of coalbed methane is not only the theoretical foundation of coalbed methane geology but also serves as the basis for coalbed methane surveys, exploration, and evaluation.

2. COALBED METHANE GEOLOGICAL CONNOTATIONS AND BASIC CHARACTERISTICS

2.1. Six Fundamental Geological Connotations of Coalbed Methane

Coalbed methane (CBM) broadly refers to all types of natural gas found in coal-bearing strata, a classification based on reservoir genesis or geological carriers[8,9]. CBM primarily consists of endogenous humic-type gas within coal seams, with gas accumulation either in the same strata (source-reservoir co-location) or in adjacent strata (source-reservoir separation). These can be categorized into two basic types: endogenous self-contained gas and endogenous gas in other strata, which include coal seam gas, coalbed sandstone gas, shale gas, and coal-derived carbonate gas.Compared to broader unconventional natural gases, CBM has the following distinctive geological characteristics: (1) The gas occurs in various forms, including adsorbed, free, and mixed states, with natural gas hydrates potentially forming under specific geological conditions[10]. (2) The reservoir rock types are diverse, with frequent interbedding and strong cyclicity. This results in multiple sequences related to sequence stratigraphy, typically thin and lithologically variable, creating source-reservoir relationships and multiple internal seals. (3) The gas-water distribution within coal seams is complex, with multiple source-reservoir-cap combinations leading to vertically (stratigraphically) coexisting fluid pressure systems, resulting in superimposed gas-bearing systems[11]. (4) The source-reservoir-cap relationships are variable, with a single layer (e.g., coal seams and mud shale layers) potentially serving as a reservoir, source, and cap, leading to diverse gas reservoir types[12]. (5) The superimposed gas systems are often in close proximity, with a fragile dynamic balance between them. They are susceptible to disturbances during extraction, leading to inter-system interference and significant compatibility issues in co-production geological conditions. (6) Within a single gas-bearing system, significant mechanical property differences exist between different lithology reservoirs. For example, coal reservoirs are often adjacent to shale or tight sandstone reservoirs, making it challenging to apply unified and effective methods for reservoir stimulation and production[13].

2.2. Basic Characteristics of Coalbed Methane

Coalbed methane (CBM) can be classified into three types based on the coal rank: High-rank coalbed methane ($Ro \geq 1.9\%$), Medium-rank coalbed methane (Ro between 0.79% and 1.9%), Low-rank coalbed methane ($Ro \leq 0.79\%$). The degree of coalification affects the gas generation potential of coal seams. Generally, the higher the coal rank, the greater the gas generation potential. Due to the basin's developmental history, coalbed methane can also be categorized by its origin into biological, thermal, and mixed-type methane. In CBM research, factors such as reservoir gas content, coal rank, permeability, gas saturation, fracture development, burial depth, reservoir pressure, tectonics, and hydrogeological conditions play critical roles in the accumulation of coalbed methane. These factors are essential parameters for evaluating CBM enrichment patterns and resource potential.

Shale gas shares similar origin types with coalbed methane, including thermal, biological, and mixed-origin gases. The gas occurs in various states, including adsorbed, free, and dissolved, with adsorption and free gas being the most common. Typically, shale gas accumulates in thick, dark mudstone/shale formations within a basin. These dark mudstones not only serve as the source rock for gas generation but also act as both the reservoir and cap rock for gas accumulation. Shale reservoirs have extremely low porosity and permeability. Gas is generally stored in fractures, intergranular pores, or adsorbed on organic matter surfaces. Due to their low porosity and permeability, shale gas reservoirs are difficult to exploit, typically requiring hydraulic fracturing. This process presents technical challenges and continues to require improvements.

The formation of tight sandstone gas reservoirs requires both sufficient gas source and favorable trapping conditions to preserve the gas. The pores within tight sandstone serve as the primary storage space for the gas. Tight sandstone reservoirs are characterized by low permeability. Regarding particle size, coarse sandstone, medium sandstone, and fine sandstone can all serve as suitable rocks for tight sandstone gas reservoirs. The reservoir's pore-filling materials generally contain higher amounts of mixed matrix and clay minerals, and the presence of authigenic clays is well-developed. Additionally, the types of cementing materials are diverse. Typically, feldspar and lithic fragments are the dominant components of tight sandstone.

3. ANALYSIS OF COALBED METHANE ACCUMULATION CHARACTERISTICS USING THE ORDOS BASIN AS AN EXAMPLE

3.1. Northern Ordos Basin

In the northern part of the Ordos Basin, the primary source rocks from the Paleozoic era are coal-bearing strata, which are characteristic of the transitional marine-terrestrial and lacustrine facies. These strata are predominantly found in the Taiyuan and Shanxi formations, with coal and dark mudstone as the dominant lithologies, followed by limestone. The distribution of dark mudstones exhibits a thinning trend from south to north and from west to east[14].

According to studies by Dai Jinxing et al.[15-18], the organic matter in the source rocks is primarily humic in nature. Hydrocarbon generation has undergone three main stages: The maturation of the Paleozoic source rocks began in the late Triassic, marking the onset of gas generation, with the gas generation intensity increasing from north to south. From the Middle Jurassic to the Late Cretaceous, the burial depth of the source rocks continued to increase, with their maturity also rising, reaching a peak in hydrocarbon generation. This period represents the primary phase of gas generation for the Paleozoic source rocks. In the Late Cretaceous and continuing into the present, the organic matter entered a high maturity phase, characterized by limited oil production and dominant gas generation. Ultimately, due to tectonic uplift and erosion, the temperature and pressure of the source rocks decreased, leading to a decline in hydrocarbon generation efficiency.

In the Paleozoic strata, mudstones, as conventional source rocks, are widely distributed across various layers, although their thickness varies. The Shiqianfeng Formation is primarily composed of lacustrine mudstones with good continuity, serving as a regional cap rock. The Shangshihezi Formation consists mainly of lacustrine mudstones and fluvial sandstones, with a thickness ranging from 60 to 120 meters, also acting as a regional cap rock. The Lower Shihezi Formation mainly develops local cap rocks, with fluvial sandstones as the primary lithology. The Shanxi Formation has poor continuity and features lacustrine mudstones and coal seams in swamp facies. The Taiyuan Formation predominantly develops mudstones and coal seams in a coastal swamp facies, with thickness distribution varying across the basin, being thicker in the west and thinner in the east. The Benxi Formation also has poor continuity, with lacustrine mudstone and coal seams commonly present.

The gas content of shale reservoirs in the study area ranges from 1.22 to 6.97 m^3/t, with an average of 3.35 m^3/t. The gas content of sandstone reservoirs ranges from 1.88 to 12.37 m^3/t, with an average of 5.04 m^3/t, and the gas saturation varies from 28.49% to 73.18%, with an average value of 56.03%. The gas content of coal reservoirs ranges from 19.54 to 26.07 m^3/t, with an average of 22.39 m^3/t, indicating strong potential for the development of unconventional natural gas resources[19].

3.2. The Middle Section of Linxing in the Eastern Margin of the Ordos Basin

The gas content of coal seams in the middle section of Linxing ranges from 6.1 to 24.6 m^3/t. Due to the intrusion of the Zijinshan pluton, the gas content exhibits exceptionally high values around the Zijinshan area, which decrease radially towards the surrounding regions. The shale reservoirs have relatively low porosity development and weaker gas content, generally ranging from 0.2 to 2.6 m^3/t. The distribution pattern of gas content in shales is the opposite of that in coal seams, with lower gas content in the vicinity of the Zijinshan pluton and higher gas content around the periphery. The gas content in sandstone reservoirs ranges from 0.4 to 4.5 m^3/t, and their distribution is uneven. The gas content is higher in the northern part, with a boundary at Caijiahuai, and lower in the southern part, showing a "north-high, south-low" distribution characteristic.

The Zijinshan uplift area has a complex structure, and the coal-bearing reservoirs are relatively thin. The intrusion of magmatic rocks facilitates the maturation of source rocks, providing abundant gas supply. The coal seams, as both source rocks and reservoirs, exhibit high gas content. In this region, coal seam gas (CSG) is predominantly autochthonous (self-sourced and self-stored). The surrounding Zijinshan syncline area is also structurally complex, where coal seam gas, sandstone gas, and shale gas coexist. All three types of gas exhibit considerable gas content, with CSG being concentrated in the northern part. In this area, coal-bearing reservoirs are well-developed, and mudstones and coal seams alternate frequently. Coal seams and mudstones act as source-reservoir-cap systems, producing and storing gas jointly while mutually sealing each other. Additionally, thick sandstone layers provide ample storage space. The gas combination in this region is primarily characterized by three types of gas (coal seam gas, sandstone gas, and shale gas) being self-sourced and co-stored. In the gently structured areas, the structure is simple, and coal seam gas and sandstone gas have high content. The coal and sandstone layers are well-developed, with coal seams and mudstones serving as source rocks. The gas migration and accumulation are driven by the pressure difference between source and reservoir, with gas migrating into adjacent thick sandstone layers for accumulation. In this area, the primary gas combination consists of two types of gas (coal seam gas and sandstone gas) being self-sourced and co-stored[20].

3.3. The Ma Si Section in the Central Ordos Basin

The discovery of the Jingan gas field at the top of the Ordovician system and the breakthrough of the Ma Wu segment's interior gas reservoir in the Ordos Basin have confirmed the exploration potential of the Ma Si section in the central Ordovician carbonate gas reservoirs[21]. The study area is located in the middle and northern part of the Yishan slope tectonic unit in the Ordos Basin, extending from Etuokeqi in the north to Yan'an in the south, from Etuoke Qianqi in the west to Jiaxian in the east, covering an area of approximately 10×10^4 km^2. The area is currently tectonically stable, with a general westward dip and local development of low-amplitude anticlinal domes and small-scale faults[22].

Under the influence of the Caledonian orogeny, the Ordovician experienced prolonged weathering and erosion. In the western part of the study area, the Ma Si section is controlled by both unconformities and lithological features, forming lithological weathering-capping traps. Due to the absence of developed lateral sealing conditions, gas-producing wells are sparse, and water-producing wells are more commonly observed. The natural gas in the Ordovician Ma Si section is a mixed gas primarily consisting of coal-type gas generated from the upper Paleozoic coal-bearing source rocks and oil-type gas from the lower Paleozoic carbonate rocks, with the former being dominant. The Ma

Si section has insufficient gas source conditions, resulting in relatively low overall gas production. In the western part of the region, the Yunping facies and granular shoal facies have well-developed pore spaces, creating favorable conditions for gas migration. However, due to limited gas source conditions, large-scale gas reservoirs are difficult to form, which is why gas wells in the Yunping facies are rare. The gray Yunping facies and Yun-gray facies have medium physical properties, with permeabilities lower than those of the Yunping facies and granular shoal facies but generally higher than the gray facies. These relatively dense reservoirs can effectively prevent further gas escape, facilitating the formation of gas reservoirs.

Porosity and fractures are the main gas storage spaces in the Ma Si section, forming a three-dimensional network system in combination with faults, which provides essential pathways for natural gas migration[23]. The gas reservoirs in the Ma Si section of the central Ordovician system in the Ordos Basin are primarily lithologic gas reservoirs. Natural gas is mainly derived from coal-type gas generated by upper Paleozoic coal-bearing source rocks, with a small amount originating from oil-type gas generated by lower Paleozoic carbonate rocks. The gas source conditions control the gas abundance, with the Ma Si section exhibiting limited gas source conditions and relatively low gas production. Reservoir characteristics influence gas accumulation in the medium-physical-property gray Yunping facies and Yun-gray facies. The three-dimensional network system of porosity, fractures, and faults provides a migration pathway for natural gas. Sealing conditions control the distribution of natural gas in the lithological changes between thick layers of dolomite and limestone, as well as in the central parts of thick limestone layers with increased dolomitic content.

4. CONCLUSION

The basic geological characteristics of coalbed methane (CBM) cannot be separated from the overall framework of unconventional gas geological conditions. However, within the broader context of unconventional gas, CBM possesses distinct characteristics, such as unique source-reservoir configurations and reservoir composite models. These features require the development of adapted exploration and exploitation technologies. A lack of proper understanding of these unique features has been one of the main reasons for the less-than-ideal results in China’s efforts to increase coalbed methane reserves and production.

It is recommended to focus research on the theme of "Coalbed Natural Gas Coexistence and Accumulation System and Orderly Development Geological Principles." This research should aim to reveal the adsorption states and desorption mechanisms of deep coalbed methane, and form a predictive theory and technical system for high-quality deep coalbed methane reservoirs. Additionally, it is important to clarify the accumulation processes and trapping effects of coalbed methane, and improve methods for selecting sweet spots in CBM reservoirs. Further studies should address the coalbed methane accumulation characteristics in thin interbedded layers and the geological control of high-quality development intervals, establish theories on the accumulation and distribution of thin interbedded coalbed methane, and develop predictive methods for sweet spot intervals in these layers. Lastly, research should explore the geological principles and technical foundation for the orderly development of coalbed methane, and lay the groundwork for efficient, orderly co-production technologies.

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