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Coal measure gas resources matter in China: Review, challenges, and perspective

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Li Li (李莉),[1] Shengming Ma (马生明),[2,3] Xin Liu (刘鑫),[2,3] Jun Liu (刘军),[4,a)] Yang Lu (吕洋),[1] Peng Zhao (赵鹏),[5] Nadhem Kassabi,[6] Essaieb Hamdi,[6] and Derek Elsworth[7]

AFFILIATIONS

[1]Key Laboratory of Deep Underground Science and Engineering (Ministry of Education), College of Architecture and Environment, Sichuan University, Chengdu 610065, China
[2]State Key Laboratory of Continental Shale Oil, Daqing 163712, China
[3]Daqing Oilfield Exploration and Development Research Institute, Daqing 163712, China
[4]Institute of New Energy and Low-Carbon Technology, Sichuan University, Chengdu 610065, China
[5]State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China
[6]Geotechnical Engineering and Georisks Laboratory (LR14ES03), National Engineering School at Tunis, Université Tunis El Manar, Tunisia
[7]Department of Energy and Mineral Engineering, Pennsylvania State University, University Park, Pennsylvania 16802, USA

[a)]**Author to whom correspondence should be addressed:** j.liu@scu.edu.cn

ABSTRACT

Achieving the dual carbon goals of peaking by 2030 and neutrality by 2060 is significantly aided by the growth of coal measure gas research and development, especially for China to optimize its primary energy consumption. We critically review the distribution, geological characteristics, methods of liberation and then recovery by hydraulic fracturing of coal measure gas in China and present a roadmap to optimize this recovery. The gas-bearing system is the focus of this recovery, but this system is embedded within its sedimentary environment and modulated by tectonic and hydrogeological controls that affect gas exploration and recovery. However, to improve the development of coal measure gas in China, bottleneck problems remain to be solved, such as accurately predicting reservoir behavior in dessert regions, optimizing well patterns, and deploying optimal horizontal well trajectories. Additionally, the technology breakthroughs on deep co-production of coal measure gas, automatic fracturing and intelligent drainage are imminent. Basically, developing new techniques and conducting improved geological surveys are essential to ensure the sustainable supply of coal measure gas resource. Thus, this review presents a comprehensive introduction to coal measure gas resources in China, of utility to academic researchers and engineers in enhancing the understanding of the current situation and in projecting future development.

I. INTRODUCTION

With the industry experiencing rapid growth in recent years, a large amount of CO_2 generated by the use of fossil energy has led to climate warming and sea level rise. This has seriously threatened personal safety and economic security, and also caused serious damage to our ecosystem.[1–7] To mitigate the greenhouse effect, the Intergovernmental Panel on Climate Change (IPCC) has put forth a proposal stating that there is a need to achieve an 80% reduction in CO_2 emissions by the year 2050.[8–12] Furthermore, the Chinese government has outlined a strategy aimed at reaching a peak in CO_2 emissions by 2030 and attaining carbon neutrality by 2060 (dual carbon goals).[13–16] In this context, research and advancements in coal measure gas play a critical role in facilitating the realization of these dual carbon goals.[17–20] This is of significance to optimize Chinese primary energy consumption—increasing the proportion of gas and reducing that of coal, to maintain energy supply but reduce carbon emissions for China as a contribution to that of the world.

In general, the natural gas created during the biochemical, physicochemical, and coalification processes from source rocks in the whole coal measures is referred to as coal measure gas. According to gas accumulation form and mechanism, distribution characteristics, exploration, and development mode, it includes conventional trap gas and unconventional continuous coalbed methane (CBM), shale gas, and tight sandstone gas.[21–23] Basically, the coal measure gas is receiving increasing attention since they are an essential component of the unconventional natural gas field.[21,24] This is because, for one reason, the coal measure resources are considerable in China, including 20×10^{12} m^3 tight gas resources, 32×10^{12} m^3 shale gas resources, and 36.8×10^{12} m^3 CBM resource in coal-related strata.[25–27]

By 2030, it is projected that the proven reserves of coal measure gas have the potential to reach approximately 5.0×10^{12} m^3, with an anticipated total coal measure gas production of more than 1000×10^8 m^3 in China—a huge and considerable energy source.[22] To realize the dual carbon goals, natural gas's share of the primary energy structure is expected to rise dramatically to 15% by 2030, compared to 7.6% in 2018.[22,28–30] Moreover, it is estimated that the domestic natural gas production in China will be approximately 2000×10^8 m^3 and its demand will exceed 6000×10^8 m^3 by 2030.[22] Therein, the estimated coal measure gas production will account for more than 52.5% of natural gas production by 2030, which indicates the coal measure gas plays an irreplaceable role in the production growth of natural gas in the future. China's coal measure gas resources are estimated to be 29.882×10^{12} m^3 based on the fourth resource evaluation. In addition, tight sandstone is predicted to have geological resources ranging from 17.0×10^{12} to 23.9×10^{12} m^3 with recoverable resources ranging from 8.1×10^{12} to 11.4×10^{12} m^3. Herein, 81% of the total resources that can be recovered are found in the Tarim, Sichuan, and Ordos basin.[22,28,31] In this way, coal measure gas plays a pivotal role in the gas supply of the coming years in China, enhancing the necessity in its exploration and exploitation.

The widely distributed coal measure resources in China can be utilized in a comprehensive manner,[21,32–35] in which the Xinjiang Uygur Autonomous Region, the Southern margin of Junggar basin, the Southern Sichuan province, and the Western Guizhou province are the main areas to research and evaluate the coal measure gas resources.[21] Furthermore, most of the coal measure gas fields are located in Ordos basin, Sichuan basin, Junggar basin, and Tarim basin (Fig. 1).[22] The wide distribution of coal measure gas resources further emphasizes its significance in the gas supply for the vast land of China.

Accordingly, focusing on coal measure gas in China, this work first examines its distribution characteristics in four primary basins, followed by the review of geological background. In addition, with respect to the unconventional reservoir–multi-petrology (superimposed coal, shale, and tight sandstone), the hydraulic fracturing item is synthetically reviewed—from both physical and numerical perspectives. Moreover, this work also reviews the current situation of gas extraction of coal measure gas, pointing the difficulties. Furthermore, it also establishes a roadmap and proposals for coal measure gas development in China, aiming to offer helpful insights to scientific researchers and engineers studying this field. Hopefully, this review is able to exhibit the challenges, concerns, and perspective regarding the coal measure gas resources in China and help its development.

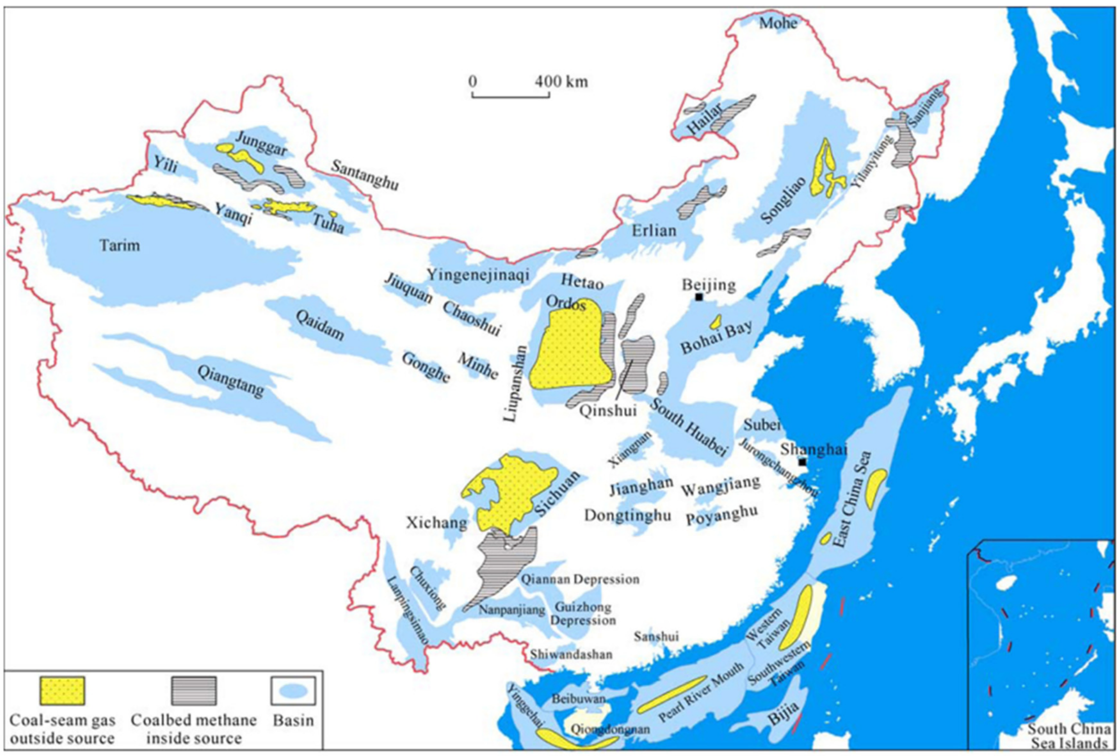

FIG. 1. Distribution of coal measure resource in China.[22] Reproduced with permission from Zou *et al.*, Pet. Explor. Dev. **46**, 451–462 (2019). Copyright 2019 Authors, licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 International (CC BY-NC-ND 4.0 DEED) license.

II. DISTRIBUTION OF COAL MEASURE GAS RESOURCES IN CHINA

In this work, four main basins for developing coal measure gas in China were introduced in a comprehensive perspective.

A. Ordos basin

Ordos basin is located in the west of North China with an area of 3.71×10^5 km^2, which is bounded by Yin mountain and Daqin mountain to the north, Huanglong mountain to the south, Luliang mountain to the east, and Helan mountain and Liupan mountain to the west. It is the second largest sedimentary basin in China, which can be divided into Yimeng uplift in the north, Weibei uplift in the south, Jinxi flexural fold belt in the east, Tianhuan depression and thrust belt in the west, and Yishan slope in the central.[36] Until 2019, the proven geological reserves of coal measure tight sandstone gas in the Carboniferous-Permian formations in the Ordos basin were more than 1000×10^8 m^3. Herein, the Sulige gas field, encompassing an exploration acreage of 4×10^4 km^2, emerged as the largest gas field in China with verified geological reserves reaching 1.65×10^{12} m^3.[37–39] As for the Shanxi formation in the Linxing area, the average content of the total organic carbon (TOC) in coal and dark mudstone is 35.0% and 1.7%, respectively. Meanwhile, the average R_o value in coal measure strata is 1.1% and indicates a high maturity stage, suggesting an attractive gas production during the geological period.[40] Moreover, the bottom of lower Shihezi formation is usually treated as a regional cap layer for coal measure gas in the Ordos basin,[41] and the cap layer has the thickness of 15–35 m, the displacement pressure of 8.17 MPa, and the porosity of $<$3.0%.[42] Therefore, the good sealing effect from the lower Shihezi formation enables the Shanxi formation in Permian to have significant development and exploration prospects in Ordos basin.[37–39,43–45] Therein, the thickness of coal seams in Benxi formation, Taiyuan formation to Shanxi formation are between 6 and 15 m with TOC higher than 70% (Fig. 2). Moreover, the dark mudstone is 30–50 m thick, and its TOC value ranges from 2% to 3%. In addition, multi-layered sandstone is vertically superimposed up to 30–100 m and extends 150–200 m from south to north. Additionally, the natural gas continuously accumulates in coal measure reservoirs which have unclear trap boundaries and complex gas–water relationship.[22]

B. Junggar basin

The Junggar basin is located in the northern part of Xinjiang Uygur Autonomous Region, which is the second largest inland basin in China.[46] Situated at the eastern extension of the Kazakhstan Plate, the Junggar basin occupies the intersection area of the Tarim Plate, Siberia Plate, and Kazakhstan Plate. Herein, developed in the late Hercynian Movement, the periphery of the multi-stage superposed Junggar basin was sutured by Paleozoic folds.[46] It is one of China's eight oil and gas-rich onshore basins, spanning an area of 13.5×10^4 km^2.[47] Known by its abundant natural gas reserves, the basin has geological resources of $23\,072 \times 10^8$ m^3 at the end of 2016.[47] In 2009, significant discoveries were made in the Ludong-Wucaiwan and Zhundong areas, located in the heart of the Junggar basin. Gas reservoirs and gas-bearing structures of Carboniferous origin were identified, leading to the successful production of commercial gas flow from many wells within this region. The estimated proven resources for natural gas reached an impressive 2017×10^8 m^3.[48] The primary reservoirs holding gas consist of Carboniferous, Jurassic, and Permian formations. Notably, the Jurassic coal measures shale gas in the eastern coal-bearing zone of the Junggar basin is estimated to have a substantial geological reserve of 894.19×10^8 m^3, in southern Junggar coal-bearing zone is 7339.95×10^8 m^3.[49] Furthermore, the preliminary estimate of Jurassic coal measure tight sandstone gas geological resources is (11 740–13 630) $\times 10^8$ m^3, and the amount of technical recoverable resources is (5280–6140) $\times 10^8$ m^3.[49]

C. Sichuan basin

The Sichuan basin is a large intracratonic sedimentary basin and asymmetric depression in southeastern China with an area of nearly 18×10^8 km^2.[50] It is situated on the upper Yangtze craton, surrounded by the Micang-Daba mountain orogenic belt to the north, the Longmen orogenic belt to the west, the Hunan-Guizhou-Hubei thrust belt to the east, and the Mount Emei-Liangshan thrust belt to the south.[51,52] In Sichuan basin, the main coal measure strata contain the upper Triassic Xujiahe formation and the Permian Longtan formation. The thickness of coal measure strata in the Permian Longtan formation progressively becomes thicker toward the center of the Sichuan basin, while that in the Upper Triassic Xujiahe formation is thicker from east to west.[53] In south Sichuan basin, the shale is interbedded with coal and sandstone, enabling the coal measure strata of Longtan formation to have a huge cumulative thickness of over 100 m, and the recognized effective gas-bearing area is $\sim$2287.46 km^2, containing a total resource of $\sim 7129.05 \times 10^8$ m^3 with an average resource abundance of 3.12×10^8 m^3/km^2.[54] Therein, the total coal measure gas resource in gas enrichment areas (i.e., Muai, Jiacun, and Wenjiang-Tengda) is $\sim 3601.17 \times 10^8$ m^3 with an average resource abundance of $(2.66–3.75) \times 10^8$ m^3/km^2.[54] Moreover, the average TOC content in the shale strata for Longtan formation is 7.51%, and the average value of R_o is 2.22% in south Sichuan basin.[55] These characteristics ensure that the Longtan coal measure strata in Sichuan Basin have great gas production potential and become one of the targets for unconventional gas development. In the middle of Sichuan basin, the Triassic Xujiahe formation encompasses coal measure source strata and tight sandstone reservoirs arranged in a sandwich-like construction. Moreover, the coal measure gas reservoirs here predominantly belong to the continuous-type tight gas category, spanning an expansive exploration area of 6800 km^2. In addition, the proved coal measure gas reserves in the upper Triassic Xujiahe formation in Guang'an, Hechuan, and Anyue gas fields are 6000×10^8 m^3.[56] The coal seams in Xujiahe formation are steadily distributed with thickness of 5–15 m and the coal measure mudstones become thinner from west to the east with thickness of 100–800 m in Sichuan basin.[56] Moreover, the average content of TOC for source rock in Xujiahe formation is 4.09%, and the average value of R_o is 1.03%, which represent the Xujiahe coal measure is a good source rocks for oil/gas generation.[57]

D. Tarim basin

The Tarim basin is located in the southern part of Xinjiang Uygur Autonomous Region with an area of 5.6×10^6 km^2, which is the largest inland basin in China. The overall topography of Tarim basin is high in the west and low in the east, and the internal structure is complex, which is divided into Tabei uplift, Central uplift, Tanan uplift, Kuqa depression, Northern depression, Southwest depression,

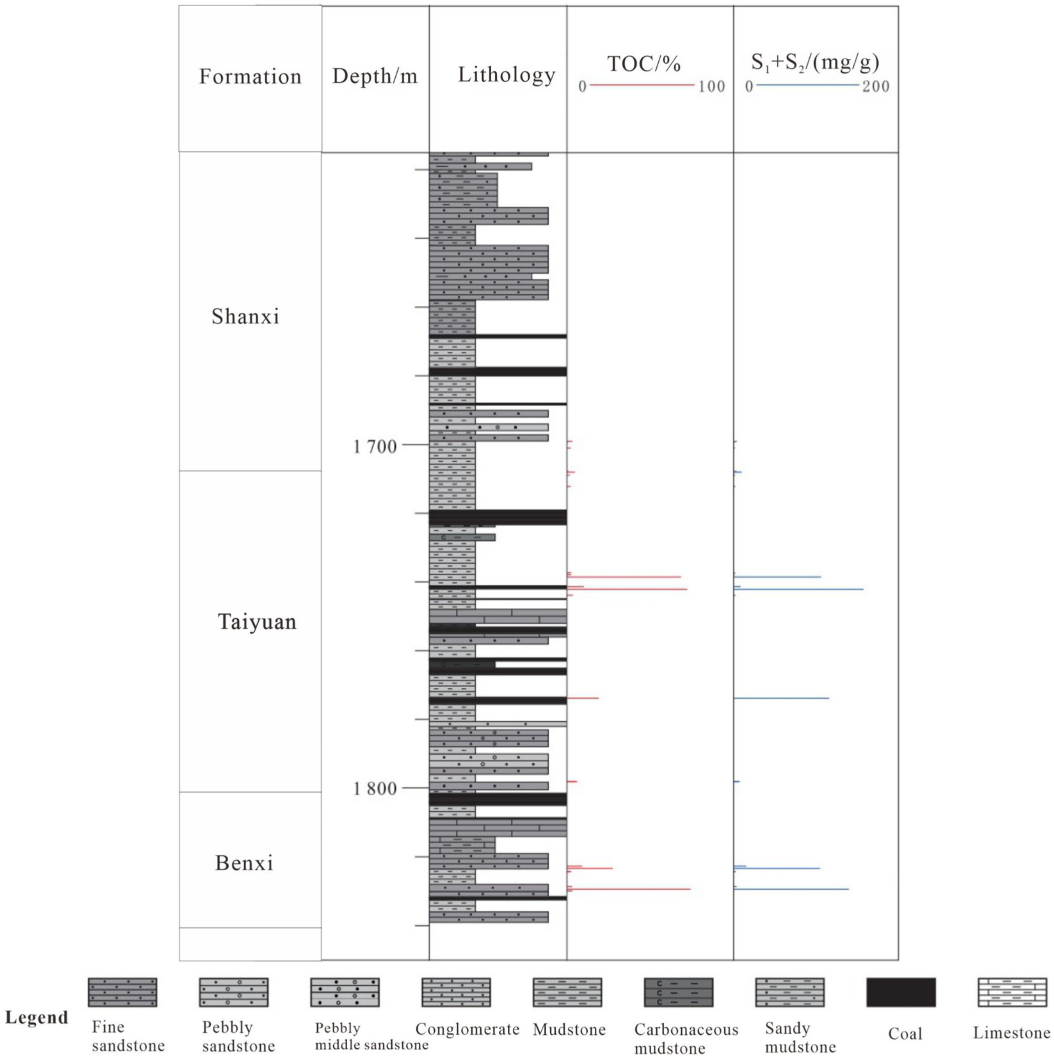

FIG. 2. Histogram of the source rock in the upper Paleozoic of well L-20 within the Linxing area.[40] Reproduced with permission from C. Liu, Complex Hydrocarbon Reservoirs **15**, 1–7 (2022). Copyright 2022 Author, licensed under a Creative Commons Attribution (CC BY) license.

and Southeast depression.[58] The Kuqa depression hosts a vast majority (over 90%) of the coal measure gas extracted from the Tarim basin, primarily from Dabei, Keshen, and Kela 2 gas fields. Within this region, trap-type coal measure gas reservoirs are found, specifically within the gas production central area of the Triassic-Jurassic coal-bearing formations. These reservoirs exhibit a gas production surpassing 100×10^8 m^3/km^2. Furthermore, the Cretaceous Bashkir-Chik formation has large-scale braided delta sandstone reservoirs that provide favorable conditions for coal measure gas accumulation and preservation for its stable gypsum salt caprock and high gas charging efficiency during late Himalayan period.[22] Therein, among the coal measure gas fields, the Kela 2 field boasts the highest production per individual well of more than 125×10^8 m^3. In addition, the area exhibits an exceptional abundance of reserves, with a remarkable 59.05×10^8 m^3/km^2. In the Tarim basin, the Keshan gas field holds the distinction of being the pioneering extremely deep coal measure gas field, reaching an astounding depth exceeding 6000 m.

In general, coal measure gas is abundant in China and has a very large exploration and development prospect. Except for the above four main basins, the Qinshui basin, Tuha basin, and Tianshan Mountain basin are of rich resources for coal measure gas in China (Table I), and their locations are exhibited in Fig. 1. The Qinshui basin, located in the southeast of Shanxi Province, is one of the most important coal-bearing basins in China, which is composed of Panzhuang block, Shizhuang block, and Zhengzhuang block in the south, Yushe block in the middle, and Gujiao block and Yangquan block in the north. In addition, Qinshui basin is a synclinal basin distributed along NE-SW strike, and the main coal measure strata there are the Upper Carboniferous Taiyuan formation and the lower Permian Shanxi formation (Table I). Turpan–Hami basin (Tuha basin) is an inland

TABLE I. Geological resource of coal measure gas in different basins. Note: C, the Carboniferous period; P, the Permian period; P_1, the early Permian epoch; P_2, the late Permian epoch;T_3, the late Triassic epoch; $J_{1\text{-}2}$, the early and middle Jurassic epoch; C_2t, the upper Carboniferous Taiyuan formation; P_1s, the lower Permian Shanxi formation; P_2l, the Upper Permian Longtan formation; P_2sh, the upper Permian Shihezi formation; J_1b, the Lower Jurassic Badaowan formation; J_1y, the lower Jurassic Yangxia formation; J_2k, the middle Jurassic Gezilenur formation; J_2x, the middle Jurassic Xishanyao formation; and T_3x, the upper Triassic Xujiahe formation.

Basin	Basin type	Geological year	Main coal measure strata	Geological resource of coal measure gas (10^{12} m^3)			Depth (m)	Coal seam thickness (m)	References
				Tight sandstone gas	Shale gas	CBM			
Ordos	Craton	C-P	P_1s, P_2sh, C_2t	6.00–8.00	3.40–5.30	9.86	400–2000	0–30	Jia *et al.*[59]
Jungar	Foreland	$J_{1\text{-}2}$, P_1	J_1b, J_2x, P_1j	0.80–1.20	2.60–5.30	3.83	400–1200	25–187	Jia *et al.*[59]
Sichuan	Foreland	T_3, P_2	T_3x, P_2l	0.43	8.75	0.6	0–3500	46–80	Fu *et al.*[60] and Guo *et al.*[61]
Tarim	Foreland	$J_{1\text{-}2}$	J_1y, J_2k	0.61	0.30	1.93	0–2000	9–12	Fu *et al.*[60]
Qinshui	Craton	C-P	C_1t, P_1s,	1.04	2.33	3.95	0–2000	1.2–23.6	Qin[17]
Tuha	Foreland	$J_{1\text{-}2}$	J_1b, J_2x	0.60–0.90	0.70–1.10	2.12	0–1500		Qin[17]
Tian mountain	Foreland	$J_{1\text{-}2}$	J_1b, J_2x	0.32	1.10	1.63	0–1500		Fu *et al.*[60]

sedimentary basin mainly in the Middle and Cenozoic with an area of 9600 km^2, in which the Taibei depression is the largest depression in the northern depression of the first-order structural unit of the basin.[22] Additionally, the Tian Mountain coal-bearing basin is located in the southern Junggar active belt of the Siberian Plate and the northern Tianshan active belt of the Tarim Plate, including three coal-accumulating regions of Yili, Yurdu, and Yanqi. The main coal measure strata in Tuha basin and Tian mountain coal-bearing basin are the Lower Jurassic Badaowan formation and the Middle Jurassic Xishanyao formation (Table I).[22]

III. GEOLOGICAL FEATURES OF COAL MEASURE GAS RESOURCES IN CHINA

A. Sedimentary environment

The depositional conditions of coal measure formations is related to the coal-accumulation depositional environment.[22] More than 99% of coal resources strongly accumulated in the end of the late Cretaceous-Paleogene, Jurassic, and the late Carboniferous-Permian.[22,62] Different sedimentary environments form multiple coal measure source-reservoir-caprock assemblages, which lead to diverse coal measure gas occurrence and reservoir type and strong cyclicity of coal measures.[63–66]

Coal measure gas encompasses various gas occurrence types, including CBM primarily in an adsorption state, tight sandstone and carbonate gas primarily in a free state, shale gas in a mixed state, and natural gas hydrate.[67–69] The distinctions between CBM reservoirs, shale gas reservoirs, and tight sandstone gas reservoirs are not readily discernible due to the heterogeneity of gas occurrence.[69] In addition, the coal measure stratum can be considered as cap rock, reservoir, and source rock simultaneously. Therefore, the coal measure reservoir types are numerous.[64] In vertical, the coal measures exhibit a strong cyclicity due to the frequent interbedding of sandstone, shale, and coal formations, which is influenced by the sequence framework (Fig. 3).[70,71]

Additionally, the interlayering of these formations has given rise to numerous combinations of cap rock, reservoir and source rock and interior seal rocks. This has led to an intricate interplay between gas and water, creating a complex relationship and a fragile equilibrium within these overlapping systems.[72–75] Herein, the shallow sea-barrier coast, alluvial fan, river-lake, and delta sedimentary environment are favorable to develop coal measure formations.[63,76] However, the delta and river depositional environment has better source-reservoir-caprock assemblage conditions than the shallow sea-barrier coast and alluvial fan sedimentary environment.[63] Additionally, compared to the shallow sea-barrier coast and alluvial fan environments, the coal seam from the delta and river depositional environment tends to have larger thickness and better continuity, which is usually interbedded with sandstone and mudstone, in which the accompanied mudstone can be favorable cap layer for preventing the gas leak off. Thus, the river and delta depositional systems are more suitable for coal measure gas comprehensive exploration. This is the reason why the Jurassic Xishanyao formation and Badaowan formation, deposited in delta and river environments in the Junggar basin, offer more favorable conditions compared to the Lower Permian Shanxi formation in the northern margin of the Ordos basin, which was deposited in an alluvial fan depositional environment.[63]

B. Tectonic conditions

Tectonic movement is the primary factor determining the formation process of coal measure gas reservoirs in coal measures. Therein, it controls the formation and features of coal measures, and further controls the hydrocarbon production of organic matter by changing burial depth and paleo-geothermal conditions. In addition, it controls the formation process of the basin, and the developed macroscopic structure and microscopic fracture system directly affect the enrichment, migration, and preservation conditions of the "three gases." Specifically, the symbiotic accumulation process of the "three gases" is controlled by the configuration relationship between coal measures burial, thermal hydrocarbon generation, and natural gas migration and injection at different structural stages, which is reflected in the dynamic evolution of tectonic and thermal dynamic energy, coupled with gas occurrence phase and reservoir physical properties.[78]

Coal measure gas reservoirs are classified into the continuous-type and the trap-type.[22] Compared with the near-source continuous-type tight gas reservoirs, the trap-type gas reservoirs located in relatively active tectonic regions have higher hydrocarbon generation capacity, higher reserves abundance, higher single well production,

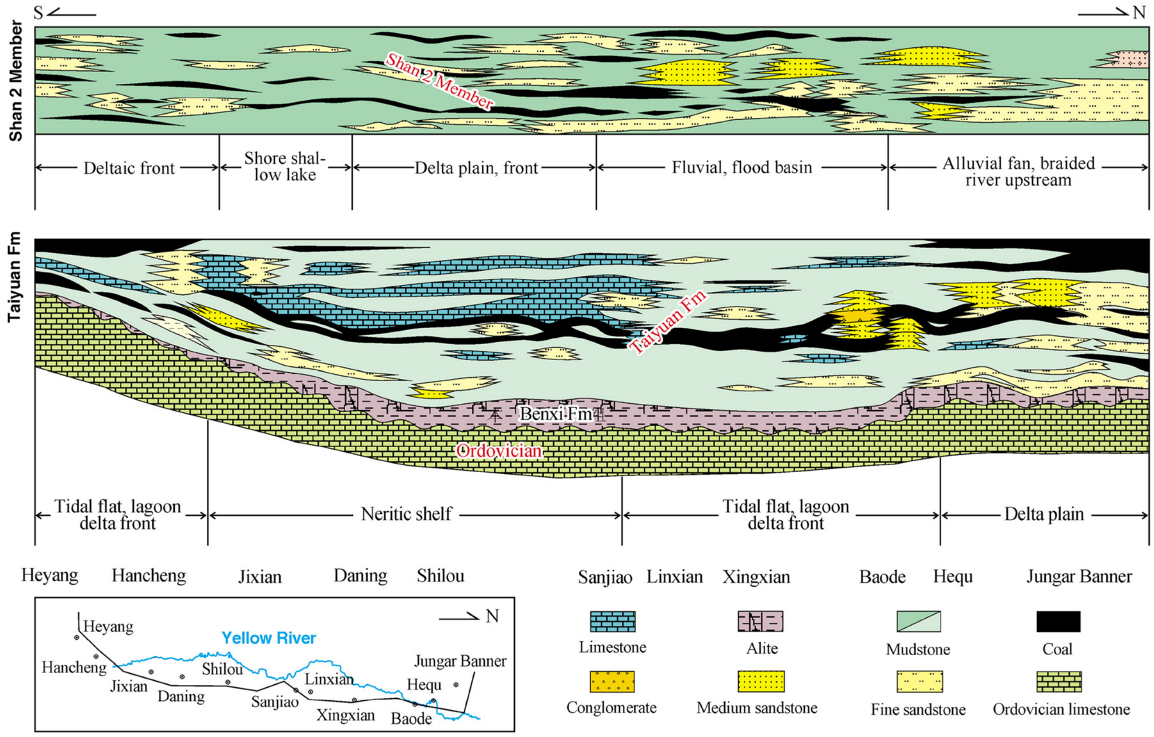

FIG. 3. Relative sedimentary facies profile of the Taiyuan Fm-Shan 2 Member, eastern margin of the Ordos basin.[77] Reproduced with permission from Ouyang *et al.*, Nat. Gas Ind. B **5**, 444–451 (2018). Copyright 2018 Authors, licensed under a Creative Commons Attribution (CC BY) license.

and more normal gas-water relationship.[22] The coal measure gas reservoirs of Carboniferous-Permian in the Ordos basin and Triassic in the Sichuan basin exhibit large-area continuous distribution, in which the coal measure strata are sandwich-like structure and the coal measure source rocks release gas through evaporation-like processes in layered formations. Moreover, the extensively distributed delta sandstone in coal measure also provides significant space for gas preservation.[22] Conversely, the coal measure gas reservoirs in the Yinggehai basin, West Sichuan depression, and Kuqa depression are characterized as trap-type reservoirs, which distribute in the area with active tectonic behavior and usually have large gas generation ability and high reserves abundance.[22]

C. Superimposed gas-bearing system

The low-permeability formations near the maximum flooding surface developed in the delta plain and the delta front sedimentary environment are called key strata. The presence of these key strata is the primary factor forming a superimposed gas-bearing system.[79,80] In vertical, this system comprises two or more independent coal measure gas-bearing systems, which result from frequent interbedding of coal measure formations.[81] In the Daning-Jixian block of Ordos basin, by analyzing variations in pressure coefficient, key strata, and total hydrocarbon content within the coal measure gas reservoirs,[82] four superimposed gas-bearing systems are divided—I, II, III, IV (Fig. 4).

The development and characteristics of the superimposed gas-bearing system are determined by the tectonic and hydrogeological conditions, and sedimentary environment.[81,83] Herein, the independent superimposed gas-bearing system is established due to the lack of hydraulic link between aquifers and coal-bearing strata, and the presence of hydraulic sealing among different rock layers. These hydrogeological conditions serve as the foundation for the independent nature of the superimposed gas-bearing system.[81] Additionally, the stratigraphic sequence structure and sedimentary environment have significant control over the gas-bearing and physical properties of coal-bearing reservoirs within the superimposed system. Moreover, the river-delta-lake facies coal measures are mostly represented as a "unified gas bearing system" vertically, and the delta-tidal flat-lagoon facies coal measures can form a "superimposition gas bearing system."[64]

However, the intricate interplay between gas and water in coal measure formations arises from the vertical evolution of multiple fluid pressure systems.[64,84] Furthermore, the spacing between unattached multiple superimposed gas bearing systems is small, which leads to interlayer interference between systems when the reservoir reconstruction is involved. For example, the hydraulic fracturing process for coal measure gas co-production tends to penetrate the superimposed gas bearing systems and thus enables gas from the layer with higher formation pressure to flow into the layer with lower one, which is usually called as interlayer interference. As a result, the dynamic balance between multiple superposed systems has been disrupted.[64,85,86] Moreover, there are significant differences in mechanical, lithology and physical features of reservoirs, making it difficult to reconstruction coal measure reservoirs.[64]

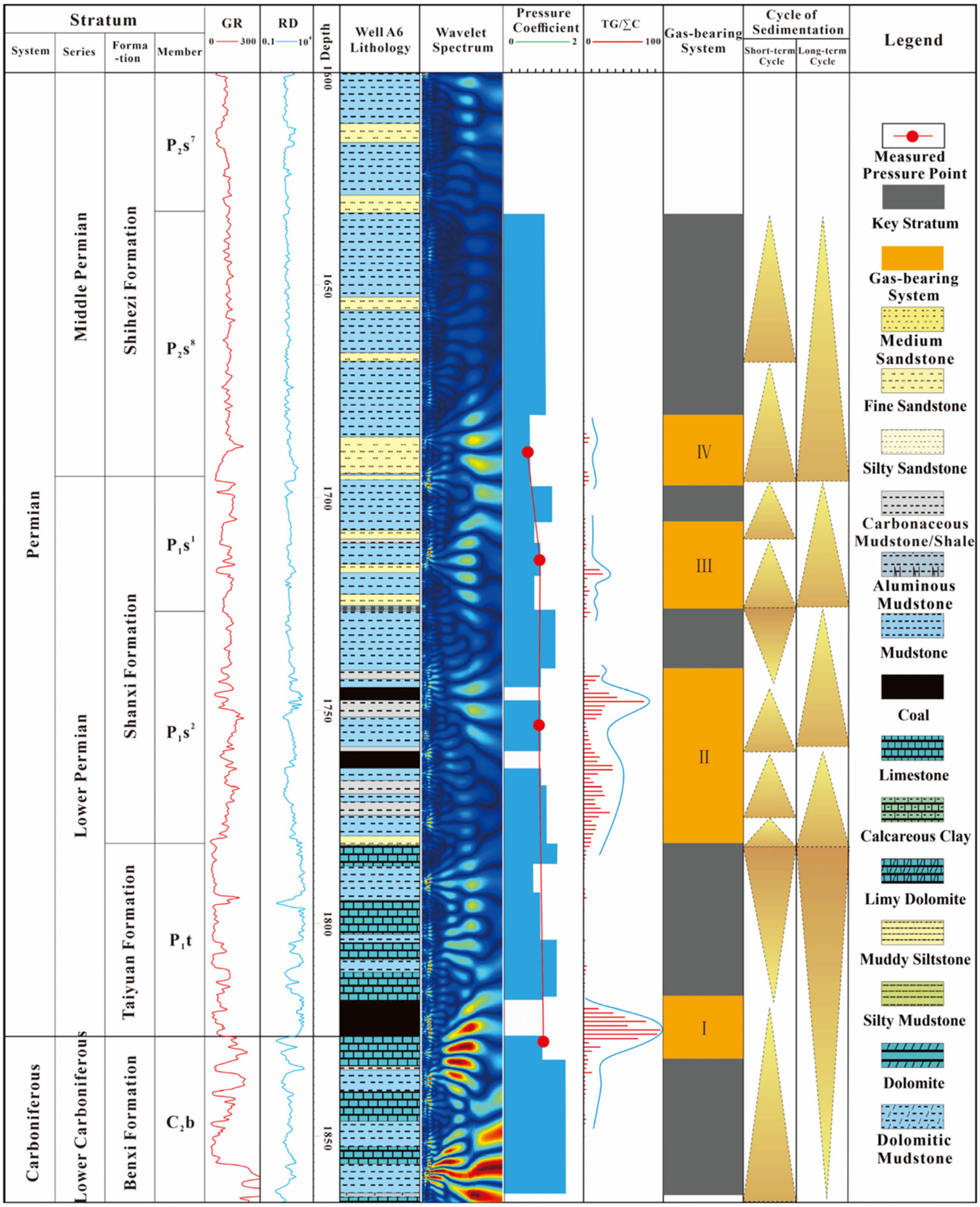

FIG. 4. Identification and division of gas-bearing system in the Daning-Jixian block.[82] Reproduced with permission from Tian *et al.*, Energies **16**, 1737 (2023). Copyright 2023 Authors, licensed under a Creative Commons Attribution (CC BY) license.

IV. HYDRAULIC FRACTURING FOR STIMULATING COAL MEASURE RESERVOIR

Hydraulic fracturing is an essential technology that stimulates the advancement of coal measure gas production by boosting the rates of recovery and production, as well as improving the profitability of resource exploitation.[87,88] It involves the highly pressurized fluids injection to create or extend fracture networks in the reservoir, thereby enhancing permeability and productivity.[89]

The vertical propagation range and morphology of fracture in coal measure formations are significant factors influencing the hydraulic fracturing efficiency and coal measure gas recovery.[90–92] In addition, the reservoir conditions and fracture construction conditions affect the propagation behavior of hydraulic fractures among superimposed gas-bearing systems. Basically, before the hydraulic fracturing is applied in field for coal measure gas development, this technique was investigated through physical experiments and numerical simulation.[90,93,94]

A. Physical simulations in the laboratory

The utilization of multi-layer combined recovery physical simulations is extensively employed in the realm of conventional oil and gas engineering, which effectively guides the development of layer division and the optimization of the joint mining scheme.[95]

By conducting a true triaxial test on multiple layers of sandstone and coal specimens collected from Linxing–Shenfu coalfield northeast of the Ordos basin, the hydraulic fracture has the capability to penetrate the coal measure formations characterized by significant stress differences.[25] In addition, the simulation of superimposed gas-bearing systems with multiple layers reveals that the high-pressure and the low-pressure formations interact, leading to intensified interference as the pressure differential between them rises. Consequently, the permeability undergoes progressive changes in stages.[96–98] An experiment on double-layer combined mining was conducted using anthracite samples obtained from the old plant block located in the eastern region of Yunnan province. The findings of this experiment illustrated that the difference in permeability between these layers significantly impacted the effectiveness of coal measure gas exploration. Moreover, the variational reservoir pressure had a primary effect on the gas production contribution of the upper pay formation.[99] A simulation system, specifically designed and developed for the combined development of multi-layer superimposed gas reservoirs, was utilized to conduct a range of physical simulation experiments. These experiments sought to study the combined production of CBM from two layers, while taking into account different levels of fluid pressure and permeability combinations. Moreover, based on the self-developed physical simulation system using coal samples from the Bide-Santang basin, southern Qinshui basin, and northeastern Ordos basin, the compatibility of these conditions was evaluated and classified into four distinct levels: I, II, III, and IV, on the basis of the grading of gas production contribution.[100] In the physical simulation of coal measure gas co-production, less attention is paid to gas well production allocation, replacement methods, and co-production layers.[95]

In order to better understand how hydraulic fractures propagate and the geometric patterns they create, a sequence of servo-controlled tri-axial fracturing tests were carried out in naturally fractured reservoirs (Fig. 5).[101] These experiments accounted for various factors, such as shear strength of existing fractures, approach angle and horizontal

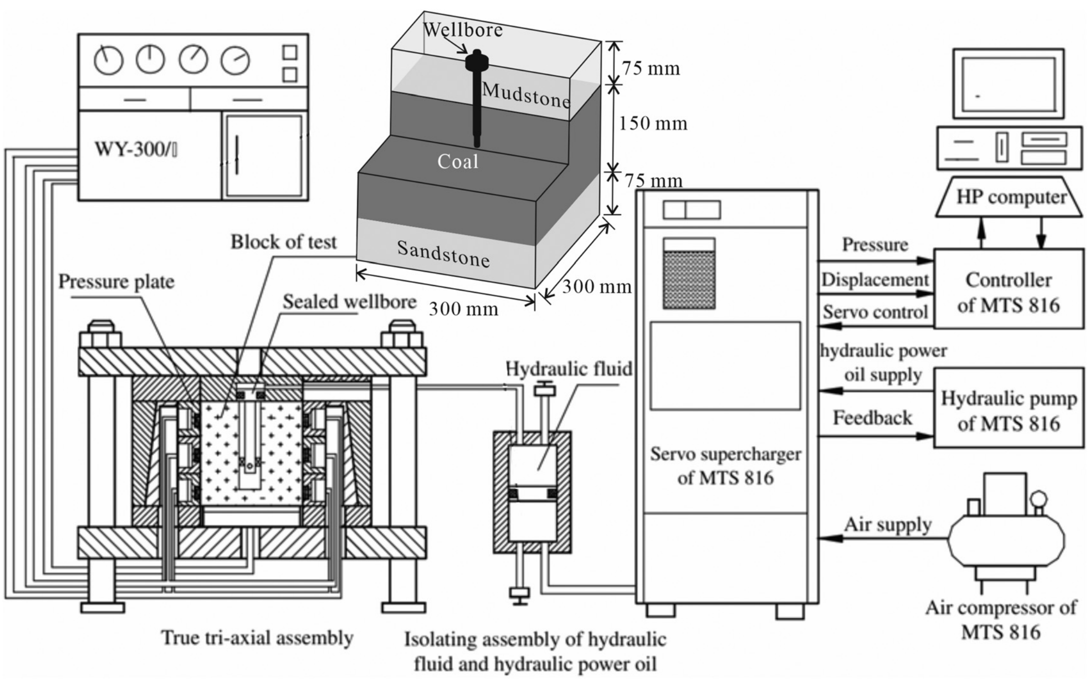

FIG. 5. Schematic of a tri-axial hydraulic fracturing testing system and Internal structure of the testing block.[101] Reproduced with permission from Zhou *et al.*, Int. J. Rock Mech. Min. Sci. **45**, 1143–1152 (2008). Copyright 2008 Elsevier.

stress, in order to precisely control the performance of fracture propagation. Observations indicated that increasing the shear strength of preexisting fractures led to a larger area of arrested behavior. The results revealed two distinct patterns of hydraulic fractures under various stress conditions. Under normal stress, fractures created interconnected branches as a result of existing fractures. Conversely, when one of the horizontal stresses became the maximum principal stress, the hydraulic fractures took on a twisted pattern aligned with the fracture height direction.[101]

Variations in interlayer modulus have a major impact on the vertical penetration properties of cracks (Fig. 6). The fracture penetration interface continues to expand as a hydraulic fracture spreads from a high elastic modulus rock to a low elastic modulus rock.[102] The concept of "Stimulated Rock Area (SRA)" is introduced as a metric to evaluate the outcomes of hydraulic fracturing. Through the analysis of experimental data of the coal measure shale in Sichuan basin, researchers have discovered that hydraulic fracturing operations in shale reservoirs have the capability to create intricate fractures networks.[102] Numerous factors impact these networks, such as diminished stress differentials in brittle shale formations and closer proximity of the fracture to the bedding surface. As a result, these factors contribute to the development of larger SRA and more complex fracture geometry. The orientation of the maximum horizontal stress with respect to the bedding plane is a crucial factor, with a 90° or greater angle increasing the likelihood of fracture network generation. Additionally, a hydraulic fracture approaching a well-opened natural fracture at an angle close to 90° also promotes fracture network formation. In addition, the utilization of fluids with high flow rates and low viscosity is conducive to the generation of a larger SRA. Finally, modifying the flow rate serves to heighten the probability that the hydraulic fracture will link to both the bedding planes and the natural fractures already present.

It has been observed that not only the orientation but also the magnitude of the *in situ* stress influences the initiation stress and location of fractures. As the coefficient of horizontal principal stress difference increases, the impact of the maximum horizontal principal stress and the angle between natural cracks on fracture pressure becomes more pronounced.[104]

The hydraulic fracturing process in coal and rock formations is influenced by the presence of natural cleats and fractures, resulting in high-pressure conditions with frequent fluctuations and complex fracture morphology. Hydraulic fractures originate in numerous directions and form multiple cracks, primarily following the natural cleavage planes, when the difference in horizontal principal stress is minor. The direction of fracture expansion becomes random in this case. Nevertheless, with an increased discrepancy in horizontal principal stress, the hydraulic fracture predominantly propagates parallel to the vertical minimum horizontal principal stress, resulting in a relatively simple fracture shape. The variation of elastic modulus between coal measures does not heavily impede the transmission of hydraulic fractures through the interlayer. Instead, the ability of the fracture to permeate the layer is largely dependent on the vertical compressive stress and the properties of the interface between the coal seam and interlayer. In conditions of low vertical stress and weak interfacial cementation strength, the hydraulic fracture experiences reduced friction factors, leading to easier transverse slipping along the interface and difficulty in penetrating the interlayer. Conversely, under high vertical stress and strong interfacial cementation strength, the friction factor increases, facilitating the propagation of the hydraulic fracture through the interlayer.[105] If the length of a hydraulic fracture surpasses a marginal value, it may occasionally spread along formation contacts or pierce boundary layers.[106] Physical studies were carried out in conjunction with concurrent acoustic emission monitoring to investigate fracture geometry in multilayer media.

B. Numerical simulation with mathematical models

The numerical simulation is also a feasibility study for coal measure gas co-production.[66,107–111]

Using the Meyer software, an analysis was conducted on the pressure drop curve that occurred after the pump and the construction data were stopped in well YMC1 situated in western Guizhou Province with the aim of optimizing the design of perforation and fracturing (Fig. 7).[21] Based on a comparison of ground microseismic monitoring data including fracture height, perforation thickness, and coal seam thickness, it is clear that Well YMC1 effectively reconstructed coal seams No. 5^{-2}, No. 13^{-2}, and No. 7, along with their corresponding roof and floor formations. This reconstruction successfully established pathways for the extraction of "three gas."[21]

During the co-production of tight sandstone gas and CBM, the two-phase flow of gas and water model indicates that there is no interference between the coal and sandstone formation when operating under a constant pressure-producing system. In comparison to CBM reservoirs, sandstone reservoirs experience a swift pressure depletion alongside a decline in gas production rate, while CBM reservoirs undergo a slower pressure decline and a gradual increase in gas production rate. The unique characteristics of individual reservoirs have a notable influence on their respective gas production performance, yet they do not have any impact on other reservoirs. Reducing the constant drainage pressure and utilizing a coal with lower Poisson's ratio value and cleat compression coefficient can considerably enhance gas production. Under the set production rate, the production contribution can be obtained. In cases where the pressure difference exceeds 3 MPa, gas and water may intrude, but reservoirs tend to reach equilibrium quickly.[107]

During the CBM co-production process, to prevent interlayer interference, it is recommended to formulate a systematic development plan that accounts for the diverse drainage dynamics and hydrogeological situations of superimposed CBM systems (Fig. 8). Additionally, the developed methods and technologies for superimposed CBM systems should be optimized based on the primary geological constraints. To facilitate the extensive utilization of multi-seam superimposed CBM across the Bide-Santang basin, it is imperative that the diverse geological situations should be taken into account at every stage of the CBM development process. According to the fluid behavior determined through the COMET3, the upper CBM system acting as the primary contributor to co-production, constrains the production of the lower and middle systems.[112]

Moreover, the 3D lattice algorithm hydraulic fracturing simulation conducted on the Lin-Xing block demonstrates that the position and length of perforations in multi-layer reservoirs significantly affect the propagation of hydraulic fractures (Fig. 9). Other factors such as rock properties, stress states, coal seam thickness, and lithological sequencing also have an impact on the maximum stimulated volume.[113] In situations where there is a significant difference in horizontal stress between the upper and lower interlayers, it is common to

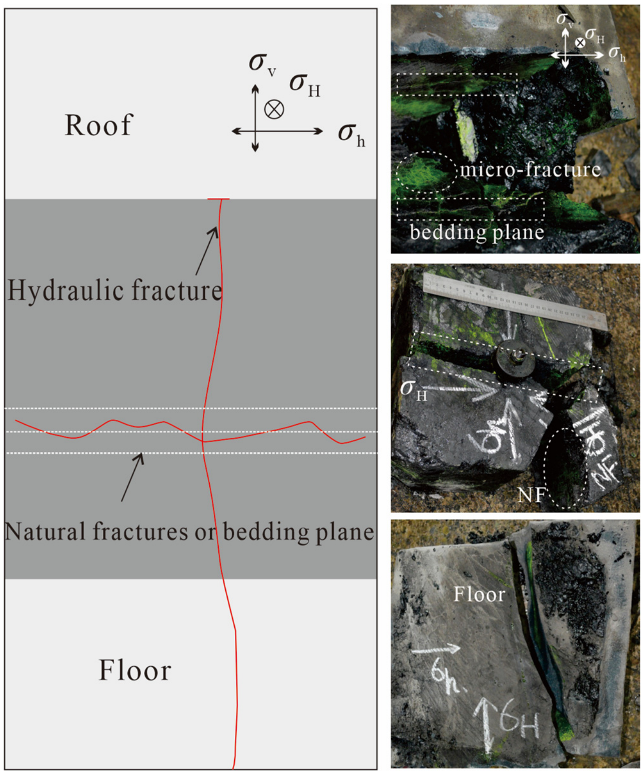

FIG. 6. Hydraulic fracture crossing bedding planes.[103] Reproduced with permission from Liu *et al.*, J. Pet. Sci. Eng. **168**, 400–408 (2018). Copyright 2018 Elsevier.

observe an uneven growth in fracture height (Fig. 10).[113] Moreover, the horizontal fractures are formed in the formation with shallow depth, while the vertical fractures are more likely to form in deeper stratum.[113] In addition, it is advisable to extract the gas separately from if the thickness of the upper and lower sandstone layers exceeds 5 m or the sandstone layer with an interlayer thickness greater than 10 m.[113] Additionally, it is recommended to primarily perforate the sandstone layer, while perforating only a smaller portion of the coal seam to minimize the differences in propagation pressure resulted from the rock mechanical properties.[113]

The practical role of numerical simulation technology in guiding coal measure gas co-production is mainly reflected in extracting co-production threshold values. This leads to guiding the selection of coal measure gas co-production blocks and layers, characterizing the formation and propagation characteristics of multiproduction layer fractures. Additionally, numerical simulation is employed to investigate the impact of composite reservoir transformation, with the aim of providing guidance for optimizing co-production fracturing schemes, revealing the fluid energy transfer behavior and production laws between co production layers, and optimizing the drainage system and development plan.[95]

C. Field practice of hydraulic fracturing of coal measures

Hydraulic fracturing is extensively introduced in improving the performance of gas production from coal measure strata. In the Panxian coal field in Guizhou province, the Permian Longtan formation is the main coal-bearing strata for coal measure gas co-production. In this area, the superimposed gas-bearing system is characterized by the interaction among thin-medium thick coal seam, mudstone, and sandstone. However, gas production of a single well is low, since the developed reservoirs are multiple and thin. According to the geological conditions of Longtan formation in the Panxian coal field, favorable gas-bearing interval in coal measure needs to be optimized, and the staged fracturing re-form is combined with small-layer perforation (viz., thin coal seam is the main perforation section) and ball sealer diversion separation technology.[114] Accordingly, a fracture network with high conductivity is formed, and a single well can realize the overall fracturing effect of coal seams in multiple favorable intervals while taking into account the interlayer sandstone. Therein, the well starts generating gas following a 35-day drainage period, and daily gas production peaks at 895.8 m^3/d, with cumulative production reaching 43 232 m^3—a good performance (Fig. 11).

As for the Yangmeishu Syncline in Liupanshui fault depression, the difference in physical and mechanical properties of coal measure strata of Longtan formation determines the time sequence of fracture in each perforated interval. In this area, the cracking sequence of perforated interval can be adjusted by changing the pumping program or applying the ball sealer, and the application of small-layer boundary-expanding perforating technology can reduce the stress difference at the interface among coal measure strata. By using these technologies, the maximum gas production reaches 4656 m^3/d.[115]

One more example, in Ordos basin, the fractures formed by conventional hydraulic fracturing are limited in the coal seam of Shanxi formation, making it difficult to effectively develop the overlying coal measure sandstone. In this area, (1) using the small-layer boundary-expanding perforating technology to reduce the strength difference of the interface between coal seam and coal measure sandstone, and (2) reforming coal seam with vertical fracture height by hydraulic fracturing to drive the transfer of coal measure gas to the overlying layer are effective methods to realize the co-production of coal measure gas.[116]

V. GAS EXTRACTION FROM COAL MEASURE FORMATIONS

According to the string structure design and drainage control measures, considering the selection of well type and fracturing method, the gas extraction from coal measure formation can be divided into three patterns: (1) layering drainage (e.g., gas release individually from each layer), (2) joint drainage (that is, gas release simultaneously from all layers), and (3) first layering then joint drainage.[117] Herein, the layering drainage pattern uses different string systems to produce coal measure gas from different lithology reservoirs or multiple reservoirs with the same lithology. This pattern can be classified into four methods, which includes drainage coal measure gas from different well in different area, drainage coal measure gas from the same well at different time, drainage coal measure gas from different reservoir in same well and drainage coal measure gas from same well at the same time.[60,117,118] Moreover, the basic principle of the first layering then joint pattern is to realize the continuous production process from single drainage from high pressure reservoir to co-layer drainage from low pressure reservoir through technical measures. Moreover, this pattern includes

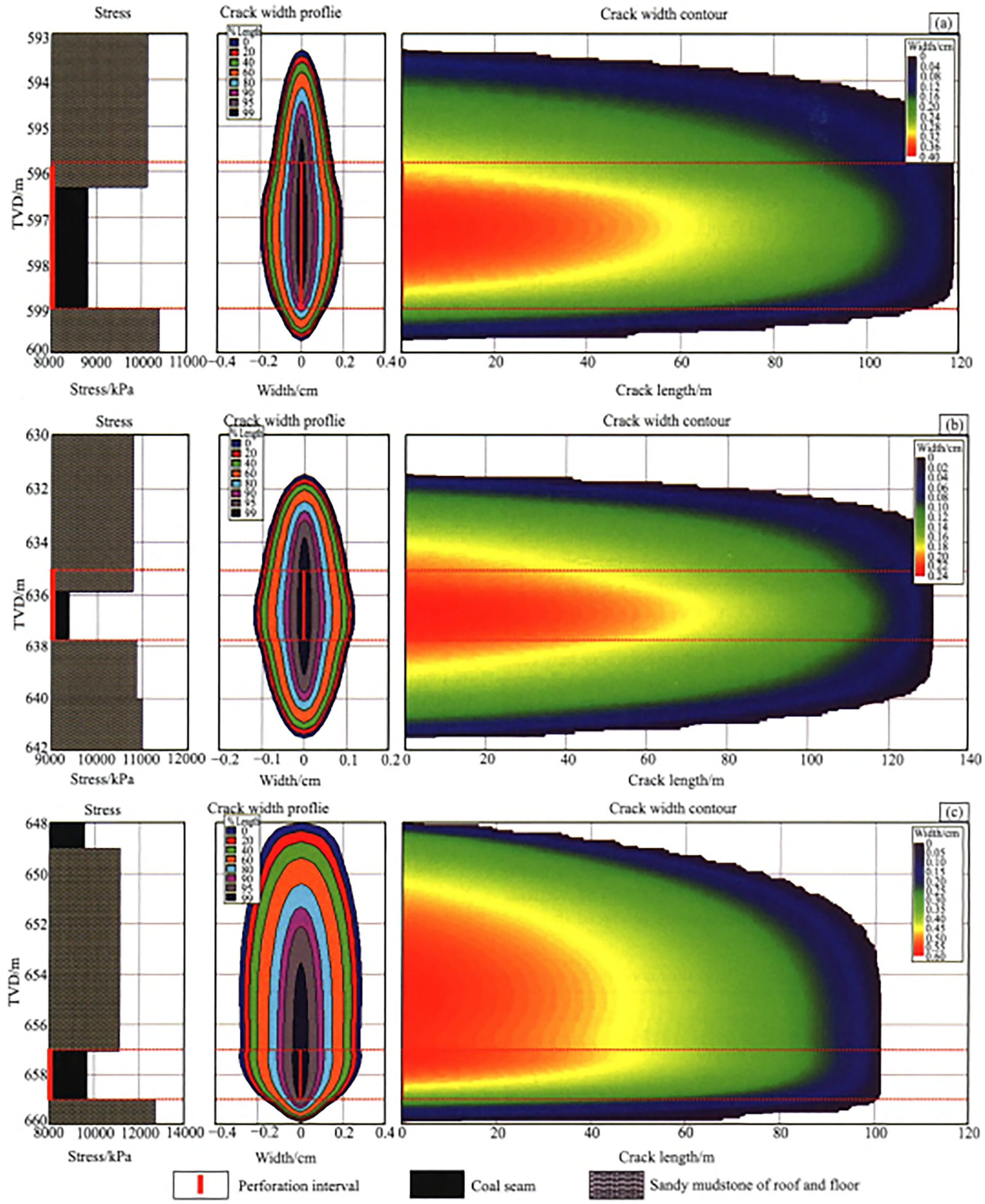

FIG. 7. Fracture profile of well YMC1.[21] Reproduced with permission from Bi *et al.*, China Geol. **3**, 38–51 (2020). Copyright 2020 Authors, licensed under a Creative Commons Attribution (CC BY) license.

drainage through progressive pressure drop and automatic control of drainage through the same string methods.[86,117,119] In addition, the joint drainage pattern is characterized by the orderly reduction from high pressure to low pressure formation in the co-layer drainage process based on stratum energy or stratum desorption ability. During the gas extraction process, the total gas production (q) should include the flow rate of seepage in the seepage fracture (q_s) and the flow rate of matrix desorption (q_d):[120]

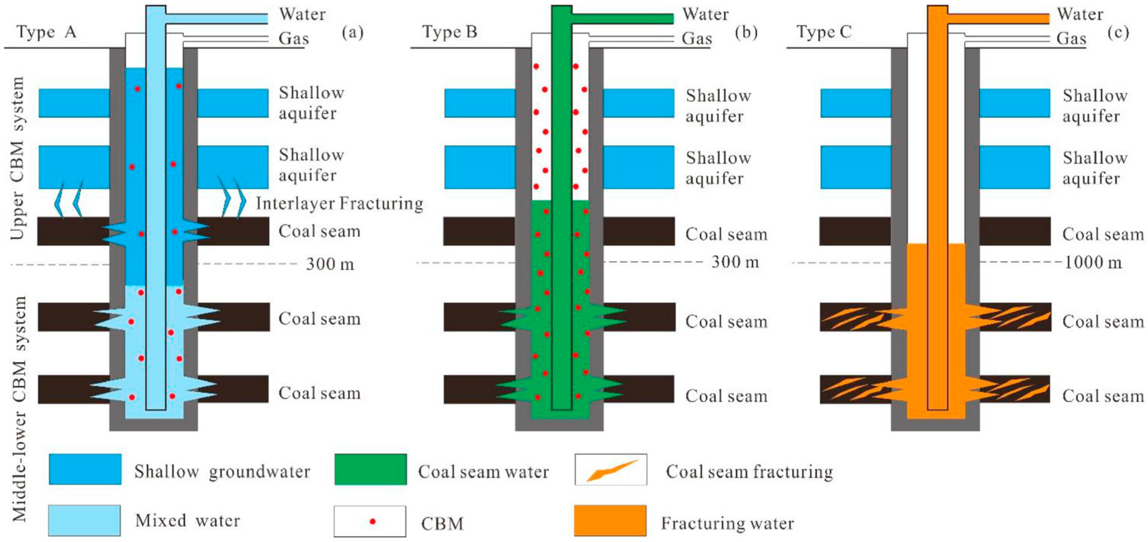

FIG. 8. CBM co-production modes in the Bide-Santang basin.[112] Reproduced with permission from Guo *et al.*, J. Pet. Sci. Eng. **189**, 107039 (2020). Copyright 2020 Elsevier.

$$q_s = \frac{-\partial J_g}{2}(P_i - P_w)^2 + J_g(P_i - P_w), \tag{1}$$

$$q_d = \pi \frac{(r_e{}^2 - r_w{}^2)h\rho_c V}{B_g}\left(\frac{P_i}{P_i + P_L} - \frac{P_{avg}}{P_{avg} + P_L}\right)^2, \tag{2}$$

$$q = \frac{-\partial J_g}{2}(P_i - P_w)^2 + J_g(P_i - P_w) + q_d, \tag{3}$$

where r_e is the supply radius, h is the thickness of coal measure, B_g is the gas volume coefficient, α is the stress sensitivity factor, P_L is the Langmuir pressure, P_i is the initial pressure, and J_g is the gas production index.

Aiming to explore the co-production of coal measure gas, previous works made a series of simulations to explore the best manner for getting greater gas recovery,[121] where the multi-layer superimposed gas bearing system is commonly adopted (Fig. 12). Accordingly, it is found that the interlayer interference seems to be a common and serious phenomenon during co-production from multiple coal reservoirs, and its intensity is correlated with reservoir pressure in a negative manner.[122–124] Basically, the interlayer interference means the backflow phenomenon of gas from the high-pressure layer to the low-pressure layer in the early stage (Fig. 13). At the early stage, the minimum production contribution of coal seams is −0.11%, −0.25%, and −0.44% when the interlayer pressure difference is 0.7, 1.4, and 2.1 MPa, respectively.[123] Herein, the negative production contribution indicates the backflow phenomenon in coal measures. Moreover, the backflow phenomenon becomes more obvious and interlayer interference are stronger with the increase in the interlayer pressure difference in the early stage.[123]

To solve the compatibility contradiction of co-production of coal measure gas, multi-layer horizontal wells and interlayer horizontal

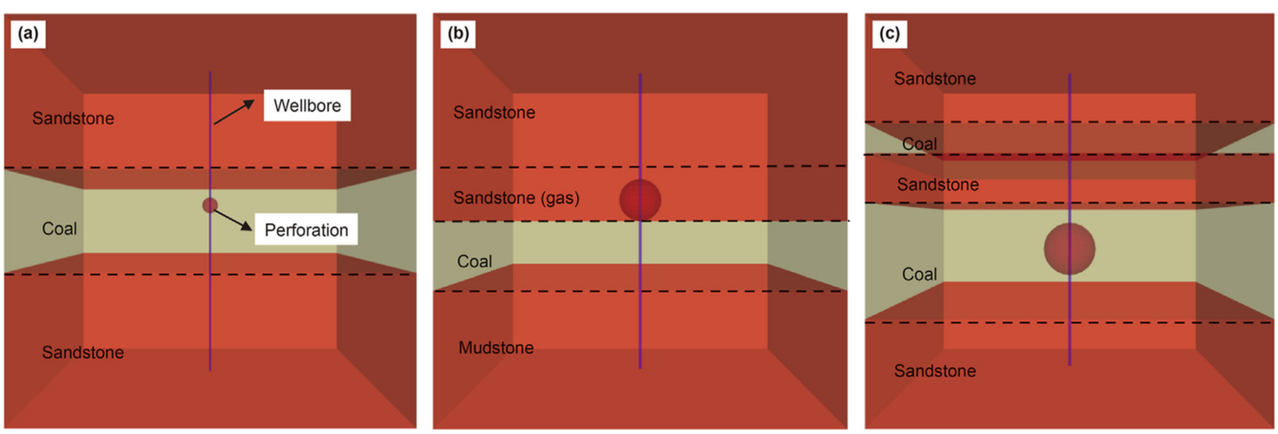

FIG. 9. Schematic diagrams of different simulation cases.[113] Reproduced with permission from Hou *et al.*, Pet. Sci. **19**, 1718–1734 (2022). Copyright 2022 Authors, licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 International (CC BY-NC-ND 4.0 DEED) license.

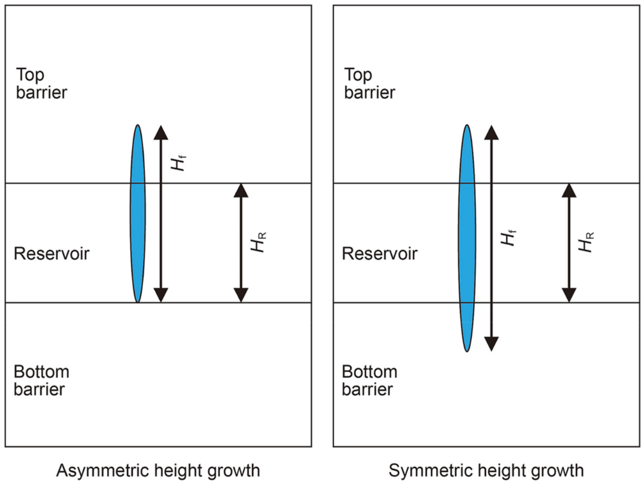

FIG. 10. Asymmetric and symmetric height growth (H_f, overall fracture height; H_R, reservoir height).[113] Reproduced with permission from Hou *et al.*, Pet. Sci. **19**, 1718–1734 (2022). Copyright 2022 Authors, licensed under a Creative Commons Attribution-NonCommercial-NoDerivs 4.0 International (CC BY-NC-ND 4.0 DEED) license.

wells have also been used in fracturing in recent years.[117,125–127] In the Ordos basin, through the joint drainage, it is reported that some wells (LM03, LM05, LM07, LM08, LM09, and LM10) in Linxing area have realized the gas co-production from coal measures, which suggests a good potential for gas extraction practice. In this area, the greatest gas production rate even reached 20 000 m^3/d for a well. Meanwhile, the gas extraction from different layers was also investigated; taking LM08 well as an example, the free gas produced in the early stage was from the sandstone, which contributed ~43% to the total production, which was followed by the desorption gas from coal seam that accounted for ~57%.[117]

In Tiefa basin, the production layer of DT26 well is the upper coal-bearing section (corresponding to gas-bearing system a), and the production layer of DT32 well is the lower coal-bearing section (corresponding to gas-bearing system b, c and d). In addition, well DT31 is a co-production well of the upper and lower coal bearing sections. Herein, the DT31 well produced gas for 1787 days, with a cumulative gas production of 4.08×10^6 m^3, an average daily gas production of 2280 m^3/d, and an average daily water production of 5.6 m^3/d. Moreover, the DT26 well produced gas for 2789 days, the cumulative gas production was 9.09×10^6 m^3, the average daily gas production was 3247 m^3/d, and the average daily water production was 2.9 m^3/d. For the DT32 well, total gas production was 3.84×10^6 m^3 in 2846 days, average daily gas production was 1349 m^3/d and average daily water production was 2.7 m^3/d.[128] Therein, the contribution rate of the upper coal bearing section is higher than that of the lower coal bearing section, and the ratio of the contribution rate of the upper and lower coal bearing sections is 2.4:1. However, the average daily production of DT31 well is only 70% of that of DT26 well, and the cumulative gas production of single well is only 45% of that of DT26, which indicates that there is great interlayer interference during the co-production.[128] Hence, for the complex geological conditions of coal measure gas, technology maturity, convenience and timeliness should be comprehensively considered to select the gas extraction pattern.

In Jixi basin, based on the reservoir thickness, permeability, gas bearing capacity, porosity and reservoir pressure of Cretaceous Chengzihe formation, a comprehensive evaluation index of coal measure gas co-production was established:[129]

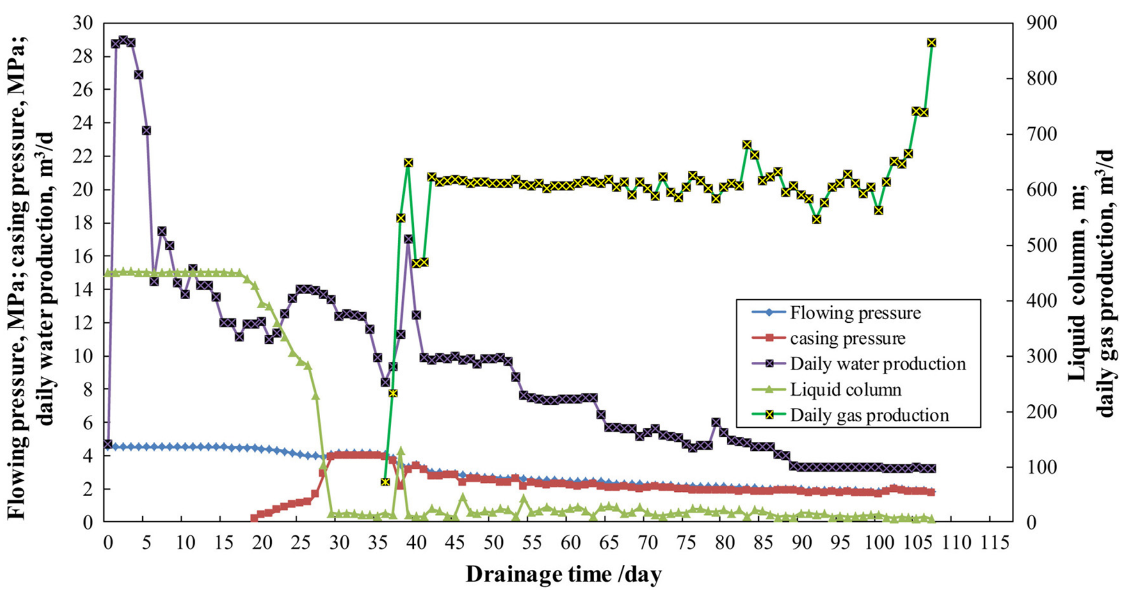

FIG. 11. The drainage curves of multiple fracturing intervals in SH1 well in Panxian coal field.[114] Reproduced with permission from Jia *et al.*, J. Pet. Sci. Eng. **146**, 489–504 (2016). Copyright 2016 Elsevier.

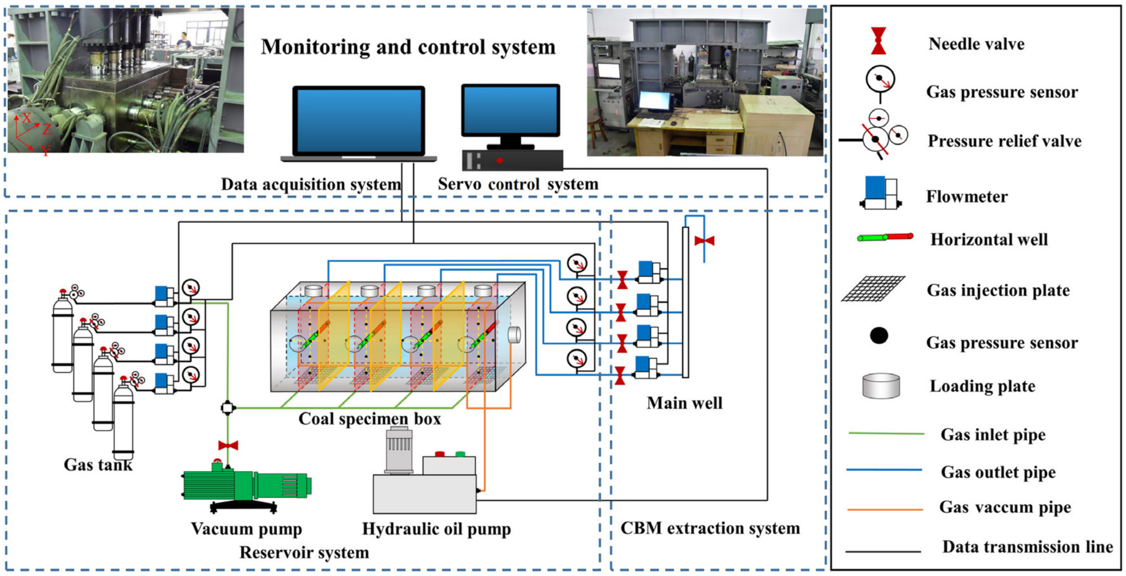

FIG. 12. Experimental setup for co-production of coal measure gas.[121] Reproduced with permission from Li *et al.*, Energy Sci. Eng. **8**, 1370–1385 (2019). Copyright 2019 Authors, licensed under a Creative Commons Attribution (CC BY) license.

$$I_z = \frac{H_s}{H_m} \times \frac{\emptyset_s}{\emptyset_m} \times \frac{K_s}{K_m} \times \frac{P_s}{P_m}, \quad (4)$$

where I_z is the comprehensive evaluation index of coal measure gas co-production, H_s is the thickness of coal measure sandstone, H_m is the thickness of coal seam, ϕ_s is the porosity of the coal measure sandstone, ϕ_m is the porosity of the coal seam, K_s is the permeability of coal measure sandstone, K_m is the permeability of coal seam, P_s is the reservoir pressure of coal measure sandstone, and P_m is the reservoir pressure of coal seam.

In addition, the comprehensive evaluation index of well HJD1 is 1.83×10^{-5}–0.0086, which is in the range of 1.012×10^{-5}–4.879. Therefore, the coal measure sandstone and coal seam are suitable for co-production. Moreover, the cumulative gas production of coal measure gas well HJD1 is 526 820 m^3 in 399 days, and the average daily gas production is 1320.35 m^3. The cumulative water production is 5161.94 m^3, and the average daily water production is 12.94 m^3.[129]

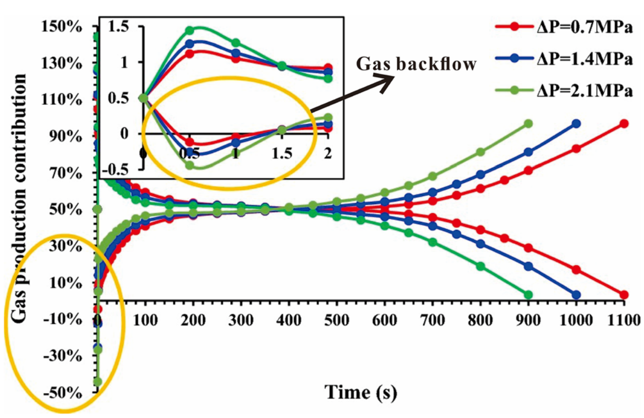

FIG. 13. Interlayer interference during co-production of coal measure gas.[123] Reproduced with permission from Liu *et al.*, J. Pet. Explor. Prod. Technol. **12**, 3263–3274 (2022). Copyright 2022 Authors, licensed under a Creative Commons Attribution (CC BY) license.

VI. CHALLENGES AND PROPOSALS FOR COAL MEASURE GAS DEVELOPMENT IN CHINA

A. Current scientific issues and limitations in coal measure gas development

1. Additional research into the spatial differentiation mechanism of superimposed gas-bearing systems across various regions

Understanding the spatial distribution and formation mechanism, co-accumulation model, and overall makeup of superimposed gas-bearing systems is critical for successful co-exploration and co-production of coal measures gas.[130,131] The success of co-exploration and co-production operations in coal measures gas is largely dependent on the compatibility of the superimposed gas-bearing system,[117,132–134] which is necessary to guide the process optimization and technological innovation of co-production of coal measures gas. However, the interlayer interference is the key problem of the compatibility of the superimposed gas-bearing system. During the co-production of coal measure gas, the superimposed gas-bearing systems are connected through wellbore. Herein, the balance of dynamic energy states between systems is disrupted, causing the gas to move from high pressure gas-bearing systems to lower pressure ones in search of a new balance.[135] Therefore, to improve the compatibility of the superimposed gas-bearing system during co-production, investigations on the geological variation mechanism of reservoir pressure and gas elastic energy, technologies for the high-resolution identification of the coal measure gas production contribution, and the optimization approaches for production layer combination should be developed. In this work, we also suggest that the layered pressure relief in surface wells and interlayer gas (like CO_2, N_2) injection with differential pressures during coal measure gas co-production may be effective methods to balance the fluid energy of each gas producing layer and thus to reduce the interlayer interference. In addition, it is essential to investigate the co-occurrence characteristics of coal measure gas, develop co-exploration methods based on the co-occurrence state features of coal measure gas, and reveal the interrelationship of symbiotic main units. Furthermore, to enhance resource development and serve efficient exploration, it is indispensable to achieve high-resolution identification of effective gas-bearing intervals, improve the classification and zoning evaluation system of coal measure gas resources,[41,136–138] and obtain key geological parameters of co-production.[134]

2. Innovation in geological technology for coal measure gas co-production

It is also necessary to establish a geological technology integrating system compatibility and technical adaptability, strengthen the concept of "one well, one policy," and continuously optimize the drainage and production system by leveraging the essential elements that drive efficient coal measure gas co-production.

Coal measure tight gas exhibits characteristics such as a tight reservoir with significant heterogeneity, intricate gas-water relationship and dessert identification difficulty. In addition, the pressure coefficients of some coal measure tight gas reservoirs in China (0.7–0.9) are comparatively lower than those observed in the United States, which typically range from 1.1 to 1.4.[22] Herein, low pressure system makes it more difficult to improve the recovery of coal measure gas co-production. For the complicated geological characteristics, there are many bottleneck problems, including comprehensive enhancements of recovery factor, effective stimulation of reservoir, evaluation of seepage law and productivity, optimization of horizontal well trajectory, strategic deployment of well patterns, and dessert prediction and so on. Consequently, the recovery rate of coal measure tight gas, currently standing at 20%, falls behind that of the United States.[22]

Nowadays, the degree of control and reliability of coal measure gas exploitation potential still need to be improved. First, the gas content of coal measure reservoirs obtained using traditional and current standards is relatively low, which affects the objectivity of resource scale understanding. Measurement methods of gas content in coal methods can be divided into direct method and indirect method. The direct method is to measure the gas content of coal samples directly by desorption after obtaining samples, for example, on-site desorption method. This method calculates the total gas content by summing up the desorption gas content, the lost gas content and the residual gas content. In addition, indirect method refers to the prediction of coal seam gas content by gas emission, adsorption isothermal curve and logging interpretation, including isothermal adsorption method, regression analysis method, BP neural network method, support vector machine method, and deep learning method and so on.[139–143] The gas content measurement methods mentioned above are for a single coal seam, and methods for coal measure strata needs to be further improved. Second, the uncertainty of the recoverable coefficient of coal measure gas determined by different methods is significant, and the reliability of economic prediction for coal measure gas development needs to be improved. Third, the gas-bearing characteristics of deep coal seams exhibit dissimilarities as opposed to those of shallow coal seams, and previous understanding has seriously underestimated the scale and recoverable potential of deep coal seam methane resources. Fourth, although estimates have been made on the scale and exploitable potential of coal measure gas resources in some basins and layers, most of the work has not yet risen to the level of strict geological investigation, and there is a lack of comparability understanding under unified standards and method constraints.

B. Promising approaches for boosting coal measure gas development in China

China holds significant potential in coal measure gas resources, but its development is somehow limited, because there exist substantial deficiencies in the understanding and perception of these resources. Conducting geological surveys and ensuring the sustainable supply of coal measure gas resources are one of the key tasks of the new round of strategic breakthroughs in gas exploration nationwide. First, given the specific geological characteristics of coal measure gas, the investigation plan aims to be precise and tailored accordingly. Second, the geological research of shallow coal measure gas primarily emphasizes the validation process, whereas the investigation work places a higher priority on exploring deep coal measure gas resources. Third, pay attention to the exploration of the potential and large-scale release value of deep CBM resources, and develop a model for predicting and evaluating essential characteristics of deep coal reservoirs. Fourth, enhance gas content testing procedures and techniques in coal-bearing reservoir, expand the utilization scope of high reliability calibration methods, and promote the geological investigation of coal measure gas to be closer to the development effect. Fifth, move beyond the conventional limitations of singular reservoir thickness and concentrate on extremely large-scale accumulation and high permeability circumstances, specifically targeting thin interbedded coal measure gas. Additionally, it is also necessary to intensify the investigation of coal-bearing formations with a deep buried depth, which contains attractive gas resources but is reserved in a more complicated environment like higher pressure and higher temperature.

VII. CONCLUDING REMARKS

We review the geographical distribution, geological characteristics, and principles of hydraulic fracturing used in the extraction of coal measure gas and provide perspectives for the accelerated development of gas recovery in China.

1. Coal measure gas resources in China are abundant and widely distributed. The geological setup and feature characteristics, geological characteristics of the coal measure strata, and the amount of coal measure gas resources of the Tarim, Sichuan, Junggar, and Ordos basins are summarized, respectively.
2. Through the comprehensive analysis of sedimentary environment and tectonic conditions, the trap-type gas reservoirs formed in the river and delta depositional systems are more suitable for coal measure gas comprehensive exploration. In addition, the potential of these various deposits is controlled by the sedimentary environment and prevailing hydrogeological and tectonic conditions with the superimposed gas-bearing systems the primary issue for gas exploration and extraction.
3. Key needs in stimulation are in limiting formation damage, extending penetration potentially across multiple layers and in

guaranteeing high fracture conductivity to more effectively and fully recover the coal measure gas resource. Moreover, the physical and numerical simulations of hydraulic fracturing in the process of coal measure gas co-production are summarized, and the field practice of hydraulic fracturing in Longtan formation of Panxian coal field, Longtan formation of Yangmeishu Syncline, and Shanxi formation of Ordos basin is introduced.

4. Gas recovery from coal measure formations can be divided into three patterns: (1) layering drainage (gas release individually from each layer), (2) joint drainage (gas release simultaneously from all layers), (3) first layering then joint drainage. Furthermore, during the gas extraction from coal measure strata in Ordos basin, Tiefa basin, and Jixi basin are summarized, interlayer interference phenomena restrict the full recovery of the reserve, which awaits new and novel solutions—both in technology and equipment.
5. In addition, some characteristics specific to China also hinder the development of the coal measure gas resource—including bottleneck problems such as accurately predicting reservoir behavior in dessert regions, optimizing well patterns, deploying optimal horizontal well trajectories, effective reservoir stimulation and enhancing overall recovery factors—all warranting more attentions in top-level design specific to the Chinese energy system. Accordingly, developing new techniques, conducting improved geological surveys, and ensuring the sustainable supply of coal measure gas resources are helpful in the new round of strategic breakthroughs in recovering the coal measure gas resource—a source of energy with great potential in China.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Li Li: Data curation (equal); Writing – original draft (equal). **Shengming Ma:** Data curation (equal). **Xin Liu:** Investigation (equal). **Jun Liu:** Conceptualization (lead); Investigation (lead); Resources (lead); Writing – review & editing (equal). **Yang Lu:** Investigation (equal). **Peng Zhao:** Investigation (equal). **Nadhem Kassabi:** Writing – review & editing (equal). **Essaieb Hamdi:** Writing – review & editing (equal). **Derek Elsworth:** Methodology (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this review are available from the corresponding author upon reasonable request.

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