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Editorial

Sustainable development of shale oil and gas: Insights into accumulation mechanisms and green-efficient exploitation technologies

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Abstract:
Shale oil and gas differ greatly in reservoir characteristics and accumulation mechanisms. This work compares the enrichment characteristics of marine and continental shale oil and gas, and systematically summarizes targeted green-efficient exploitation technologies for shale resources. Two quantitative theoretical models are established, namely the multi-field coupling accumulation model for shale gas and the nanoconfinement synergistic conversion model for shale oil. The integrated framework provides theoretical support for the differentiated low-carbon development of shale oil and gas and facilitates the achievement of dual carbon goals. Future research directions regarding mechanism study, technological innovation, and green evaluation systems are also prospected.

1. Introduction

As typical self-sourced and self-accumulated unconventional hydrocarbon resources, shale oil and gas play a crucial role in reserve replacement, production stabilization, and the steady transition of energy systems. Shale reservoirs are characterized by fine-grained sedimentary lithofacies, tight pore structures, and strong petrophysical heterogeneity. Accordingly, shale oil and gas exhibit distinct differences in reservoir conditions, accumulation mechanisms, and production behaviors. This work synthesizes the research advances presented in the special session “Accumulation Mechanism and Green-Efficient Development of Shale Oil and Gas” at the second “International Geo-Energy Frontier Forum”. It systematically addresses the core scientific and technological challenges in this field, including the multi-field coupling mechanisms that control the accumulation and high productivity of shale oil and gas, and presents a comparative analysis of their intrinsic differences. Furthermore, this work reviews the state-of-the-art green-efficient development technologies applicable to shale oil and gas. Ultimately, by integrating theoretical models with engineering practices, this study provides systematic theoretical support for the differentiated, green-efficient development of shale oil and gas.

2. Accumulation mechanisms

The accumulation of shale oil and gas constitutes a sequential geological process jointly governed by paleoenvironmental conditions, organic matter enrichment, hydrocarbon generation, pore and fracture evolution, fluid occurrence, hydrocarbon migration, and preservation. These factors do not function

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independently but are interrelated through sedimentary differentiation, diagenetic evolution, thermal maturation, tectonic modification, and fluid-rock interactions (Tan et al., 2021).

Abundant marine and continental shale gas resources are widely distributed, yet their enrichment mechanisms differ significantly. Marine shale gas is predominantly developed in relatively stable and extensive marine sedimentary environments, characterized by continuous shale deposition and widespread lateral distribution. Organic matter is dominated by Type I-II kerogen with high abundance and relatively high and uniform thermal maturity, conferring strong gas generation potential. Marine shale reservoirs are featured by high siliceous mineral content, favorable brittleness, and well-developed organic pores and microfractures, which afford adequate gas storage space. Benefiting from stable tectonic settings and excellent caprock sealing capacity, marine shale gas reservoirs display weak heterogeneity and favorable lateral continuity in gas content, indicating superior preservation conditions (Wang et al., 2023). In contrast, continental shale gas occurs in lacustrine sedimentary systems that are strongly governed by lake basin evolution, with complex lithology, frequent sedimentary cycles, and rapid lateral facies variations. Organic matter is dominated by Type II_2-III kerogen, with pronounced spatial heterogeneity in abundance and thermal maturity, and the generated hydrocarbons are dominated by wet gas and associated gas. Continental shale reservoirs are marked by high clay mineral content and relatively low brittleness, complex pore structures with limited connectivity, and fracture development that is highly sensitive to tectonic activity. Owing to relatively intense tectonic deformation and significant regional variations in sealing conditions, continental shale gas systems exhibit strong heterogeneity, and gas-enriched sweet spots are spatially localized.

China's shale oil is primarily hosted in high-quality source rocks deposited in semi-deep to deep lacustrine facies, mostly in continental lake basins. These shales are characterized by high organic abundance, dominated by Type I-II kerogen, and thermal maturity within the oil-generation window, providing a robust material foundation for oil generation (Zou et al., 2013). Shale oil reservoirs feature a nanoscale pore-throat system dominated by organic pores, interparticle pores, intercrystalline pores, and microfractures. Moderate content of brittle minerals and variable clay content exert significant control on pore structure and oil mobility. Shale oil occurs mainly in free state (in pores and microfractures) and adsorbed state (on organic matter and mineral surfaces), with a small portion in dissolved state, among which free oil constitutes the major recoverable fraction (Jin et al., 2021). Shale oil systems display strong heterogeneity vertically and laterally, controlled by sedimentary cycles, rapid lithofacies variations, and differential diagenesis, leading to large fluctuations in oil content. Favorable preservation relies on stable tectonic settings and effective caprock sealing, while overpressure is conducive to oil retention and enrichment; intensive faulting and tectonic uplift usually result in oil dissipation (Luo et al., 2024).

3. Green-efficient technologies

To achieve green-efficient development of shale oil and gas, it is essential to transition from reliance on traditional extraction methods to the comprehensive application of geological analysis, multi-scale reservoir characterization, reservoir stimulation, enhanced recovery, dynamic production monitoring, and low-carbon regulation. Based on the accumulation mechanisms discussed above, the key technologies for shale oil and gas development can be classified into a unified framework. Within this framework, delineation of the sweet spot establishes geological foundation; reservoir stimulation constructs effective seepage channels; CO_2-related methods and *in-situ* conversion enhance hydrocarbon mobility and ultimate recovery; and intelligent monitoring enables dynamic optimization.

Green-efficient technologies for shale gas development focus on intelligent *in-situ* stress assessment, waterless fracturing techniques, and optimized staged fracturing (Wu et al., 2025). An intelligent multi-source fusion model for *in-situ* stress evaluation has been developed, integrating experimental calibration, well-log interpretation, numerical simulation, machine learning techniques, and anisotropic stress calculation formulae (Shen et al., 2026). According to the developmental characteristics of vertical stress barrier layers, two prospective sweet-spot zones have been identified, and the optimal azimuth for horizontal wells has been confirmed. Combined with the Coulomb failure criterion, 3D finite element simulations quantify fault slip potential to inform well placement, fracturing scheme design, and geological hazard mitigation.

To address the high-water consumption and pollution associated with hydraulic fracturing, two technologies employing waterless or low-water fracturing methods have been developed and proposed. The first technique adopts 27 kHz ultrasonic stimulation to trigger microfracture extension, applicable to deep shale reservoirs buried deeper than 3500 m (Xiong et al., 2026). The second approach applies supercritical CO_2 fracturing, leveraging its low viscosity and high diffusivity to create complex fracture networks while concurrently facilitating CO_2 sequestration (Lyu et al., 2021). A fracture-height control theory has been proposed based on the identification of two stress barrier layers in southern Sichuan. Fractures rarely penetrate high-stress layers; therefore, precise control over the location and extent of the fractured zone can confine fractures within the target zone, preventing penetration into aquifers or pressure leakage. Optimizing cluster spacing, fluid volume, and sand ratio significantly enhances fracture network complexity and effective stimulated reservoir volume (Zhang et al., 2026). This technical system offers theoretical guidance for the green-efficient development of shale gas in structurally complex regions.

Green-efficient technologies for shale oil extraction include nanopore-confined adaptive CO_2 huff-n-puff, *in-situ* autothermic conversion, and superheated steam or supercritical water pyrolysis for pore creation. To account for the variations in the minimum miscibility pressure of CO_2 and oil induced by nanopore throats, a modified Peng-Robinson equation of state model was established to incorporate nanopore confinement effects (Tian et al., 2025). This model revises phase behavior parameters and integrates pore-scale mechanisms with reservoir-scale processes. It utilizes the dual effects of supercritical CO_2, including mineral dissolution and competitive adsorption, to facilitate the displacement of shale oil from nanopores.

An *in-situ* autothermic conversion model has been developed for low-to-medium maturity oil shale, in which oxygen-containing gas injection can trigger self-sustained pyrolysis after preheating, thereby improving energy utilization and reducing external heat demand. Temperature-parameter optimization studies further show that appropriate preheating and reaction-zone temperatures are critical to balancing oil yield, gas generation, and heat utilization, but the specific values of 361-425 °C, 510 °C, and 99.41% oil yield require direct verification from the original Chang 7 source before citation (Xu et al., 2023). Superheated-steam pyrolysis at high temperature can significantly alter oil-shale pore architecture by increasing pore diameter, pore volume, fracture connectivity, and specific surface area. Supercritical water pyrolysis utilizes efficient heat and mass transfer mechanisms to provide hydrogen donors, thereby creating numerous pyrolysis pores and enhancing the pore-fracture network within the reservoir. Furthermore, it can be integrated with clean thermal energy sources to facilitate low-carbon *in-situ* conversion (Li et al., 2024). Potential applications include the *in-situ* gasification of oil-prone coal and the remediation of soil.

4. Technology integration and future development directions

(1) Differentiated theoretical models and technology integration framework

Future shale oil and gas development should integrate mechanistic cognition, engineering implementation, intelligent dynamic regulation, and low-carbon constraints. The theoretical model for multi-field coupling accumulation in shale gas integrates adsorption-desorption kinetics through a modified Langmuir equation, multi-scale transport mechanisms encompassing continuum flow, slip flow, and Knudsen diffusion, as well as stress-controlled fracturing modeled via the discontinuous finite element method and Coulomb failure criterion. This integrated framework facilitates the quantitative prediction of long-term productivity decline in shale gas wells under variable *in-situ* stress conditions. The theoretical model for shale oil nanoconfinement synergistic conversion integrates corrections for nanoconfined phase behavior within a synergistic framework. This model utilizes a pore size-dependent Peng-Robinson equation of state and integrates thermal conversion kinetics, described by a piecewise Arrhenius equation, with interactions between CO_2 and crude oil, which are primarily characterized by competitive adsorption and dissolution-induced pore enhancement. It quantitatively determines the upper limit of shale oil recovery efficiency considering variable pore sizes, temperatures, and injection pressures. The two theoretical models elucidate the mechanistic differences between shale gas and shale oil, thereby offering quantifiable theoretical support for fracturing parameter optimization, *in-situ* pyrolysis, and CO_2 huff-n-puff process design.

(2) Theoretical prospects for future development directions

Future research should focus on three principal areas. First, it is essential to enhance fundamental mechanistic understanding by quantitatively distinguishing various gas flow processes within nanopores and elucidating the physical mechanisms underlying nonlinear permeability evolution. Furthermore, comprehensive investigations into volcanic activity, climate variability, and biological evolution are necessary to refine theoretical models of organic matter accumulation. Second, technological innovation should be advanced through the integration of digital twin and real-time monitoring technologies to facilitate dynamic prediction of *in-situ* stress. Additionally, optimization of nanoconfined phase behavior models is required to accommodate the complexities of fracture networks and realistic pore size distributions. The implementation of field tests and numerical simulations is crucial to promote the industrial application of *in-situ* pyrolysis technology. Third, adherence to green and low-carbon principles is essential. This includes the development of waterless fracturing and CO_2 recycling technologies to reduce dependence on water resources and carbon emissions. Moreover, establishing a comprehensive green development evaluation system is vital to ensure the coordinated advancement of energy development and ecological protection.

5. Conclusions

Through systematic analysis, this work concludes that shale gas and shale oil possess fundamentally distinct accumulation mechanisms. Shale gas is primarily characterized by high thermal maturity methane, with its accumulation controlled by adsorption-desorption behaviors, multi-scale transport processes, and stress-regulated fracturing. Shale oil is a complex mixture of hydrocarbons characterized by low to moderate thermal maturity. Its accumulation relies on the synergistic interactions among nanoconfined phase evolution, pore enlargement through pyrolysis, and viscosity reduction facilitated by CO_2. In response to these differential mechanisms, the implementation of targeted green-efficient technologies is essential. Shale gas development focuses on intelligent *in-situ* stress evaluation, waterless fracturing, and stress barrier optimization. Shale oil development prioritizes *in-situ* autothermal conversion, nanopore-confined adaptive CO_2 huff-n-puff, and superheated steam pyrolysis to facilitate pore formation. Two theoretical models are summarized, including the multi-scale coupling accumulation model for shale gas and the nanoconfinement synergistic conversion model for shale oil. These models provide quantitative guidance for optimizing fracturing parameters, *in-situ* pyrolysis processes, and CO_2 injection strategies. This comprehensive technical framework facilitates CO_2 recycling and clean heat integration under low-carbon constraints, thereby promoting the differentiated development of shale oil and gas and supporting the coordinated advancement of carbon peaking and carbon neutrality goals.

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Conflicts of interest

The authors declare no competing interest.

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