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Editorial: Efficient exploration and development of unconventional natural gas

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Editorial on the Research Topic
Efficient exploration and development of unconventional natural gas

1 Introduction

Unconventional natural gas resources—including shale gas, coalbed methane (CBM), and natural gas hydrates—serve as critical drivers of the global low-carbon energy transition, profoundly reshaping conventional exploration and development paradigms (Bocora, 2012; Flores and Moore, 2025; Tao et al., 2019). With sustained progress in the shale gas revolution and breakthroughs in gas hydrate trial production technologies, unconventional resources, such as CBM, tight sandstone gas, and shale gas, are becoming increasingly important components of energy security (Boswell and Collett, 2011; Guo et al., 2025). These resources demonstrate strategic significance in mitigating hydrocarbon supply-demand imbalances and optimizing energy structures. Guided by China's "Dual Carbon" strategy—targeting a national CO_2 emissions peak before 2030 and carbon neutrality by 2060—unconventional natural gas exploration and development are increasingly guided by two interlinked priorities: intelligent target identification and low-carbon process regulation. This aligns with global decarbonization trajectories, where CCUS emerges as a pivotal technology. McLaughlin et al. (2023) provide a sociotechnical synthesis of CCUS's role in industrial decarbonization, outlining both technical challenges and policy implications, while Yusuf and Al-Ansari (2023) highlight how integrating CCUS within natural gas supply chains—particularly in the context of low-carbon hydrogen production—can significantly enhance sectoral sustainability. Together, these international perspectives enrich the framing of China's geology–engineering integration framework within the wider context of global low-carbon transitions.

In conventional natural gas development, enhanced recovery technologies continue to evolve, establishing an engineering framework centered on enhanced hydrocarbon recovery (EOR), multi–stage hydraulic fracturing, and precision well completion. These techniques have demonstrated robust production stability in low-to-medium permeability reservoirs (Abdulhadi et al., 2025; Akbarabadi et al., 2023; Gomaa et al., 2024; Sambo et al., 2023). Current research priorities are rapidly shifting from conventional to unconventional reservoirs, driving the multidimensional reconstruction of technological approaches. Core efforts focus on optimizing coupled processes in CO_2 displacement mechanisms (Zhou et al., 2024), molecular-level tuning of fracturing fluid structures (Yang et al., 2024), and upgrading intelligent completion systems based on formation response. These innovations address challenges posed by microscopic heterogeneity and thermo–hydro–mechanical–chemical (THMC) coupling complexities in shale, tight sandstone, and coal reservoirs. In field applications, shale gas development addresses nanoscale pore–throat constraints by establishing confined flow control mechanisms centered on chemical stimulation, significantly enhancing capillary-driven flow efficiency. For tight sandstone reservoirs, rock brittleness classification models enable precise fracturing parameter matching and optimized fracture propagation pathways (Wu et al., 2024). The development of CBM utilizes organic matter–fluid interaction mechanisms to formulate fracturing fluids incorporating long-chain alkyl surfactants, which exhibit targeted dissolution behavior and thereby minimize structural disruption while enhancing pore connectivity and methane adsorption capacity (Zhao et al., 2024). Global research trends further indicate a shift toward multi-driver mechanisms in unconventional gas development. Specifically, CO_2/N_2 coinjection demonstrates superior pressure-synergistic effects in coal seams, optimizing gas desorption-production dynamics (Wang et al., 2025); gas hydrate production employs coupled depressurization-displacement mechanisms to enhance methane recovery efficiency and production stability (Kasala et al., 2025). Supported by high-fidelity multiphysics simulations and advanced data-driven algorithms, an intelligent production control paradigm for unconventional reservoirs is emerging. Physics-informed machine learning is increasingly applied to improve interpretability, accuracy, and adaptability of reservoir models, while hybrid frameworks integrating statistical analysis, machine learning, and optimization have enhanced production forecasting and decision-making in shale gas development (Meng et al., 2023). These advances highlight the convergence of mechanistic modeling and data-driven optimization toward digitally enabled, mechanism-driven reservoir management.

Breakthroughs in intelligent low-carbon development technologies for unconventional natural gas have addressed core bottlenecks throughout resource extraction processes. To overcome geological target identification uncertainties, the integrated application of deep learning–based 3D geological modeling and real-time intelligent drilling decision systems has enhanced sweet-spot targeting accuracy and well placement precision (Carpenter, 2023). The development of multimechanism coupled flow models, integrated with digital rock core high-resolution characterization techniques, provides theoretical insights and parameterization support for fracture network design and flow channel optimization under nano-/micro-pore–scale mass transfer constraints (Yu et al., 2019). Amid tightening carbon constraints, lifecycle carbon footprint assessment models pinpoint primary emission sources across process chains, accelerating deployment of clean energy-powered fracturing systems and subsurface carbon capture–production integration systems (Khan et al., 2025). Frontier advancements reveal that integrating multienergy coupled supply systems with closed-loop intelligent carbon management platforms is catalyzing unprecedented deep integration of intelligence, systematization, and carbon neutrality in unconventional gas development (Brown et al., 2017).

This introductory review for the *Frontiers in Earth Science* Research Topic addresses technical challenges in geology–engineering integration for unconventional natural gas development. The Research Topic presents ten representative studies systematically presenting recent advances in intelligent algorithms and low-carbon technologies aimed at high-efficiency unconventional gas development.

2 Review of research presented in This Research Topic

This Research Topic compiles cutting-edge advances in efficient unconventional gas exploration and development, encompassing critical technological pathways including geological target identification, reservoir stimulation mechanisms, and intelligent low-carbon regulation. These contributions span diverse reservoirs—shale gas, CBM, gas hydrates, and tight sandstone—yielding systematic breakthroughs in structural–sedimentary interpretation, flow regulation optimization, and mechanistic-based modeling. Collectively, they highlight a dual-driven technological transition toward enhanced efficiency and emission abatement in unconventional gas development.

2.1 Intelligent exploration and synergistic appraisal

Unconventional natural gas exploration confronts three primary challenges: unpredictability of fracture networks, lack of diagnostic indicators for coexisting critical minerals, and poorly constrained deep sweet-spot positioning. This theme centers on the integration of multi-source geological, logging, and seismic data, promoting the reconstruction of integrated natural gas–critical mineral co-exploration frameworks (Mirzaee Mahmoodabadi and Zahiri, 2023; Mubarak and Koeshidayatullah, 2023; Prochnow et al., 2022). Specifically, Wu et al. integrated surface fracture outcrop distributions with coal seam thickness constraints to reconstruct paleotectonic stress field models, elucidating fracture networks predominantly governed by structural curvature. The Laochang Block, situated in eastern Yunnan Province, China, is a tectonically complex coalbed methane–bearing region characterized by intense multi-phase deformation and heterogeneous stress regimes. Application of this integrated approach markedly improved the accuracy of CBM sweet-spot identification in the block, offering novel geomechanical insights into fracture development and permeability enhancement in structurally intricate reservoirs. Mu et al. employed K-means clustering to extract natural gamma-ray and resistivity responses, establishing logging identification criteria and resource co-evaluation systems for Li-enriched coal seams. These advances integrated exploration technologies for unconventional gas and critical minerals. Additionally, Zhang et al. applied multifrequency seismic attribute fusion—combining high–frequency amplitude with low-frequency coherence—to jointly characterize sedimentary facies and fault systems. Their methodology elucidates reservoir–controlling mechanisms, establishes intelligent prediction pathways for deep carbonate sweet spots, and facilitates substantial exploration success in the Dengying Formation, located within the Sichuan Basin of southwestern China—one of the country's most prolific hydrocarbon provinces.

2.2 Fracture network stimulation and multiphase flow regulation

Unconventional reservoir development must urgently overcome core bottlenecks in multiphase flow control—including gas–condensate–hydrate multiphase systems, heterogeneity in fracture network stimulation responses to fracture network stimulation, and high flow initiation thresholds. Research presented herein drives the transition of reservoir engineering from experience-driven to mechanism-driven paradigms through mechanistic analysis and modeling innovations (Yuan et al., 2023). Specifically, Wei et al. developed a dynamic depressurization model for marine hydrate extraction, demonstrating that horizontal well development in three-phase zones can simultaneously enhance gas and hydrate recovery efficiency. Their proposed well type–layer matching criterion for multiphase flow regulation guides commercial development in the Shenhu Area, South China Sea. Zhao et al. utilized *in situ* computed tomography (CT) scanning to track cyclic gas injection processes, revealing induced phase transitions of condensate from wavy to slug flow patterns, thereby significantly improving oil–gas phase distribution. The first injection cycle contributed most significantly to saturation reduction, underscoring the dominant role of fracture systems in condensate reservoir recovery mechanisms. Additionally, Ren et al. established a material-balance-driven fracture network propagation model to quantify synergistic controls of natural fracture development and fracturing fluid imbibition on stimulated reservoir volume. They developed a fracturing optimization pathway based on physical response parameters, marking a paradigm shift from experience-based to mechanism-driven fracturing design in tight reservoirs. Li et al. develop a coupled permeability–pressure–water–cut threshold flow initiation equation through physical experiments and regression analysis. Confirming water saturation as the primary control variable for threshold pressure changes, providing fundamental basis for dynamic control of high–water–cut gas reservoirs. Notably, Zhang and Liu identified a critical stress–state transition zone at ~1,500 m depth in coal seams of eastern Hubei Province, central China, located along the margin of the Jianghan Basin. This zone governs abrupt permeability changes and conductivity evolution. Their proposed slow-depressurization, rapid-drainage strategy sustains deep CBM reservoir conductivity, enabling breakthroughs in economic recovery.

2.3 Intelligent decision-making and carbon-constrained development

Unconventional gas development urgently requires overcoming dual bottlenecks: poorly understood microscale seepage mechanisms and high uncertainty in production decision-making. This work focuses on adsorption–seepage–emission reduction coupling mechanisms and intelligent decision algorithms, driving the transition toward intelligently coordinated, carbon-constrained development paradigms (Chiamaka et al., 2024; Di et al., 2021). Notably, Xu et al. employed low-pressure N_2 adsorption combined with SEM imaging to reveal the carbon sequestration mechanisms of methane molecules in anthracite-hosted organic micropores within organic micropores (<2 nm). Their work demonstrates that adsorbed methane desorption requires overcoming critical energy barriers, providing theoretical foundations for efficient CBM development and carbon storage. Furthermore, Li et al. developed an integrated Bayesian network–Gaussian mixture model (BN–GMM) framework to quantify production fluctuation probabilities and carbon footprint sensitivity under multifactorial coupling. By identifying recovery factor and reserve-to-production ratio as the primary controls of production stability, their approach drives the transition from static resource allocation to carbon-constrained intelligent decision-making in natural gas development within the Sichuan Basin.

3 Conclusion

This Research Topic compiles cutting-edge advances in efficient unconventional gas exploration and development, spanning geological modeling, engineering optimization, and intelligent technology integration. Featured studies encompass representative technological pathways including fracture network prediction, gas injection-enhanced recovery, fracturing parameter design and production uncertainty modeling. These contributions demonstrate theoretical innovations and engineering applications across shale gas, CBM, and gas hydrate reservoirs. The methodologies and case studies herein offer valuable references for understanding technological evolution in unconventional gas development while providing actionable insights for future research and practical applications.

Author contributions

ST: Conceptualization, Writing – review and editing. ZZ: Investigation, Writing – review and editing. SC: Investigation, Writing – review and editing. YJ: Supervision, Writing – review and editing. JW: Methodology, Writing – review and editing.

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Conflict of interest

Author JW was employed by EMM Consulting Pty Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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