Fundamental Theory and Key Technologies for Shale Gas Exploration and Development: Postprint

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Abstract

Shale gas refers to unconventional natural gas hosted in organic-rich mudstone and shale and their interlayers, primarily occurring in adsorbed and free states, representing a clean and efficient energy resource. Mudstone and shale account for approximately 60% of global sedimentary rocks, indicating enormous potential for shale gas resources. U.S. shale gas production rapidly increased from 196 billion cubic meters in 2005 to 3,806 billion cubic meters in 2014, establishing the country as the world' s largest gas-producing nation, significantly impacting the global energy landscape, an event referred to as the "shale gas revolution." The shale gas revolution also directly spurred breakthroughs in shale oil technology. According to estimates from the "China Shale Gas Resources Investigation Report" (2014) published by the Ministry of Land and Resources in 2015, China' s recoverable shale gas reserves reach 25 trillion cubic meters (Fig. 1), with marine, marine-terrestrial transitional, and terrestrial facies each accounting for roughly one-third. Exploration and development of shale gas will effectively alleviate China' s current energy shortage and can significantly improve the atmospheric environment.

Full Text

Preamble

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Basic Theory and Key Technologies for Shale Gas Exploration and Development

1. Background and Significance

China' s shale gas basins are characterized by diverse sedimentary facies, high thermal maturity, and multi-phase tectonic reformation. This raises critical questions: Where are the relatively gas-rich sweet spots? How can exploitability be evaluated? Shale condensate and wet gas contain valuable condensate oil, yet the distribution and enrichment patterns of these resources in China, along with the phase transformation behavior and control technologies for shale condensate gas development, remain urgent challenges. Shale reservoirs exhibit extremely low permeability, with gas primarily stored in micro- and nano-scale pores. Creating dense fracture networks thousands of meters underground requires addressing frontier scientific issues spanning multi-scale characteristics from nanometer to kilometer scales, multi-flow regimes from Brownian motion to Darcy flow, and solid-gas-liquid multi-phase coupling phenomena. High-precision geosteering for horizontal wells represents a core drilling technology, but current positioning and guidance systems suffer from measurement points located 15–20 meters behind the drill bit, necessitating the development of near-bit imaging while drilling (LWD) geosteering instruments to improve real-time performance and accuracy.

Shale gas is an unconventional natural gas occurring in organic-rich mud shale and interlayers, existing mainly in adsorbed and free states, representing a clean and efficient energy resource. Mud shale accounts for approximately 60% of global sedimentary rocks, indicating enormous resource potential. The United States' shale gas production surged from 19.6 billion cubic meters in 2005 to 380.6 billion cubic meters in 2014, making it the world' s leading gas producer and triggering a "shale gas revolution" that profoundly impacted global energy 格局 and directly drove breakthroughs in shale oil technology. According to the Ministry of Land and Resources' 2015 "China Shale Gas Resource Survey Report" (2014 data), China' s technically recoverable shale gas reserves reach 25 trillion cubic meters [Figure 1: see original paper], with marine, marine-terrestrial transitional, and terrestrial facies each contributing roughly one-third. Developing shale gas will effectively alleviate China' s energy constraints while significantly improving atmospheric environmental quality.

2. Progress Made

2.1 Establishment of Stratigraphic Division Standards for Shale Gas Enrichment Horizons

Based on high-resolution biostratigraphy integrated with chemostratigraphy, quantitative stratigraphy, and other multidisciplinary approaches, the program established refined stratigraphic frameworks. Using the Lower Paleozoic Wufeng and Longmaxi black shales—two critical source rock intervals in South China—as examples, recent graptolite biostratigraphic studies enable division into 10–13 graptolite zones, each tens of centimeters to meters thick with an average temporal resolution of approximately 0.8 million years. This scheme far exceeds the precision of conventional three- or four-fold divisions, with higher-resolution quantitative stratigraphy capable of further refinement. The framework exhibits excellent chronostratigraphic consistency, effectively minimizing biases from paleogeography, stratigraphic distribution, tectonic activity, metamorphism, and weathering, and can be widely applied to high-precision stratigraphic correlation in drill cores and outcrop sections, thereby providing accurate temporal constraints for identifying organic matter enrichment patterns.

2.2 Quantification of Shale Condensate Gas Resources and Distribution in China

Through international collaboration, the program collected data from approximately 2,000 U.S. shale wells to establish probability models for shale oil, condensate gas, wet gas, and dry gas occurrence, proposing new maturity thresholds for distribution prediction [Figure 2: see original paper] that enhance reliability. Building upon global applicability verification and integrating parameters including organic matter type, content, thickness, and burial depth, the program conducted the first comprehensive evaluation of shale condensate and wet gas resources across 45 Chinese basins (regions), identifying 94 favorable zones and calculating national resource totals exceeding 11.4 billion tons of oil equivalent, comparable to U.S. resources [Figure 3: see original paper].

2.3 Development of Methane Adsorption Force Calculation Model in Micro-Nano Pores

The program developed a precise van der Waals force field that accurately predicts gas molecular density and storage capacity in micro- and nano-porous materials. This precise intermolecular van der Waals force field accurately predicts gas densities (including methane, carbon dioxide, nitrogen, ethylene, oxygen, and hydrogen), demonstrating significantly superior simulation accuracy under high-pressure conditions compared to four classical force fields [Figure 4: see original paper]. Based on common atomic types in shale kerogen composition, various organic molecules were designed to interact with gas molecules, yielding precise van der Waals force field parameters for gas-kerogen interactions that accurately predict experimental measurements [Figure 5: see original paper].

2.4 Development of Computational Simulation Software Suite for Shale Gas Extraction

The program established pore-fracture spatial geometric models, revealed multi-scale fracture mechanisms in shale reservoirs, and developed theoretical models for different fracture initiation and propagation patterns, creating numerical simulation software for shale fracturing [Figure 6: see original paper]. Microseismic source mechanisms and dynamic characteristics were investigated, leading to high-resolution microseismic migration imaging methods and multifunctional microseismic monitoring and data processing software [Figure 7: see original paper]. A seepage mathematical model incorporating adsorption and multi-flow mechanisms was developed, enabling the creation of shale gas reservoir simulation and numerical well test software based on PEBI and hybrid grids with history matching and production forecasting capabilities [Figure 8: see original paper]. This integrated software suite, with independent intellectual property rights, simulates the complete shale gas extraction process including hydraulic fracturing, microseismic monitoring, and production prediction, and has been preliminarily applied in engineering operations.

2.5 Development of Industrial Prototype Near-Bit Geosteering Instrument

The program advanced the LWD geosteering system to the drill bit position, developing a near-bit imaging geosteering instrument to improve steering accuracy and real-time performance. Key technical challenges were overcome, including temperature compensation for inertial sensors (accelerometers, magnetometers) in high-temperature environments [Figure 9: see original paper], gravity acceleration measurement under strong vibration, impact, and high-speed rotation conditions, and geomagnetic field measurement in strongly magnetic interference environments (drill bit, positive displacement motor, etc.) [Figure 10: see original paper]. A memory-type near-bit imaging geosteering instrument was developed with capabilities for near-bit dynamic wellbore trajectory and azimuthal gamma imaging measurements. The instrument passed high-temperature, high-pressure, vibration, and torque tests before field deployment.

2.7 Establishment of Micro-Nano Scale Research and Testing Platform for Shale Gas

The program established a shale micro-nano scale research platform comprising nuclear magnetic resonance (NMR), micro-CT, mineral analysis-scanning electron microscopy (AMICSCAN), focused ion beam-scanning electron microscopy (FIB-SEM) dual-beam systems, and helium-neon-gallium triple-ion-beam microscopes, representing world-class capabilities for multi-scale shale characterization and providing essential testing methods and technical support for fundamental shale gas research [Figure 13: see original paper].

2.6 Development of Deep Reservoir In-Situ Stress Testing Instrument

The program developed a contact-type optical micro-drilling-measuring integrated in-situ stress testing system featuring real-time optical micro-displacement measurement with high temperature, high pressure, and water resistance capabilities, and internal automatic recording in the probe to achieve drilling-measuring integration. This technology can guide rational horizontal well placement and fracturing design for shale gas extraction. The prototype has been completed, including an optical micro-measurement system, real-time automatic recording system, drilling-measuring integrated connection system, and drill bit system [Figure 11: see original paper], with successful laboratory and field testing of the integrated drilling-measuring functionality [Figure 12: see original paper].

3. Originality

The established stratigraphic division standards for shale gas enrichment horizons created a high-precision stratigraphic framework for the Wufeng-Longmaxi black shales in South China, providing an accurate geological time scale for various petroleum geology studies. The program investigated distribution and enrichment patterns of shale condensate and wet gas in China, along with phase transformation behavior and control technologies during development, filling a research gap in this domain.

The developed methane adsorption force calculation model in micro-nano pores enables theoretical prediction of methane storage capacity in shale, positioning this research at the international forefront. The integrated numerical simulation software suite for shale gas extraction, encompassing hydraulic fracturing, microseismic monitoring, and production prediction, fills a domestic industry gap, with underlying theoretical methods and models meeting or exceeding current international mainstream software capabilities.

The near-bit imaging geosteering instrument pioneered complete near-bit wellbore trajectory parameter measurement in near-bit environments, achieving precise measurement of inclination and toolface angles under dynamic conditions. Near-bit measurement technology enables continuous wellbore trajectory monitoring, eliminating blind zones from intermittent MWD measurements. The developed short-range electromagnetic telemetry technology based on drill collar antennas enables real-time transmission of near-bit imaging data to the surface through the drilling and measurement system.

The deep reservoir in-situ stress testing instrument employs uniformly distributed contact needles to sense borehole wall deformation, using optical micro-displacement measurement to identify probe movement, with drilling-measuring integration enabling measurement and relief actions in a single drilling run, allowing calculation of principal stress directions from borehole morphology.

The established micro-nano scale research and testing platform enables sample analysis from two-dimensional to four-dimensional, scales from meters to micrometers, and resolutions from 1 mm to 0.5 nm, innovatively integrating a uniaxial compressor into a 700 nm resolution micro-CT to achieve near-synchronous monitoring of rock compression-fracture processes and stress-strain evolution.

5. Future Recommendations for Disciplinary Development, Industrial Advancement, and Talent Cultivation

The stratigraphic division standards enabled comprehensive stratigraphic studies along a series of Wufeng-Longmaxi reference sections from northern Guizhou through the eastern Sichuan Basin to the Shennongjia region in northwestern Hubei, as well as integrated stratigraphic research on over 30 exploration or production wells including Jiaoye 1, 4, 7, 8, Wuxi 1, 2, Wei 202, 203, 204, and Ning 211. The national-scale distribution prediction of shale condensate and wet gas resources provides crucial basis for formulating or adjusting China' s shale oil and gas industrial development strategy. Future research will focus on phase transformation behavior and control technologies for shale condensate gas to support efficient development.

The precise van der Waals force field, compared with traditional classical force fields, more accurately predicts gas densities under various pressures and adsorption performance in several microporous materials, providing an advanced and reliable theoretical method for such studies. Since atomic types in this force field were designed for common elements in kerogen, it can predict methane storage capacity in kerogen and further establish foundation for predicting shale gas reserves.

The computational simulation software suite can predict and evaluate reservoir fracturing, directly serving optimization of fracturing design in industrial shale gas development and breaking foreign software monopolies in China's fracturing industry. Near-bit imaging geosteering technology integrates both geometric and geological steering functions with zero measurement lag, making it suitable for thin and ultra-thin layer geosteering and poised to play important roles in future unconventional, deep, and offshore oil and gas exploration.

The deep reservoir in-situ stress testing instrument advances testing technology for deep shale reservoirs, completing technical reserves that meet national strategic needs in shale gas exploration and development.

Moving forward, China' s unique geological conditions require development of a complete theoretical system, key technologies, supporting equipment, and software series for shale gas exploration and development to drive overall advancement of related disciplines. The program urgently needs to conduct field testing and validation of these technologies and methods through close collaboration with domestic oil and gas industry departments on sweet spot evaluation, horizontal well design and drilling, and fracturing design optimization, aiming to establish demonstration areas for well site trials that promote localization of shale gas industry software and hardware and break foreign technology monopolies.

Note: Figure translations are in progress. See original paper for figures.