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Progress and Development Prospect of Coalbed Methane (CBM) and Coal Rock Gas Exploration in China

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Abstract

The backdrop of the accelerated advancement of the "dual carbon" goals and energy transition, coal rock gas, as a new type of unconventional natural gas resource, has emerged as a new highlight for increasing natural gas production and ensuring stable supply in China due to its enormous resource potential and unique development advantages. This paper systematically summarizes the major geological theoretical innovation achievements in China's coal rock gas exploration field, outlines the resource potential and current status of exploration breakthroughs nationwide and in key basins, elaborates on the core progress of key technologies such as seismic exploration and drilling engineering, analyzes the main challenges facing current exploration and development, and finally looks forward to the future development direction. Research shows that China's geological resources of coal rock gas exceed 50 trillion cubic meters, and an exploration trend of "multi-point breakthroughs and rapid growth" has been achieved. With the continuous upgrading of theories and technologies, it is expected to become an important strategic replacement resource for safeguarding national energy security.

Keywords

Coalbed Methane (CBM); Coal Rock Gas; Exploration Progress; Geological Theory; Core Technologies; Resource Distribution; Development Prospect.

1. Introduction

China's energy structure is in a critical stage of transitioning from traditional fossil energy to clean and low-carbon energy. As a high-quality, efficient, and low-carbon energy source, increasing natural gas production and ensuring stable supply have become core concerns for safeguarding national energy security and promoting the realization of the "dual carbon" goals[1]. In this context, shallow coalbed methane (buried depth less than 1500 meters) has long been exploited as an associated resource of coal production. Early development was mainly to ensure coal mine safety production and turn coalbed methane from a "hazard into a benefit". However, with the deepening of exploration and development, it has faced development bottlenecks such as reduced reserves and declining benefits, and there is an urgent need to find new resource replacement directions [2]. For a long time, China's unconventional natural gas exploration and development have focused on coalbed methane, shale gas, and other fields. Due to limitations in traditional theoretical cognition, deep coal rock intervals with a buried depth greater than 1500 meters have long been regarded as a "development forbidden zone". Traditional concepts generally hold that increased burial depth leads to poor reservoir storage conditions, reduced adsorbed gas content, and high mining costs. Even the United States attempted to develop deep coal rock gas but failed to achieve large-scale production due to inadequate technologies[3]. In recent years, Chinese exploration and research personnel have broken through the constraints of traditional theories in practice and discovered a new type of natural gas resource characterized by "coexistence of free and adsorbed states with high free gas content"—coal rock gas. Its occurrence characteristics are close to those of shale gas, and its development method integrates the technical characteristics of both shale gas and tight gas. The core difference is that traditional shallow coalbed methane is dominated by adsorbed gas, accounting for more than 90% of the total gas content, and requires the "water drainage - pressure reduction - desorption" mining mode. In contrast, the free gas ratio of coal rock gas can reach 20% - 50%, which endows it with the production advantage of rapid and high yield after fracturing and well completion, significantly improving development economic benefits. This discovery has opened up a new field of natural gas exploration. Based on the latest exploration practices and scientific research achievements, this paper comprehensively summarizes the theoretical innovations, resource achievements, and technological breakthroughs of domestic coal rock gas exploration, providing a reference for subsequent large-scale exploration and development.

2. Core Geological Theoretical Innovations in Coal Rock Gas Exploration

The major breakthroughs in coal rock gas exploration primarily stem from the subversive innovation of geological theories, breaking the limitations of traditional petroleum geology theories and constructing a coal rock gas accumulation theoretical system consistent with China's geological conditions.。

2.1. Proposal and Definition of the Coal Rock Gas Concept

Traditional coalbed methane theory holds that the main development depth of coalbed methane should be limited to 300m - 1200m. When the burial depth exceeds 1500 meters, the increase in formation temperature will significantly reduce the adsorption capacity of coal matrix for methane, leading to a substantial decrease in adsorbed gas content. Moreover, the cost of deep drilling and development rises exponentially. Therefore, this depth interval has long been designated as a "forbidden zone" for coalbed methane development[4]. In fact, this cognitive limitation is not unique to China. Early on, the United States also conducted explorations on deep coal rock gas but failed to form large-scale development due to failure to break through technical bottlenecks and low development benefits. China's exploration of deep coal rock gas did not start in 2017. As early as 2005, PetroChina Xinjiang Oilfield obtained a test gas production of 7000 cubic meters per day in the deep coal rock interval of the Baijiahai area in the Junggar Basin. In 2016, Huabei Oilfield also achieved a gas breakthrough with the first coal rock gas horizontal well deployed in the Bohai Bay Basin. These early discoveries have initially revealed the gas-bearing potential of deep coal rock[5]. Since 2017, PetroChina's scientific research team has systematically carried out research on deep unconventional oil and gas resources and clearly found that natural gas shows in deep coal rock intervals are not only widespread but also their occurrence states (such as free gas ratio) and development characteristics are significantly different from those of traditional shallow coalbed methane. In April 2023, PetroChina held a special technical seminar and officially named this new type of unconventional natural gas "coal rock gas" for the first time. In March 2025, the research team from PetroChina Research Institute of Petroleum Exploration & Development released the relevant concepts and geological theories to the world at the 43rd "CERAWeek", which received high international recognition. Daniel Yergin, Vice Chairman of S&P Global, commented that this theory "opens up a new field for the clean and low-carbon development of global energy".

Completely different from traditional coalbed methane, which is dominated by the adsorbed state (the free gas ratio is extremely low and almost negligible)[4], coal rock gas refers to

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hydrocarbon gases generated by coal rock itself or migrated from other gas sources and accumulated in coal rock.

Table 1. Comparison of Characteristics of Different Types of Unconventional Natural Gas

Type	Definition	Geological Characteristics			Development Technologies		
		Reservoir Type	Occurrence Characteristics	Accumulation Type	Development Method	Core Technologies	Production Characteristics
Coalbed Methane (CBM)	Adsorbed and free gas in coal, industrially exploitable	Coal seam, micro-pores, macro-fractures	Free gas ratio: 20%-50%, high gas saturation in overpressure zones	Self-generated and self-reserved, coal measure migration and accumulation	Depletion mining	Horizontal multi-stage fracturing, etc.	Gas production immediately after well completion, high initial yield, long production cycle
Coal-derived Gas	Hydrocarbon gas generated from coal measures, dissolved in coal seam water and fractures	Coal seam, micro and macro fractures	Free gas ratio: nearly 100%, low gas-water ratio, adsorbed gas saturation < 100%	Self-generated and self-reserved, coal measure retention	Water drainage and pressure reduction mining	Vertical well fracturing, horizontal wells, etc.	Gas production after 1-2 years of water drainage, stable production for 2-5 years
Shale Gas	Free and adsorbed gas in organic-rich shale, low pressure and low permeability	Organic-rich shale, micro-pores	Small pore diameter, free gas ratio: 50%-80%, partial overpressure	Self-generated and self-reserved, retention	Depletion mining	Horizontal multi-stage fracturing	High initial yield, approximately 50% of EUR (Estimated Ultimate Recovery) produced in 3 years
Tight Sandstone Gas	Low-permeability sandstone gas, no single well productivity without technological modification	Tight sandstone, macro-pores	Fine pore throats, complex gas-water relationship, frequent water locking	Near-source accumulation	Depletion mining	Vertical well fracturing, horizontal multi-stage fracturing	Rapid decline in initial high yield, approximately 40% of EUR produced in 3 years

It is characterized by the "coexistence of free and adsorbed states" and "high free gas content", with the free gas ratio reaching 20% - 50%, which is much higher than that of shallow coalbed methane [6]. This feature endows it with the typical production characteristic of "gas production immediately after well completion - desorption relay in the middle and later stages": in the early stage of development, free gas is the main output, without going through the long water drainage and pressure reduction stage of traditional coalbed methane. In the later stage, as the formation pressure decreases, the adsorbed gas is gradually desorbed to supplement production capacity, significantly improving development efficiency. Practical data shows that the single well production of traditional shallow coalbed methane is generally low, while the initial daily gas production of coal rock gas horizontal wells can be stably maintained at 50,000 - 100,000 cubic meters, and the development modes of the two are significantly different. Meanwhile, based on the summary of exploration practices in multiple basins, coal rock gas generally has the "five-high" characteristics: high formation pressure, high formation temperature, high gas content, high adsorbed gas saturation, and high free gas content. These characteristics collectively form the geological foundation for its efficient development.

2.2. Construction of Core Accumulation Theoretical System

The core support for the theoretical innovation of coal rock gas is the "total petroleum system" theory. Proposed by Academician Jia Chengzao of the Chinese Academy of Sciences in 2014, this theory breaks the limitation of traditional petroleum geology that separates conventional and unconventional oil and gas research. It unifies both into a complete accumulation system from a holistic perspective, clarifies the full-chain controlling factors of oil and gas from generation, migration to accumulation, and effectively makes up for the insufficiency of traditional theories in explaining the accumulation mechanism of unconventional oil and gas with no clear boundaries and large-scale continuous distribution[7] (Figure 1). This theory not only provides a new academic paradigm for China's unconventional oil and gas exploration but also becomes the core guidance for the accumulation research of cross-boundary resources such as coal rock gas[5]. Under this framework, the scientific research team of PetroChina Research Institute of Petroleum Exploration & Development further deepened the research and proposed a "coal measure total petroleum system" geological model with coal-bearing strata as the core. This model emphasizes the coordinated development characteristics of source rocks, reservoirs, and cap rocks within the coal measure system, reveals the distribution law of symbiotic superposition and ordered combination of coal rock gas, coalbed methane, tight sandstone gas, shale gas, and other gas reservoirs in the system, and fundamentally scientifically explains the accumulation mechanism and enrichment conditions of coal rock gas[2,4,8]. Practice has shown that this model can effectively guide the optimization of coal rock gas exploration targets in multiple basins and significantly improve the exploration success rate.

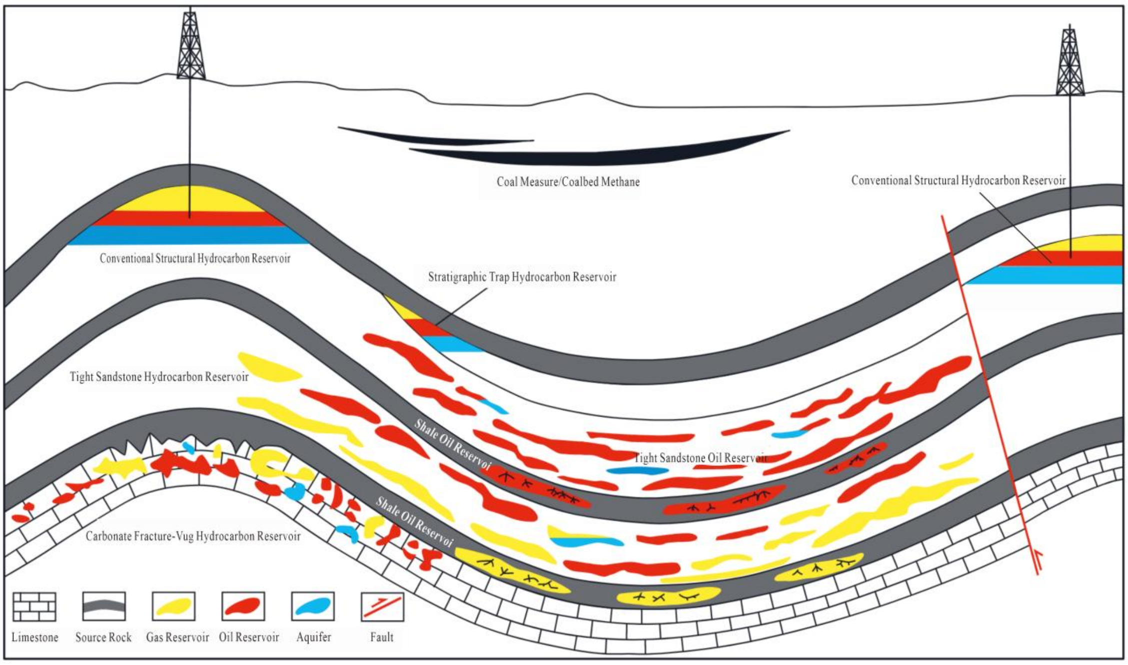

Figure 1. Accumulation Modes of Conventional and Unconventional Oil and Gas in the Total Petroleum System

Based on a large number of exploration practice data and laboratory experimental analysis results from multiple basins nationwide, the joint research team of PetroChina Research Institute of Petroleum Exploration & Development and universities proposed the "three-field" controlled accumulation mechanism, namely, the constrained dynamic field, free dynamic field, and limited dynamic field jointly regulate the formation and enrichment process of coal rock gas [9].

Among them, the constrained dynamic field is mainly composed of the adsorption of coal matrix and the capillary force of the reservoir, controlling the occurrence of adsorbed gas; the free dynamic field is dominated by formation pressure and tectonic dynamics, affecting the migration of free gas;

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Table 2. Types and Main Characteristics of Coal Rock Gas

Category		Coal Rock Gas Type	Core Accumulation Characteristics	Core Reservoir Characteristics	Core Development Characteristics
Deep Coal Rock Gas	Primary Deep Coal Rock Gas	Deep coal rock accumulation, good gas reservoir preservation conditions, thermogenic gas, self-generated and self-reserved	High temperature and high pressure, bituminous coal to anthracite, porosity: 2% - 8%, permeability: (0.01 - 0.10) $\times 10^{-3}\mu m^2$, burial depth > 1000m, free gas > 10%	Gas production immediately after well completion, rapid production of free gas in the early stage with fast yield decline, co-production of adsorbed gas and free gas in the middle to later stages with relatively slow yield decline	Carboniferous - Permian Coalbed Methane Field in the Ordos Basin
	Regenerated Coal Rock Gas	Deep coal rock accumulation, exogenous gas supply or secondary gas generation after the destruction of primary coal rock gas, self-generated and self-reserved	High temperature and high pressure, bituminous coal, porosity: 3% - 12%, permeability: (1.000 - 2.000)$\times 10^{-3}\mu m^2$, burial depth > 1500m, free gas > 10%	Rapid gas production without water drainage and pressure reduction, high initial yield, little or no water production, self-spray production, with a certain stable production period	Jurassic Baijiahai Coal Rock Gas Field in the Junggar Basin
Shallow Coal Rock Gas	Residual Coal Rock Gas	Deep coal rock accumulation, later uplift or re-burial with supercritical deep burial, partial retention of primary gas after the modification of primary coal rock gas, self-generated and self-reserved	Low temperature and low pressure, bituminous coal to anthracite, porosity: 2% - 10%, permeability: (2.000 - 3.000)$\times 10^{-3}\mu m^2$, burial depth < 1000m, no free gas	Water drainage and pressure reduction, slow desorption and production of adsorbed gas	Carboniferous - Permian Coalbed Methane Field in the Qinshui Basin
	Primary Deep Coal Rock Gas	Deep coal rock accumulation, good gas reservoir preservation conditions, thermogenic gas, self-generated and self-reserved	High temperature and high pressure, bituminous coal to anthracite, porosity: 2% - 8%, permeability: (0.01 - 0.10)$\times 10^{-3}\mu m^2$, burial depth > 1000m, free gas > 10%	Gas production immediately after well completion, rapid production of free gas in the early stage with fast yield decline, co-production of adsorbed gas and free gas in the middle to later stages with relatively slow yield decline	Carboniferous - Permian Coalbed Methane Field in the Ordos Basin
	Regenerated Coal Rock Gas	Deep coal rock accumulation, exogenous gas supply or secondary gas generation after the destruction of primary coal rock gas, self-generated and self-reserved	High temperature and high pressure, bituminous coal, porosity: 3% - 12%, permeability: (1.000 - 2.000)$\times 10^{-3}\mu m^2$, burial depth > 1500m, free gas > 10%	Rapid gas production without water drainage and pressure reduction, high initial yield, little or no water production, self-spray production, with a certain stable production period	Jurassic Baijiahai Coal Rock Gas Field in the Junggar Basin

the limited dynamic field depends on the sealing capacity of the cap rock and hydrodynamic conditions, determining the preservation effect of the gas reservoir[3]. This mechanism clearly defines the scope of action and synergistic relationship of different dynamic fields, providing a new theoretical framework and quantitative evaluation indicators for the prediction of sweet spots and exploration deployment of deep coal rock gas. According to the differences in accumulation sources and processes, coal rock gas is divided into four types: primary type, regenerated type, residual type, and biogenic type (Table 2). Among them, the primary type refers to the gas generated by coal rock itself during the thermal evolution process and stored in situ. Due to stable accumulation conditions and large resource scale, it has become the main target type for current exploration[10,11]. Taking the Ordos Basin as an example, this area has weak tectonic activity, gentle strata, and the top and bottom plates of the coal measure are mainly mudstone and shale with strong sealing capacity. Additionally, the hydrodynamic environment is weak, providing superior conditions for the self-generated and self-reserved accumulation of medium-high rank coal. Gas reservoirs can be formed in all thermal evolution stages of coalification from long-flame coal to anthracite. The occurrence of oil asphalt in some areas further blocks the gas escape channels, significantly improving the resource exploration value.

3. Resource Potential and Exploration Achievements in Key Regions

China has a wide distribution of coal-bearing basins and excellent coal rock gas resource endowments. After systematic exploration in recent years, significant breakthroughs have been achieved in multiple basins, with proven reserves and production growing rapidly.

3.1. Overview of National Resource Potential

According to the "Coalbed Methane Resource Potential Evaluation Report" by the Ministry of Land and Resources, the geological resource volume of coalbed methane with a burial depth of less than 2000 meters in 42 major coal-bearing basins in China is 36.81×10^{12} cubic meters, with a resource abundance of 0.98×10^{8} cubic meters per square kilometer; the recoverable resource volume of coalbed methane with a burial depth of less than 1500 meters is 10.87×10^{12} cubic meters; the prospective resource volume with a burial depth of less than 3000 meters is approximately 55.2×10^{12} cubic meters. By the end of 2016, the cumulative proven geological reserves of coalbed methane nationwide reached 6869.12×10^{8} cubic meters, mainly distributed in Shanxi Province, the eastern part of the Ordos Basin, and other regions. China's coalbed methane resources can be divided into four major accumulation areas: Northeast, North China, Northwest, and South China (Figure 2, Table 3).

Northeast Gas Area: Mainly distributed in the Hailar Basin (Group), Erlian Basin (Group) in eastern Inner Mongolia, and the Songliao Basin (Group) in the three northeastern provinces. This area has favorable economic and geographical conditions, abundant coalbed methane resources, and a solid foundation for coal seam and coalbed methane exploration and research, making it an important strategic area for coalbed methane exploration and development in China.

North China Gas Area: Spanning four provinces and autonomous regions (Shaanxi, Gansu, Ningxia, and Inner Mongolia), it mainly includes the Ordos Basin, Datong - Ningwu Basin and Qinshui Basin in Shanxi, Bohai Bay Basin in northern North China, and various basins in southern North China. This area concentrates the most potential coalbed methane target areas for exploration and development in China and is currently the most active area for coalbed methane exploration and development nationwide.

Northwest Gas Area: Distributed in the Junggar, Santanghu, Yanqi, Turpan-Hami, Tarim, and other basins in Xinjiang, as well as the Qaidam Basin in Qinghai. Among them, the Junggar Basin and Tarim Basin have the most concentrated resources. This area has thick coal seams, good physical properties, and high gas content, with favorable conditions for coalbed methane enrichment and recoverability. The Baiyanghe - Fukang Coalbed Methane Development Demonstration Zone has been built.

South China Gas Area: Mainly located in the southern Sichuan - western Guizhou - eastern Yunnan region, covering the Sichuan Basin, Chuxiong Basin, Shiwandashan Basin, Sanshui Basin, and other basins. This area has well-developed Late Permian coal-bearing strata with thick coal seams, multiple layers, and high gas content, making it an important strategic replacement area for coalbed methane exploration and development in China.

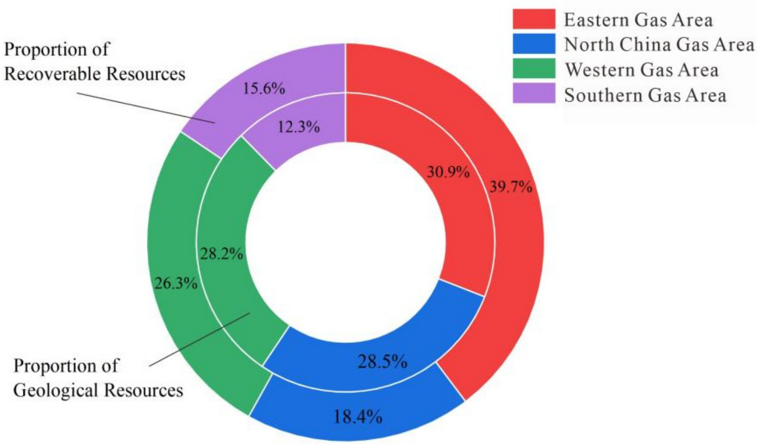

Figure 2. Proportion of Resource Volume in National Gas Areas

Table 3. Resource Volume of National Gas Areas

Gas Area	Geological Resource Volume ($\times10^{12}m^3$)	Proportion of National Total	Recoverable Resource Volume ($\times10^{12}m^3$)	Proportion of National Total
Eastern Gas Area	11.32	30.8%	4.32	39.7%
North China Gas Area	10.47	28.4%	2.00	18.4%
Western Gas Area	10.36	28.1%	2.86	26.3%
South China Gas Area	4.66	12.3%	1.70	15.6%

3.2. Exploration Breakthroughs in Key Basins

China's coal rock gas exploration has shown a good trend of "multi-point breakthroughs and rapid growth". Six major coal-bearing basins, including the Ordos, Junggar, Sichuan, Tarim, Bohai Bay, and Turpan-Hami Basins, have been proven to have a resource foundation for efficient exploration and development through preliminary resource evaluation. Among them, the Ordos Basin has become the core area with the most significant current exploration achievements due to its large resource scale and superior accumulation conditions [12]. From the perspective of resource distribution characteristics, these basins cover different structural units such as the East, West, and Southwest China, with thickly developed coal measure strata and moderate thermal evolution degree, providing favorable geological conditions for the generation and enrichment of coal rock gas[13]. It is worth noting that there are significant differences in the occurrence characteristics of coal rock gas in different basins: the eastern basins are dominated by medium-high rank coal with a higher free gas ratio; while in the western basins, due to relatively intense tectonic activities, the preservation conditions of gas reservoirs have become the key to exploration[14].

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The Ordos Basin has coal rock gas resources exceeding 25 trillion cubic meters, accounting for 52% of the national total, making it the core strategic area for coal rock gas exploration and development in China. PetroChina has successively proven three 100-billion-cubic-meter-class large gas fields (Daji, Mizhi, and Hengshan) in the basin, with cumulative geological reserves exceeding 5000 billion cubic meters. Among them, the Mizhi Coal Rock Gas Field, proven in 2023, has geological reserves of 1800 billion cubic meters, becoming the second 100-billion-cubic-meter-class large-scale gas reservoir in the basin. Based on these resource foundations, China has successfully built the first million-ton-class deep coal rock gas field - the Daji Coal Rock Gas Field. Located in the Jinxi flexure belt on the eastern margin of the Ordos Basin, the main coal-bearing strata of the gas field are the Permian Shanxi Formation and Carboniferous Taiyuan Formation, with a stable coal seam thickness of 15-25 meters and a gas saturation of 75%-85%[14]. The estimated resource volume of the gas field is about 6000 billion cubic meters. A pilot test project was launched in 2019. Through optimizing drilling and fracturing technologies, the first pilot vertical well (Daji 3-7-2 Well) obtained an industrial gas flow of 12,000 cubic meters per day, with a single well production 5 to 10 times that of shallow coalbed methane wells, verifying the development potential of deep coal rock gas[6]. In 2021, the world's first coal rock gas breakthrough well (Jishen 6-7 Ping 01 Well) adopted horizontal well multi-stage fracturing technology, achieving a test production of 101,000 cubic meters per day, setting a record for single well production of deep coal rock gas at that time and laying the foundation for commercial development. By February 2025, the cumulative production of coal rock gas in the Daji Gas Field exceeded 3 billion cubic meters, with an annual output of 1.69 billion cubic meters in 2024, a year-on-year increase of 79.2%. The average production cost per well has decreased by 30% compared with the initial development stage, showing excellent development benefits. In addition, Changqing Oilfield has drilled a number of high-yield wells with a daily gas production of more than 50,000 cubic meters in blocks such as Mizhi and Hengshan in Shaanxi through the technology combination of "precise sweet spot prediction - horizontal well optimized fast drilling - large-scale volume fracturing". Among them, the Mizhen 10-1 Horizontal Well in the Mizhi Block has a daily gas production of 86,000 cubic meters. Currently, the region is advancing overall exploration and development on the scale of a trillion-cubic-meter-class large gas area[15]. Liaohe Oilfield and Jidong Oilfield have carried out cross-basin exploration in Yichuan, Shenmu, and other places, and obtained multiple high-yield wells with a daily gas production of more than 50,000 cubic meters in 2024, further expanding the exploration scope and potential boundary of coal rock gas in the Ordos Basin.

As an important coal-bearing basin in western China, the Junggar Basin has the largest coal resource volume in the country, and significant breakthroughs have been achieved in deep coal rock gas exploration in recent years. Guided by the "coal measure total petroleum system" theory, the scientific research team deployed the Baishen 13 Well in the Baijiahai Uplift area in the central part of the basin and obtained an industrial gas flow of 32,000 cubic meters per day in the Jurassic Xishanyao Formation coal rock interval with a burial depth of 2800-3200 meters, verifying the commercial development potential of deep coal rock gas in this region[4]. The coal rock in this block is mainly medium-low rank coal. Although the adsorbed gas content is slightly lower than that in the Ordos Basin, the free gas ratio can reach 35%-40% due to the high reservoir porosity, providing a good production foundation[10]. At present, Xinjiang Oilfield has completed 3D seismic exploration covering 1500 square kilometers in this region, initially delineated 3 favorable exploration zones, and the estimated resource volume exceeds 3 trillion cubic meters, laying the foundation for subsequent large-scale exploration.

The exploration and evaluation of coal rock gas in the Sichuan Basin are also advancing in an orderly manner. Through the analysis of coal rock samples from the Dazhu Mining Area in the northeastern part of the basin, the scientific research team of Southwest Petroleum University confirmed that the coal rock interval with a burial depth of 2000-3500 meters in this region has a large gas content and good reservoir permeability, with an initial estimated resource volume exceeding 8 trillion cubic meters[16]. In 2024, the Dashen 5 Well deployed by Sinopec Southwest Oilfield Branch obtained an industrial gas flow of 28,000 cubic meters per day, marking the initial breakthrough in coal rock gas exploration in the Sichuan Basin. The Tarim Basin focuses on key areas such as the Kuqa Depression. Through comprehensive evaluation of coal measure strata, it has been initially confirmed that this region has geological conditions for forming large-scale coal rock gas reservoirs. At present, drilling of 4 parameter wells has been completed, and abundant basic data of coal rock reservoirs have been obtained, which is expected to become an important replacement area for coal rock gas exploration in western China in the future.

4. Core Breakthroughs in Key Exploration and Development Technologies

The rapid advancement of coal rock gas exploration and development is inseparable from the collaborative innovation of key technologies such as seismic exploration, drilling engineering, and reservoir stimulation, overcoming a series of technical bottlenecks under complex deep geological conditions.

4.1. Breakthroughs in Seismic Exploration Technology

Aiming at the world-class exploration challenges in the eastern Ordos Basin, such as thick loess (maximum thickness exceeding 300 meters), rugged terrain, well-developed underground microstructures (amplitude mostly less than 10 meters), thin reservoirs (single layer thickness 2-8 meters), and complex lithological combinations, BGP Inc. and Changqing Oilfield carried out integrated research and innovation, forming a number of core technology systems covering the entire process of acquisition, processing, and interpretation. The "2023 Ordos Basin Coal Rock Gas Exploration Project - Mizhi Area 3D Seismic Acquisition Engineering", implemented as the largest-scale 3D seismic acquisition project for deep coal rock gas in loess mountainous areas in China, won the only gold award of the 2025 Engineering Technology Innovation Achievement Award of the Chinese Geophysical Society at the 11th Fourth Director's Expansion Meeting of the Chinese Geophysical Society held in Chengdu in October 2025. This award indicates that China's seismic exploration technology for deep coal rock gas in loess mountainous areas has reached the international advanced level. The project focused on innovating 7 key core technologies such as well-seismic hybrid acquisition and micro-amplitude structure characterization, successfully breaking through the bottlenecks of poor data quality, difficult construction, and low efficiency faced by traditional technologies in this region. Among them, the combination of 3D observation system design, UAV shot point layout, and full-pneumatic air drilling technology was adopted. UAV shot point layout can achieve precise positioning of shot points under complex terrain with a positioning error controlled within 0.5 meters. Full-pneumatic air drilling solves the problem of easy hole collapse in loess layer drilling. The collaboration of the two technologies increases the signal-to-noise ratio of original seismic data by more than 35% and improves the resolution by 20%. Through the USM+SSC dual-source excitation technology, while improving the uniformity of excitation energy, the construction efficiency per square kilometer is increased by 25% and the exploration cost is reduced by 20%[17]. The application of paleogeomorphology-constrained inversion and depth-domain micro-structure characterization technology effectively improves the seismic imaging quality of deep coal rock reservoirs, increasing the reservoir prediction coincidence rate from the original 65% to 82% and significantly improving the accuracy of coal rock reservoir prediction. Relying on this project, 5 invention patents, 2 enterprise standards, and 10 technical papers and other tangible achievements have been formed. Its high-quality results have strongly supported the major discovery of the Mengshan-Shaanxi large-scale coal rock gas field. The project has also successively won the Special Award for Comprehensive Breakthrough in Efficient Exploration of Coal Rock Gas in the Ordos Basin in 2024 by the Group Corporation and the Quality Engineering Award of Changqing Oilfield Company, setting a technical model and engineering benchmark for large-scale exploration and development of deep coal rock gas.

4.2. Innovation in Drilling Engineering Technology

Deep coal rock drilling faces extremely complex technical difficulties. The core problems are: deep coal rock has high brittleness, developed fractures, and uneven in-situ stress distribution, making wellbore collapse prone to occur during drilling; at the same time, coal rock reservoirs have significant lateral heterogeneity, making it extremely difficult to accurately guide the horizontal well trajectory, which is easy to deviate from the target reservoir; in addition, deep drilling requires high lubricity of drilling fluid, resulting in high drill string friction and a high risk of drill string sticking[18]. To overcome these problems, Changqing Oilfield adheres to the core concept of "geology-engineering integration", constructs a full-chain synchronous optimization technology system of "scheme design - geological steering - equipment matching - mud performance", and successfully drilled China's first 2500-meter ultra-long horizontal section coal rock gas horizontal well, setting three industry records in China's onshore coal rock gas: ultra-long horizontal section extension length, single-trip drilling footage in horizontal section, and longest open hole section length, providing a key technical template for large-scale development of deep coal rock gas.

On this basis, the scientific research team further tackled key problems and finalized the optimized fast drilling technology system in the eastern part of the basin, focusing on promoting the low-cost anti-collapse drilling fluid system. By optimizing the ratio of polymer inhibitors and lubricants, this system significantly improves the inhibition and lubrication performance of drilling fluid, reduces the drill string sticking rate to below 3%, and lowers the cost by 18% compared with traditional drilling fluid. At the same time, it innovatively adopts the "three-high" drilling mode of "high rotation speed, high pump pressure, and high displacement", combined with personalized wellbore cleaning measures, effectively carrying cuttings and reducing the formation of cuttings beds, shortening the average single well drilling cycle by 22%, and significantly improving construction efficiency and operational safety. In the field of cementing technology, aiming at the problem that cementing quality is difficult to guarantee under deep high-temperature and high-pressure environments, a special pre-flush fluid combination, high-temperature resistant and pollution-resistant characteristic cement slurry system, and a series of high-efficiency cementing tools have been developed. Among them, the pre-flush fluid can achieve efficient removal of wellbore mud cake, and the cement slurry system can maintain excellent setting performance under the conditions of 150℃ and 60MPa, increasing the cementing qualification rate from the original 85% to more than 98%, providing a solid guarantee for subsequent fracturing stimulation and safe production. Up to now, the Natural Gas Evaluation Project Team of Changqing Oilfield in the eastern part of the basin has drilled 50 coal rock gas horizontal wells, with cumulative gas production exceeding 190 million cubic meters, fully verifying the reliability and large-scale application potential of this set of drilling technology system.

4.3. Optimization of Reservoir Stimulation and Mining Technology

Aiming at the occurrence characteristics of coal rock gas of "coexistence of free and adsorbed states", the scientific research team broke through the traditional single stimulation idea of coalbed methane and optimized the adaptive reservoir stimulation technology scheme of "reservoir classification evaluation - precise stage design - multi-medium composite stimulation". The core is to construct a complex fracture network system through large-scale volume fracturing, which not only realizes the rapid production of free gas but also ensures the efficient desorption and relay gas production of adsorbed gas in the middle and later stages[19]. Based on parameters such as coal rock brittleness index and pore structure, this scheme

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classifies reservoirs into three types (I-III) and adopts different fracturing fluid systems and construction parameters for different types: for type I high-quality reservoirs, large-scale slickwater sand fracturing is used to expand the fracture network extension range; for type II-III reservoirs, foam fracturing is used to improve sand-carrying capacity and reduce reservoir damage. Laboratory experiments and field practices show that this technology can increase the permeability of coal rock reservoirs by 3-5 orders of magnitude, shorten the free gas production cycle by more than 40%, and improve the desorption efficiency of adsorbed gas by 25%.

Taking the Daji Gas Field, a core production area, as an example, the main development blocks adopt the horizontal well fracturing technology of "long horizontal section + high-density staging + large-scale sanding". The horizontal section length is generally controlled at 1500-2500 meters, the number of stages reaches 20-30, and the single well sanding volume exceeds 2000 cubic meters. Compared with the early fracturing technology, the single well production is increased by more than 60%. Among them, after being reconstructed by this technology, the Jishen 6-7 Ping 02 Well has a stable daily gas production of 123,000 cubic meters, setting a new high for single well production of coal rock gas in this region and laying a solid technical foundation for commercial development[20]. In terms of the optimization of mining technology, the focus is on promoting the "geology-engineering integration" full-process management mode. Through the deep integration of seismic sweet spot prediction, while-drilling geological steering, real-time fracturing monitoring, and dynamic production regulation, the accuracy of well location deployment is improved by 30%, and the fracturing parameter adaptability rate reaches more than 90%. At the same time, the innovative mining strategy of "water drainage and pressure control - stepped gas production" is adopted, dynamically adjusting the water drainage volume according to the formation pressure changes in different production stages, avoiding reservoir damage and maximizing the cumulative single well production of gas wells, reducing the unit development cost by 35% compared with the initial development stage. In addition, aiming at the problem of slow desorption rate of adsorbed gas in the process of coal rock gas development, nitrogen-assisted desorption technology has been developed and field tests have been carried out, which can advance the peak production of adsorbed gas by 1-2 months and increase the final recovery rate of single wells by 8-12 percentage points, providing a new path for the efficient development of low-permeability coal rock gas reservoirs[16].

5. Main Challenges Faced Currently

Despite the significant progress made in China's coal rock gas exploration, a series of challenges still exist in the process of large-scale and commercial development, restricting the full release of resource potential. Firstly, the deep exploration theory needs to be deepened. At present, coal rock gas exploration is mainly concentrated in the shallow and medium-deep coal rock intervals. For areas with greater burial depth and more complex geological conditions, the understanding of their accumulation laws and main enrichment controlling factors is still insufficient, and the prediction accuracy of sweet spots needs to be further improved. Secondly, there is great pressure on technical cost control. Deep coal rock gas exploration and development involve high-end technologies such as ultra-long horizontal well drilling and complex reservoir stimulation, with large initial investment and high construction difficulty. How to further optimize the technical system and reduce the unit exploration and development cost is the key to realizing large-scale development. Thirdly, environmental protection constraints are increasingly strengthened. Environmental issues such as fracturing fluid treatment and formation water discharge during coal rock gas development have attracted much attention. There is an urgent need to develop environmentally friendly fracturing fluid systems and formation water treatment technologies to realize the coordinated development of exploration and development and ecological protection. Fourthly, the standard system is not yet perfect. As

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a new type of unconventional natural gas resource, the industry standards and specifications for coal rock gas in terms of resource evaluation, reserve calculation, and development technology are still in the improvement stage, restricting the standardized advancement of exploration and development.

6. Development Prospect

In the future, with the continuous innovation of geological theories, the iterative upgrading of key technologies, and the continuous strengthening of policy support, China's coal rock gas exploration and development are expected to enter a new stage of large-scale development.

In terms of theoretical research, efforts should be made to further deepen the "coal measure total petroleum system" theory, focus on the research on the accumulation mechanism of deep and ultra-deep coal rock gas, improve the "three-field" controlled accumulation theoretical system, enhance the prediction accuracy of sweet spots, and expand the exploration space. In terms of technological innovation, key efforts should be made to tackle core technologies such as seismic exploration of ultra-deep coal rock gas, efficient and low-cost drilling, and green reservoir stimulation, promote intelligent exploration and development, and use big data, artificial intelligence, and other technologies to improve the accuracy of well location deployment and fracturing construction, and reduce development costs. In terms of regional expansion, in addition to continuing to deepen the exploration and development of the Ordos Basin, accelerate the exploration and evaluation progress of the Junggar, Sichuan, Tarim, and other basins, and realize an exploration pattern of "multi-point blooming". In terms of policy support, it is recommended to improve the incentive policies for coal rock gas exploration and development, establish and improve the industry standard system, increase support for the research and development of environmental protection technologies, and promote the standardized and green development of the coal rock gas industry.

In addition, with technological progress, it is expected to discover more coal rock oil and gas reservoirs rich in condensate oil and gas in the future, further improving the development value of coal rock gas resources. It is predicted that by 2035, China's coal rock gas production capacity will reach more than 30 billion cubic meters, becoming an important strategic force for safeguarding national energy security and promoting energy structure transformation.

7. Conclusion

China's coal rock gas exploration field has achieved leapfrog development from theoretical breakthroughs to resource discovery and then to technological maturity, constructing a coal rock gas geological theoretical system with Chinese characteristics, proving multiple exploration blocks with the Ordos Basin as the core, and forming a set of key technology systems with independent intellectual property rights. At present, coal rock gas has entered a critical development period of "multi-point breakthroughs and rapid growth", with enormous resource potential and broad development prospects. Despite facing challenges such as insufficient deep exploration theory and high technical costs, with the continuous innovation of theories and technologies and the continuous improvement of the policy system, coal rock gas will surely play an increasingly important role in safeguarding national energy security and realizing the "dual carbon" goals. In the future, efforts should be made to further increase investment in exploration and development and scientific research, and promote the high-quality development of the coal rock gas industry.

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