ISSN: 1813-4890

A Review of the Key Characteristics, Exploration and Development Technologies, and Utilization Prospects of Coalbed Methane

Ziqi Lu

Xi 'an Shiyou University, Xi 'an, Shaanxi 710065, China

Abstract

Coalbed methane (CBM) is an unconventional natural gas resource, primarily composed of methane, which is stored within coal seams. It exists predominantly as gas adsorbed onto the surface of coal matrix particles (70-95%), with a minor proportion occurring as free gas in cleats and other fractures or pores (10-20%), and a trace amount dissolved in groundwater. CBM reservoirs are self-sourcing, meaning the coal seam acts as both the source rock and the reservoir rock. As an abundant and widely distributed resource, CBM is characterized by its cleanliness, high efficiency, and renewability, making it a significant alternative energy source. Its exploitation and utilization are of great importance for mitigating energy crises, optimizing the energy mix, and protecting the environment. This paper presents a comprehensive review of CBM, encompassing its general characteristics, formation mechanisms, factors influencing gas storage, exploration and development technologies, as well as the associated challenges and strategies, to provide a holistic understanding of this resource.

Keywords

Coalbed methane; CBM formation; Gas occurrence controls; CBM exploration and development technologies.

1. Introduction

Coalbed methane (CBM) is an unconventional natural gas resource, primarily composed of methane (CH_4), which is stored in coal seams and coal-bearing strata. It exists predominantly in an adsorbed state on the surface of the coal matrix, with minor amounts of free gas. As an emerging, clean, and high-quality energy source, CBM also contains variable proportions of nitrogen (N_2), carbon dioxide (CO_2), and trace other gases[1].High-concentration coalbed methane, characterized by a methane content exceeding 90% and a calorific value greater than 8000 kcal/m^3, is comparable in quality to conventional natural gas. This makes it a high-grade energy source and chemical feedstock[2].A key economic advantage of coalbed methane over conventional natural gas is its simpler composition, which eliminates the need for the separation and recovery of C_2-C_4 hydrocarbons. Against the backdrop of stringent coal mine safety regulations, tightening natural gas supplies, and global climate change concerns, CBM is garnering increasing strategic importance in China. Primary utilization pathways include power generation, residential heating, and combustion in dedicated mine-methane boilers[3]. Coalbed methane production follows a unique mechanism: dewatering-depressurization-desorption-production. CBM wells extract water to reduce reservoir pressure, which triggers the desorption of methane molecules from the coal matrix. The desorbed gas then diffuses through the micropores of the matrix to the cleats, driven by a concentration gradient. Subsequently, the gas migrates through the cleat system and finally flows towards the production wellbore, driven by the fluid potential gradient.

This paper provides a comprehensive review of CBM, encompassing its general characteristics, genesis, factors controlling gas storage, exploration and development technologies, as well as the associated challenges and strategies. The aim is to present a holistic understanding of CBM resources and their utilization.

2. General Characteristics of Coalbed Methane

2.1. Resources and Distribution

China's coal resources are predominantly distributed in the North China and Northwest China regions, spanning from Mohe in the north to Hainan Island in the south, and from Yining in the west to the offshore areas in the east. The country contains 39 major coal-bearing basins, which can be subdivided into 60 significant coalfields, with total coal resources of approximately 5×10^{12} tonnes, ranking third in the world[4]. According to the Fourth National Oil and Gas Resources Assessment, China hosts over 100 CBM-enriched zones, with total estimated in-place resources of about 30.8×10^{12} m^3. These are categorized as follows: 14 zones hold resources greater than 0.5×10^{12} m^3, accounting for 93.4% of the total; 10 zones have resources between 0.1×10^{12} m^3 and 0.5×10^{12} m^3, constituting 5.6%; and 17 zones possess resources less than 0.1×10^{12} m^3, making up the remaining 1.0%[5].

2.2. Status of Exploration and Development

The United States pioneered the commercial development of coalbed methane globally. Its exploration history can be divided into four distinct phases: pioneering, breakthrough, rapid expansion, and decline. As early as 1976, the discovery of significant CBM accumulations in basins such as the Williston, Powder River, and Illinois marked a critical juncture, prompting the commencement of systematic CBM development and utilization in the country[6].With the commencement of production from the first commercial CBM field in 1986, the United States entered the modern era of its CBM industry. This period was subsequently marked by the discovery of major CBM accumulations in basins such as the Black Warrior, San Juan, and Appalachia[7].Spurred by the energy crisis at the end of the 20th century, the United States intensified its efforts in CBM development.By the end of 1989, annual CBM production had reached 26×10^8 m^3, representing a significant production breakthrough and establishing a preliminary commercial scale.

Driven by a deeper understanding of the accumulation mechanisms in low to medium-rank coal reservoirs and maturing extraction technologies, the United States witnessed an explosive growth in CBM production starting in 1992. This growth phase lasted 16 years, culminating in a peak annual production of 549×108m^3[8].Following the year 2000, a surge in shale gas production led to a sharp decline in U.S. natural gas prices, which at their lowest point reached approximately $0.07 per cubic meter. Within this context, financial investment in CBM projects was drastically reduced, resulting in a significant decrease in the number of new CBM wells drilled. Consequently, annual CBM production entered a period of precipitous decline, marking the onset of a contraction phase for the U.S. CBM industry.Globally, beyond the United States, countries such as Russia, Canada, and Brazil also possess substantial CBM reserves. Given this widespread resource base, the global development prospects for CBM remain highly promising.

Although China's CBM development started relatively late, it has experienced a rapid upward trend over the past decade. Spurred by the successful commercialization of CBM abroad, China has prioritized its development, increasing financial investment and enacting numerous supportive policies to pave the way for its commercial viability[9].This phase was marked by the introduction of pioneering foreign technologies, which directly led to the establishment of two major, unified CBM fields in the Fuxin and Qinshui regions, each with reserves exceeding 100 billion cubic meters (Bcm)[10].The period from 2013 to 2020 marked the phase of commercial-scale development for China's CBM industry, which saw a rapid increase in technically recoverable reserves, the number of drilled wells, and cumulative production[11].

Following years of independent exploration, China conducted pilot tests in prolific CBM regions such as Shanxi and Inner Mongolia. These efforts led to the establishment of two major demonstration zones in the Ordos and Qinshui Basins, culminating in the commencement of small-scale production in areas like Southern Sichuan and Western Liaoning[3].Since 2014, CBM extraction technologies in China have matured significantly, leading to independent breakthroughs in the development of mid-deep coalbed methane reservoirs. Recent years have witnessed notable exploration successes in new frontiers. Commercial gas flows have been achieved from medium- to high-rank coal seams in regions such as Ningxia, Shaanxi, and Heilongjiang[12]. These areas hold strong potential for future production breakthroughs and large-scale development, positioning them as critical successor regions for China's CBM industry.

3. Formation of Coalbed Methane

Coalbed methane is generated through two primary pathways: thermogenic and biogenic processes. Thermogenic CBM forms when organic matter in coal undergoes chemical reactions under the combined effects of high temperature and subsurface pressure, leading to deoxygenation, dehydrogenation, carbon enrichment, and the release of large volumes of methane and other gases. Biogenic CBM results from the action of diverse microorganisms that, under suitable environmental conditions, convert complex organic compounds in coal into gaseous methane (CH_4) and carbon dioxide (CO_2). Furthermore, biogenic gas can be classified into primary and secondary biogenic gas based on its origin. Primary biogenic gas is generated during the peatification stage and may escape to the surface under low confining pressure. Secondary biogenic gas forms through a series of geological processes-such as burial, coalification, uplift, and erosion—often driven by bacterial fermentation introduced via groundwater, particularly along basin margins[13].

3.1. Primary Biogenic Gas

Primary biogenic gas forms during the peat to lignite stage. Due to shallow burial depths (<400 m) and low temperatures, thermal energy is insufficient to significantly alter the structure of the organic matter and generate gas. At this stage, changes in the composition and structure of organic material occur mainly through microbially mediated chemical reactions. Methane, the principal component of this gas, is primarily generated in peat swamp environments via microbial decomposition of organic matter[14].

3.2. Secondary Biogenic Gas

During later uplift stages of a coal seam, environmental conditions may again become suitable for microbial activity. These microorganisms are typically introduced into the coal seam through meteoric water infiltration, often via outcrops in recharge zones. Under relatively low temperatures, they metabolize wet gas, n-alkanes, and other organic compounds, producing CH_4 and CO_2. In coal-bearing basins, the depth interval where secondary biogenic processes are active and significantly alter gas composition is referred to as the alteration zone, generally located at basin margins or in intermediate to shallow depths. Gas in the deeper parts of the basin, which remains unaffected by these processes, is termed the primary gas zone.

3.3. Thermogenic Gas

From the perspective of source rock evolution, the coalffication process can be divided into the low maturity, maturity, and high maturity stages. Biogenic gas is primarily formed during the low maturity stage, whereas genuine thermogenic gas generation occurs throughout the long-flame coal to anthracite stages.

(1) Maturity Stage: Under thermal effects, free functional groups and side chains decompose sequentially based on their activation energies, converting into hydrocarbons with varying molecular structures. Isotopic composition of the generated gases undergoes corresponding fractionation effects, dependent on the reactivity of the precursors.

(2) High Maturity Stage: As most aliphatic side chains on aromatic structures were consumed during the maturity stage, chemical reactions shift from cleavage-dominated processes to condensation between aromatic nuclei. This condensation generates significant volumes of methane. During this stage, the aromaticity of the organic matter increases from 0.85 to 0.97, with carbon atoms becoming almost exclusively concentrated within the aromatic structures.

4. Controls on Coalbed Methane Occurrence

The formation and occurrence of coalbed methane are influenced by multiple factors. Volcanic activity, for instance, can accelerate secondary alterations of coal, enhancing its saturation and increasing CBM content. Local thermal dynamics also significantly impact CBM generation and distribution. The presence of high-temperature zones within coal-bearing sequences, coupled with effective sealing conditions that slow heat dissipation, promotes the adsorption of gas onto the coal matrix. Subsequent thermal diffusion then facilitates the migration of gas into reservoir spaces. Furthermore, water within coal seams is a critical factor affecting CBM occurrence, often leading to lower gas saturation under its influence. This section reviews the fundamental characteristics of CBM and its key controlling factors[15].

4.1. Impact of Seals on CBM Occurrence

When CBM reaches a critical saturation state, free-phase gas can readily escape from the reservoir. In the absence of an effective seal, this gas may diffuse out of the reservoir, leading to pressure depletion and accelerated gas loss. An effective seal exists when its displacement pressure exceeds the buoyancy pressure exerted by the CBM column, thereby trapping the gas relatively stably within the coal matrix. To prevent gas escape during development, the placement or presence of a competent seal is crucial. Seals can be categorized based on their displacement pressure, rock permeability, and fracture density to evaluate their sealing capacity. Seals with a displacement pressure index >1.0, permeability $<10^{-3}$ mD, and poorly developed fractures are classified as barrier seals (e.g., mudstone, silty mudstone, limestone). These rocks, characterized by small and sparse pores, effectively inhibit gas escape and are ideal for CBM storage. Those with a displacement pressure index of 0.1-1.0, permeability $<10^{-2}$ mD, and moderately developed fractures are semi-barrier seals (e.g., sandy mudstone, siltstone), which offer moderate sealing efficiency. Seals with a displacement pressure index <0.1, permeability $>10^{-2}$ mD, and well-developed fractures are leaky seals (e.g., sandstone, claystone, fractured limestone). Their abundant and interconnected pore systems facilitate gas migration from underlying coal seams, resulting in poor sealing performance.

4.2. Impact of Hydrogeological Conditions on CBM Occurrence

Hydrodynamic conditions significantly influence CBM distribution, and their proper management is essential for efficient exploration and production. Static water bodies can seal coal pores, stabilizing the gas-liquid interface at a high capillary pressure and effectively preventing gas escape into the atmosphere. This sealing effect is most pronounced in deep water zones, where hydrostatic pressure enhances confinement. Groundwater can also block gas migration; as CBM tends to migrate upwards, groundwater infiltration can accumulate and trap it within specific structural compartments. Conversely, dynamic groundwater flows can transport CBM. On one hand, water flow can reduce gas partial pressure or desorb gas from the coal matrix, converting it into a free phase that migrates through fractures. On the other hand, flowing water can dissolve CBM, transporting it to other areas, particularly along faults with high hydraulic conductivity. Additionally, water influx into coal fractures may displace gas; however, since most CBM is adsorbed, this displacement effect is generally minimal.

4.3. Impact of Structural Conditions on CBM Occurrence

Besides the factors mentioned above, structural settings of coal seams also exert critical controls on CBM characteristics. Gas naturally migrates from high-to low-concentration zones, but fold structures can create sealed compartments where impermeable rocks are tightly juxtaposed, inhibiting such migration. Furthermore, tectonic uplift or subsidence, driven by changes in temperature and pressure, can alter the adsorption-desorption equilibrium, potentially leading to gas escape. Faulting is another key structural factor influencing seam integrity and seal capacity. Normal faults, typically extensional, tend to be conduits for gas escape (open fractures), whereas reverse faults, often compressional, act as better seals (closed fractures). Generally, highly permeable structural zones associated with large-scale, long-lasting, wide, and sparsely filled faults promote extensive fracture networks, accelerating gas dissipation and thus being unfavorable for CBM retention.

5. Key Technologies for CBM Exploration and Development in China

5.1. Fine Seismic Characterization of CBM Reservoirs

Fine seismic characterization of CBM reservoirs refers to a suite of techniques for the detailed interpretation of seismic data and prediction of reservoir properties, serving as a crucial method in CBM exploration and development[16]. Analyzing the parameters derived from this characterization, optimizing key parameters, and establishing evaluation criteria enable the classification and comprehensive assessment of favorable CBM areas. This process effectively predicts high-gas-concentration and high-productivity zones and guides the optimal placement of development wells, which is significant for efficient CBM extraction. Addressing the specific challenges of domestic CBM exploration, economically effective seismic interpretation and favorable area prediction technologies have been developed through advancements in seismic acquisition and data processing. These include techniques for CBM reservoir fracture prediction, high-precision static corrections, comprehensive noise attenuation in complex areas, and 3D azimuthal processing[17].

5.2. CBM Reservoir Logging Evaluation Technology

Logging evaluation technology effectively identifies the gas-bearing properties of CBM reservoirs, paving the way for selecting high-potential development areas. By comprehensively classifying logging parameters such as coal porosity, thickness, gas content, permeability, and water saturation, this technology effectively guides operational decisions including optimal perforation interval selection and reservoir stimulation strategies. Logging evaluation is integral to various stages of CBM development[18]. During the exploration phase, it is primarily used to optimize estimates of gas content and lithology, identifying favorable reservoirs. In the development phase, integrating conventional and imaging logging technologies helps evaluate water saturation and free gas distribution, allowing operators to avoid aquifers and low-permeability zones, thereby enhancing drilling and development efficiency.

5.3. CBM Drilling Technologies

The development of CBM in China faces challenges such as high drilling costs and a lack of well-matched drilling technologies, making research into advanced drilling methods particularly important. Vertical and directional wells were the earliest well types deployed for CBM in China. While technologically straightforward, they are characterized by rapid production decline and are best suited for medium to high-permeability coal seams[19]. Horizontal well drilling is now the dominant CBM drilling technology globally. Through years of field trials, China has established a suite of horizontal well development strategies tailored to its specific geological conditions, including multi-lateral, U-shaped, L-shaped, and radial horizontal wells[20]. Multi-lateral horizontal drilling is the primary method used internationally for CBM development. This technology offers long completed intervals and extensive wellbore exposure, allowing the wellbore to intersect the coal's natural fracture system and create a "super fracture network," thereby maximizing well productivity. Continuous research and trial have led to the successful application of multi-lateral drilling technology in major CBM fields in China, such as the Qinshui and Ordos Basins[21].

5.4. CBM Stimulation and Enhancement Technologies

Due to the low permeability of most Chinese coal seams, CBM wells typically yield negligible production without hydraulic fracturing stimulation. Creating an "artificial fracture network" through fracturing is essential to unlock commercial gas rates. Targeting the three main coal structure types (intact, cataclastic, and granulated coal), and considering fracturing mechanics and key factors affecting conductivity damage, China has developed an efficient propped fracturing technology system for medium- to high-rank coals. This system utilizes supporting techniques like variable-rate pumping, multi-stage slug injection, and hybrid fracturing, with the objectives of extending main fracture length, achieving deep reservoir modification, and improving proppant placement far into the fracture network[22]. Commonly used CBM reservoir stimulation techniques include fracturing through the thin roof rock above the coal seam (to enhance connectivity), composite fracturing within the coal seam, and re-fracturing of existing wells.

The generally low permeability, shallow depth, and strong adsorption characteristics of domestic coal seams present specific challenges. Damage caused by gel breaking and fluid adsorption from polymer-based fracturing fluids is a primary concern. Furthermore, the typically moderate per-well productivity of CBM wells means that high costs often constrain the economic effectiveness of stimulation treatments[23]. To address these challenges, integrated technologies utilizing low-cost and low-damage fracturing fluids have been developed. These systems include coal-fines-suspending active water and low-concentration guar gum fracturing fluids, which have been successfully applied in the development of mid-deep CBM fields such as Shizhuang, Daning, and Huaibei.

5.5. CBM Production and Drainage Technologies

De-watering for gas production is a standard CBM development technique, involving a four-stage process: dewatering-depressurization-desorption-production. Chinese CBM wells often experience long dewatering periods, slow production build-up, and significant variation in water production. Learning from international successful experiences, China has innovated and implemented tailored production technologies for different coal ranks, including staged-quantitative and quantitative-guided drainage strategies. After years of development trials, automated production technology has become relatively mature in China. Quantitative production control protocols, centered on flowing bottom-hole pressure control and fully automated throughout the well's life, are implemented based on specific reservoir characteristics. Utilizing wireless data transmission, automated data analysis, and automatic adjustment of operating parameters, these systems aim to precisely control pressure decline rates, flowing pressures, and casing pressures[24]. Currently, the utilization of supercritical CO_2 for coalbed methane (CBM) recovery represents the cutting edge of CBM extraction technology. Compared to conventional water injection methods, CO_2-ECBM (enhanced coalbed methane recovery) offers significant advantages: it not only effectively addresses bottlenecks associated with water-based recovery but also utilizes liquid/supercritical CO_2 to dissolve organic matter within the coal seam, thereby enhancing coal permeability[25]. However, CO_2-ECBM technology is still in the exploratory stage in China, having been tested only in pilot trials within a few demonstration areas, with many subsidiary processes requiring further development.

5.6. CBM Surface Engineering Technologies

Reflecting the characteristics of CBM development in China, extensive research has focused on optimizing and simplifying gas gathering and transportation processes, optimizing pipeline network structures, and improving materials, station design, construction models, and produced water handling. This effort has led to the preliminary establishment of a characteristic CBM surface engineering technology system. This system is centered on a "wellhead measurement-wellsite clustering-station separation-centralized processing" flow and emphasizes standardization, skid-mounted modularization, and intelligent construction. The collection, transportation, and treatment of produced water are critical aspects of CBM surface engineering, presenting not only technical challenges but also economic and environmental considerations. Currently, four main produced water treatment technologies are used domestically and internationally (see table below). Through continuous research and practical application, China has gradually developed a produced water management approach involving dedicated gathering pipelines, zonal collection, and centralized treatment[26]. The specific work process involves laying water gathering pipelines in the same trench as the gas flow lines from the wellhead. This water gathering network transports the produced water from well sites to distributed water treatment stations for processing prior to compliant discharge or disposal.

Table 1 Comparison of Advantages and Disadvantages of CBM Produced Water Treatment Technologies

Treatment Process	Principle	Advantage	Disadvantages
Surface Discharge	Direct discharge into nearby rivers	Simple and economical	High requirements for water quality
Evaporation	Natural evaporation: Direct evaporation into the atmosphere	No discharge, low investment	Large land area required, high topographic constraints
	Forced Evaporation: Achieves rapid evaporation through external means	Can be used in combination with natural evaporation	Few mature and reliable technical systems available
Subsurface Reinjection	Pumping and pressurizing wastewater for reinjection into target formations	Simple operation and maintenance	Disrupts groundwater distribution, high cost
Factory treatment	Reducing non-compliant components through processes such as sedimentation, filtration, reverse osmosis, and ion exchange	Effective treatment, widely applicable	Complex process, high cost, intensive operation and maintenance

6. Challenges and Countermeasures

6.1. Challenges

Compared to conventional and shale oil and gas, China's coalbed methane (CBM) possesses substantial remaining and technically recoverable reserves. However, uncertainties inherent in the exploration and development process present significant technical barriers that require breakthroughs.

(1) Geological Challenges: CBM research in China started relatively late. The gas accumulation mechanisms and seepage flow characteristics in mid-deep coal seams are not yet fully understood. Furthermore, the complex topographic conditions of many domestic CBM fields pose substantial difficulties for project design and implementation, introducing numerous technical hurdles.

(2) Technical Challenges: Development technologies for CBM reservoirs in geologically complex settings are significantly underdeveloped. Many successfully applied reservoir stimulation and production techniques lack adaptability and are difficult to scale up for widespread application, thereby constraining the overall progress of CBM development.

(3) Economic Challenges: Insufficient understanding of the drainage and production behaviors of Chinese CBM reservoirs has led to the direct adoption of foreign production models, often resulting in overly rapid dewatering and suboptimal gas production. Coupled with the high costs associated with large-scale fracturing and drilling, CBM development faces the dual challenges of high investment and slow returns.

(4) Environmental Challenges: CBM produced water typically has high salinity. Improper treatment and discharge can lead to soil salinization, damaging surrounding soil and vegetation. High chloride content in the produced water can also accelerate corrosion rates in gathering pipelines.

6.2. Corresponding Countermeasures

(1) Enhance research on CBM reserve assessment and enrichment mechanisms, improving the theories and technologies for geological evaluation. Accelerate the establishment of integrated "geology-engineering" optimization techniques for CBM development.

(2) Strengthen efforts to improve the adaptability of CBM production technologies. Increase investment in R&D for core CBM development technologies, aiming to innovate new drilling and production methods.

(3) Continuously optimize the lifecycle duration and cost of each CBM production stage. Develop low-cost, low-damage drilling and fracturing fluid technologies to maximize cost reduction and efficiency gains.

(4) Improve the regulatory framework and treatment mechanisms for CBM produced water. Strengthen environmental supervision across all handling stages, with government leadership ensuring corporate compliance. Establish a stringent system of standards and specifications for CBM wastewater treatment.

7. Prospects

After years of innovation and development, China's CBM sector has achieved incremental progress in logging evaluation, reservoir stimulation, and enhanced recovery techniques. Nevertheless, research focused on reducing costs, enabling cleaner extraction, and ensuring stable and increased production from CBM wells requires further strengthening, with numerous key technologies still needing breakthroughs. The complex topography and demanding reservoir conditions prevalent in most Chinese CBM fields make it impractical to wholly replicate mature foreign development models.

It is recommended to, on one hand, intensify fundamental theoretical research on CBM. Integrating knowledge from drilling and completion engineering, seepage mechanics, and gas production engineering can provide new ideas and technologies for development. On the other hand, collaboration among enterprises, universities, and research institutions should be enhanced. A comprehensive approach considering geological, engineering, economic, and environmental aspects is necessary to steer CBM development towards intelligent, economical, and clean operations. The goal is to explore and establish a mature, comprehensive technical system for CBM drilling, stimulation, and efficiency enhancement, paving the way for a successful CBM revolution in China.

References

[1] Yunfei Peng , Qiao Zhang. Process Simulation and Analysis of Acetylene Production from Coal-Bed Methane[J]. Journal of East ChinaUniversity of Science and Technology, 2024, 50(4): 497-502.

[2] Fengyin Xu , Wei Hou, Xianyue Xiong, et al. The status and development strategy of coalbed methane industry in China[J].Petroleum Exploration and Development, 2023, 50(4): 669-682.

[3] Dehui Li, Guofu Li, Liangliang Liu, et al. Present situation and development direction of coalbed methane (gas) exploitationand utilization in Shanxi Province[J]. Mining Safety & Environmental Protection, 2022, 49(2): 132-136.

[4] Jianping Ye, Songyi Hou, Shouren Zhang. Progress of coalbed methane exploration and development in China during the13th Five-Year Plan period and the next exploration direction[J]. Coal Geology & Exploration, 2022, 50(3): 15-22.

[5] Jiwen Teng, Yuchen Wang, Xiang Si, et al. Diversified transformation of coal and coalbed methane: China's fossil energy exploration, devel-opment, supply and demand[J]. Science Technology and Engineering, 2021, 21(22): 9169-9193.

[6] Ruiyue Yang, Xiaozhou Qin, Wei Liu, et al. A Physics-Constrained Data-Driven Workflow for Predicting Coalbed Methane Well Production Using Artificial Neural Network[J]. SPE Journal, 2022, 27 (3): 1531-1552.

[7] Fan Peng, Suping Peng, Wenfeng Du, et al. Coalbed methane content predic tion using deep belief network[J]. Interpretation, 2020, 8 (2): T309-T321.

[8] Ruizhi Zhong, Johnson RL, Zhongwei Chen. Using machine learning methods to identify coal pay zones from drilling and logging-while drilling (LWD) data[J]. SPE Journal, 2020, 25(3): 1241-1258.

[9] Dehua Zhou, Gang Chen, Zhenlong Chen, et al. Exploration and development progress, key evaluation parameters and prospectof deep CBM in China[J]. Natural Gas Industry, 2022, 42(6): 43-51.

[10] Caineng Zou, Zhi Yang, Dazhong Dong, et al. Formation, Distribution and Prospect of Unconventional Hydrocarbons in Source Rock Strata in China[J]. Earth Science, 47(5): 1517-1533.

[11] Fengyin Xu, Bo Wang, Xin Zhao, et al. Thoughts and suggestions on promoting high quality development of China's CBM business under the goal of"double carbon" [J]. China Petroleum Exploration, 2021, 26(3): 9-18.

[12] Dazhen Tang, Shuguang Yang, Shuling Tang, et al. Advance on exploration-development and geological research of coalbed methane in the Junggar Basin[J]. Journal of China Coal Society, 2021, 46(8): 2412-2425.

[13] Rathi R, Lavania M, Singh N, et al. Evaluating indigenous diversity and its potential for microbial methane generation from thermogenic coal bed methane reservoir[J]. Fuel, 2019, 250: 362-372.

[14] Yuxiang Zhang, Yongzhou Li, Mo Chen. Genesis and resource distribution of coalbed methane[J]. Petroleum Knowledge, 2023(4): 6-7.

[15] Tianshou Liu. Analysis of CBM reservoir characteristics and production control factors in Liulin Block[J]. China coalbed methane, 2021, 18(6): 8-10.

[16] Dameng LIU, Qifeng Jia, Yidong Cai. Research progress on coalbed methane reservoir geology and characterization technology in China[J]. Coal Science and Technology, 2022, 50(1): 196-203.

[17] Hongwei Li, Fanyi Li, Qiuhong Qi, et al. Prediction of CBM enriched area in Jirgalangtu Sag based on the seismic multiple-attribute analysis[J]. Petroleum Geology & Oilfield Development in Daqing, 2020,39(4): 135-142.

[18] Zixi Guo, Jinzhou Zhao, Zhenjiang You, et al. Prediction of coalbed methane production based on deep learning[J]. Energy, 2021, 230(2): 120847.

[19] Deli Gao, Yansen Bi, Bao'an Xian. Technical advances in well types and drilling & completion for high-efficient development of coalbedmethane in China[J]. Natural Gas Industry, 2022, 42(6): 1-18.

[20] Guangjie Yuan, Li Fu, Yuan Wang, et al. The up-to-Date drilling and completion technologies for economic and effective development of unconventional oil & gas and suggestions for further improvements[J]. Petroleum Drilling Techniques, 2022, 50(1): 1-12.

[21] Junyao Deng, Yishan Liu, Lei Qiao, et al. Drilling and completion technology of horizontal wells with long horizontal section in the Yellow River overlay area of the Baode Coalbed Methane Field[J]. Petroleum Drilling Techniques, 2021, 49(2): 37-41.

[22] Changxin Yang, Zhaozhong Yang, Xiaogang Li, et al. Status and prospect of reservoir stimulation technologies for CBM surface wellproduction in China[J]. Natural Gas Industry, 2022, 42(6): 154-162.

[23] Richao Cong, Ruiyue Yang, Haizhu Wang, et al. Supercritical CO2 shock fracturing on coal: experimental investigation on fracture morphology and pressure characteristics[C]. 56rd U.S. Rock Mechanics/Geo mechanics Symposium, 2022.

[24] Chen Guo, Yong Qin, Tongsheng Yi, et al. A method for identifying coalbed methane co-production interference based on production characteristic curves: A case study of the Zhijin block, western Guizhou, China[J]. Petroleum Exploration and Development, 2022, 49(5): 977-986.

[25] Xiaoning He, Xuan He, Xiao Jia, et al. Research progress on development of unconventional energy by carbon dioxide[J]. Modern Chemical Industry, 2022, 42(5): 40-44.

[26] Lin Tang, Xinqiang Xiong, Qing Yun. Progress and developing trend of CNPC’s oil-gas field surface engineering technology[J]. Oil & Gas Storage and Transportation, 2022, 41(6): 640-656.