



Study on Geological Characteristics of Tight Reservoir and Adaptability of High Efficiency Development Technology

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ABSTRACT

This paper systematically analyzes the geological characteristics of tight reservoirs, including structural characteristics, sedimentary characteristics, reservoir characteristics, formation pressure and fluid characteristics and temperature field characteristics. The study shows that the distribution of tight reservoirs is significantly influenced by the tectonic environment and sedimentary facies belt, and the reservoirs are characterized by low porosity and permeability, strong heterogeneity and complex pore structure. At the same time, the properties of crude oil are complex and abnormal formation pressure is common. On this basis, this paper constructs a technical system for efficient development of tight reservoirs, covering key technologies such as reservoir evaluation, fracturing reconstruction, displacement technology, numerical simulation and real-time monitoring, and establishes an evaluation index system for technical adaptability from three aspects of reservoir conditions, development effect and economy, and realizes dynamic optimization by coupling multiple methods. In view of the technical bottleneck in the development of tight reservoirs, some improvement directions and suggestions are put forward, such as optimization of reservoir reconstruction technology, improvement of displacement technology, real-time monitoring and dynamic regulation, and optimization of development scheme, in order to provide theoretical basis and technical support for the economic and efficient development of tight reservoirs.

KEYWORDS

High Efficiency Development Technology; Geological Characteristics; Tight Reservoir.

1. INTRODUCTION

In response to the rising global energy demand and the progressive depletion of conventional oil and gas reserves, greater emphasis has been placed on the exploration and development of unconventional resources. Tight oil, as a key component of these resources, is characterized by vast reserves and widespread distribution, making it a critical area for future growth in hydrocarbon reserves and production. However, the efficient development of tight reservoirs is hindered by their complex geological features, including low porosity, ultra-low permeability, and limited fluid mobility, which pose significant technical challenges.

Conventional oil and gas development theories and technologies often struggle to effectively address the challenges of tight reservoirs. Therefore, it is crucial to conduct in-depth research into the geological features of these reservoirs and explore efficient development methods tailored to their unique conditions. This study aims to systematically analyze the geological characteristics of tight reservoirs, uncovering their formation mechanisms, reservoir properties, and fluid distribution patterns. Based on these findings, the applicability of current development technologies is assessed,

optimization strategies are proposed, and targeted technical solutions are developed to support the economically viable and efficient exploitation of tight reservoirs.

2. ANALYSIS OF GEOLOGICAL CHARACTERISTICS OF TIGHT RESERVOIRS

Tight reservoir refers to the reservoir with low porosity and permeability, and it is difficult for crude oil to flow effectively by natural energy in the reservoir [1]. Its compactness mainly comes from the mineral composition, particle size and cementation of rocks, which leads to the occurrence of crude oil in tiny pores and throats, which is significantly different from traditional conventional reservoirs in reservoir physical properties.

2.1. Tectonic characteristics

Tight reservoirs can be formed in a variety of structural environments, such as fault basins, depression basins and foreland basins. Under different structural backgrounds, the distribution law and scale of tight reservoirs are different [2]. For example, in faulted basins, it is often developed in deep lacustrine sedimentary areas, controlled by boundary faults, and the distribution of oil reservoirs is closely related to the structural subsidence center; In the foreland basin, it is mostly distributed in specific structural parts such as thrust belt or foredeep slope belt.

The structural amplitude is relatively small, and the change of stratum dip angle is larger than that in [3]. The fracture system is complex, including not only inherited large fractures, but also a large number of associated small fractures and micro-cracks. These faults have affected the connectivity and hydrocarbon migration path of tight reservoirs to some extent, and also provided potential seepage channels and favorable orientation for fracturing reconstruction for later development.

2.2. Sedimentary characteristics

Tight reservoirs are mostly developed in specific sedimentary facies zones, such as deep lake-semi-deep lake facies, delta front facies and specific microfacies of river facies. Deep-semi-deep lacustrine sedimentary tight reservoirs are mainly composed of mudstone and shale mixed with thin silty sandstone, which are rich in organic matter and have excellent hydrocarbon generation conditions, and sandstone lenses often become places where tight oil is enriched; The tight reservoir of delta front facies has the characteristics of multi-stage sand body superposition, with stable lateral distribution of sand bodies but strong vertical heterogeneity, and frequent development of argillaceous interlayer, which plays a certain role in shielding and separating the vertical migration and distribution of oil and gas [4]. The composition of rocks and minerals is complex, mainly composed of quartz, feldspar and rock debris, and the difference is obvious in different regions. Generally speaking, the structural maturity is relatively low, the particle sorting is poor, and the roundness is mostly sub angular sub circular. Such petrological characteristics lead to complex pore structure and various types of micro pores, including primary intergranular pores, secondary dissolution pores and microfractures, and the pore size distribution is uneven, which is generally characterized by low porosity and low permeability.

2.3. Reservoir characteristics

Porosity is usually low, generally between 2% and 12%, and most of them are less than 10%. The permeability is extremely low, mostly in the range of $(0.01-1) \times 10^{-3} \mu\text{m}$, which belongs to a typical tight reservoir [5]. Such low porosity and permeability make the seepage speed of oil and gas in the reservoir slow, and it is difficult to use reserves effectively by conventional mining methods. It is necessary to rely on special development technologies and processes to improve oil and gas recovery.

The pore structure is mainly micro-nano pores, and the throat is narrow and curved. According to the capillary pressure curve and mercury injection analysis, the median pore radius is small and the displacement pressure is high, indicating that oil and gas need to overcome large capillary resistance when entering the reservoir [6]. The types of throat are mostly sheet, bent sheet or tube bundle. This complex pore structure further increases the difficulty of oil and gas migration and exploitation, but it also provides a certain space for oil and gas storage.

It has strong heterogeneity, including intralayer heterogeneity, interlayer heterogeneity and plane heterogeneity. Intra-layer heterogeneity is marked by significant vertical variations in lithology and physical properties, such as differences in sandstone thickness and reservoir quality caused by rhythmic layering. Inter-layer heterogeneity refers to the contrasts in lithology, reservoir properties, and oil saturation among sand bodies formed in different sedimentary stages, with varying degrees of interlayer development. Planar heterogeneity manifests as spatial variations in the distribution, thickness, and property parameters across a horizontal plane, which are primarily influenced by factors such as sedimentary facies belts and paleogeomorphological features.

2.4. Formation pressure and fluid characteristics

Formation pressure is generally high, and abnormal pressure phenomenon is common. The formation mechanism of abnormal high pressure is mainly related to hydrocarbon generation, hydrothermal pressurization and regional tectonic stress [7]. Higher formation pressure is beneficial to the preservation and accumulation of oil and gas to a certain extent, but it also increases the safety risks in the process of drilling and development, such as increasing the difficulty of well control and prone to lost circulation.

Crude oil exhibits significant variation in properties and is typically characterized by high density, high viscosity, elevated wax content, and low sulfur levels. Its density generally ranges from 0.8 to 1.0 g/cm³, with viscosity spanning from tens to hundreds of millipascals. The wax content often falls between 10% and 30%, causing the oil to solidify easily at low temperatures, thereby complicating extraction and transportation processes [8]. Additionally, formation water is marked by high salinity and diverse types, commonly classified as CaCl₂ or Na₂SO₄. The interaction between this water and crude oil is complex, significantly influencing both hydrocarbon production and reservoir stability [9].

2.5. Temperature field characteristics

The temperature distribution in tight reservoirs is primarily influenced by burial depth and the local geothermal gradient, which varies across regions, typically ranging from 2.5 to 4.0°C per 100 meters. As depth and temperature increase, the thermal regime affects key physical properties of crude oil, such as its viscosity and volume coefficient. This, in turn, plays a crucial role in the movement, accumulation, and flow behavior of hydrocarbons during production. Elevated temperatures generally reduce oil viscosity, enhancing fluid mobility and improving extraction efficiency. However, high temperatures can also accelerate the diagenesis of reservoir rocks, potentially leading to a deterioration of the pore structure and reduced permeability.

3. EFFICIENT DEVELOPMENT TECHNOLOGY SYSTEM AND ADAPTABILITY ANALYSIS

3.1. Classification and principle of development technology

The technical system for efficient development of tight reservoirs is based on multi-scale geological characteristics analysis, combined with reservoir reconstruction and fluid displacement optimization,

forming a technical chain covering the whole life cycle. The main technical classification and principle are shown in Table 1 below.

Table 1 Classification and principle of main technologies

Technology category	Core technology principle	Application scenario
Reservoir evaluation technology	Based on multi-scale (micron-nanometer) pore structure characterization, dynamic seepage field monitoring and stress sensitivity evaluation [10]	Reservoir classification and desert area optimization
Fracturing reconstruction technology	Multi-stage fracturing of horizontal wells (nano-modified fracturing fluid and fracture network formation control)	Productivity improvement of low permeability reservoir
Displacement technology	Gas drive (co/n drive), water drive cooperative displacement and intermittent gas injection (huff-n-puff) [11]	Efficient production of microscopic remaining oil
Numerical simulation technology	Intelligent unstructured PEBI mesh generation and multi-field coupling simulation [12]	Optimization of development scheme and capacity prediction
Real-time monitoring technology	Nuclear magnetic resonance online displacement, microseismic monitoring and optical fiber sensing [13]	Evaluation of fracturing effect and dynamic regulation

Among them, reservoir evaluation technology guides the optimization of desert area through multi-scale pore structure and stress sensitivity analysis, fracturing reconstruction technology improves the productivity of low-permeability reservoir by multi-stage fracturing of horizontal wells, displacement technology improves the production rate of micro remaining oil by gas drive, water drive coordination and intermittent gas injection, numerical simulation technology relies on smart grid and multi-field coupling to optimize development scheme, and real-time monitoring technology realizes dynamic regulation and fracturing effect evaluation through nuclear magnetic resonance, microseismic and optical fiber sensing.

3.2. Evaluation index system of technical adaptability

The technical adaptability evaluation system is constructed from three aspects: reservoir conditions, development effect and economy (as shown in Table 2), covering indicators reflecting reservoir seepage and oil displacement potential, such as permeability, porosity, movable oil saturation and starting pressure gradient, as well as parameters for evaluating development effect, such as single well production, oil recovery, fracturing conductivity and water cut increase rate, and taking into account economic indicators such as single well cost, internal rate of return and energy consumption per ton of oil, so as to realize comprehensive evaluation of technical feasibility and economic benefits.

Table 2 Construction of evaluation index from three dimensions: reservoir conditions, development effect and economy

Evaluation dimension	Core indicators	Definition and significance of indicators
Reservoir conditions	Permeability, porosity, movable oil saturation, real starting pressure gradient	Reflect reservoir seepage capacity and oil displacement potential
Development effect	Single well production, oil recovery, fracturing conductivity, water cut increase rate	Evaluate the contribution of technology to productivity improvement.
Economy	Single well cost, internal rate of return, energy consumption per ton of oil	Balance technical feasibility and economic benefits

3.3. Adaptability evaluation method

Multi-method coupling is used to realize dynamic optimization, which mainly includes establishing multi-field coupling model by numerical simulation to predict the development effect; Experimental analysis method optimizes injection parameters through core displacement experiments, such as CO₂ driving the recovery rate of micro remaining oil to increase by 20%; The comprehensive index method is used to construct a classification model to guide the selection of development methods. For example, volume fracturing+gas drive is preferred for Class I reservoirs; As well as dynamic monitoring and feedback technology, micro-seismic and optical fiber sensing are used to adjust fracturing and injection-production parameters in real time to improve development efficiency.

4. TECHNICAL CHALLENGES AND COUNTERMEASURES

4.1. Main technical bottlenecks

4.1.1. Reservoir complexity

Tight reservoirs are characterized by low porosity and permeability, strong heterogeneity and complex pore structure, with low porosity (2%~12%), extremely low permeability ($0.01 \sim 1 \times 10^{-3} \mu\text{m}^2$), slow seepage velocity and frequent changes in lithology and physical properties, which make it difficult to produce reserves, and it is difficult to overcome large capillary resistance during exploitation.

4.1.2. Complex fluid characteristics

The fluid characteristics of tight reservoirs are complex, with high crude oil density (0.8~1.0g/cm³), large viscosity changes (tens to hundreds of MPA · s), high wax content (10%~30%), easy solidification at low temperature, and difficult to develop and collect; At the same time, formation water has high salinity, diverse water types and complex interaction with crude oil, which affects oil production efficiency and reservoir stability.

4.1.3. Structure and formation pressure

In terms of structure and formation pressure, tight reservoirs are often accompanied by complex fracture systems, including large fractures and a large number of small fractures and micro-fractures, which affect reservoir connectivity and development stability; At the same time, abnormal high pressure generally exists, which increases the drilling safety risk and easily leads to accidents such as lost circulation and blowout.

4.1.4. Limitation of development technology

There are still limitations in developing technology. Reservoir fracturing is difficult, and fracture control is difficult due to complex pore structure and strong heterogeneity. Displacement technology has limited effect on micro-remaining oil production and low oil recovery; The real-time monitoring and control technology is also facing the challenge of insufficient precision and real-time performance.

4.2. Improvement direction and suggestions

4.2.1. Optimization of reservoir reconstruction technology

Nano-materials are used to modify fracturing fluid, which can improve the sand carrying capacity and fracture conductivity of fracturing fluid, reduce the damage of fracturing fluid to reservoir and enhance the fracturing effect. Combining geological modeling and real-time monitoring data, optimize fracturing design, realize accurate control of fracture network, improve the connectivity between fractures and reservoirs, and improve the productivity of low permeability reservoirs. Multi-stage fracturing and staged fracturing technology are adopted in horizontal wells, and differential reconstruction is carried out according to the reservoir characteristics of different sections to improve the overall reconstruction effect.

4.2.2. Improvement of displacement technology

Optimize the synergistic displacement scheme of gas drive (such as CO₂/N₂ drive) and water drive, improve the production efficiency of micro remaining oil and increase recovery efficiency by adjusting injection parameters and sequence. Develop new displacement agents with high displacement performance, such as surfactant composite displacement agents, to reduce oil-water interfacial tension and improve displacement effect. According to the reservoir geological characteristics and development stage, the combination of intermittent gas injection (huff-n-puff) and continuous gas injection is flexibly used to improve the displacement efficiency and economic benefits.

4.2.3. Real-time monitoring and dynamic control

Combined with nuclear magnetic resonance, microseismic monitoring and optical fiber sensing technology, the real-time monitoring of fracturing effect, fracture propagation and fluid flow can be realized, and high-precision dynamic data can be provided. Based on real-time monitoring data, an intelligent control system is developed to realize dynamic optimization and adjustment of injection-production parameters and fracturing parameters, and improve development efficiency and economic benefits. Using big data analysis and artificial intelligence technology, the monitoring data are deeply mined and analyzed to assist development decision-making and optimize development scheme.

4.2.4. Optimization of development scheme

A numerical simulation model considering the coupling of geology, fluid, temperature and pressure is established to accurately predict the development effect, optimize the development plan and reduce the development risk. Using reservoir evaluation technology, combined with multi-scale pore structure characterization and stress sensitivity analysis, dessert area can be accurately identified, resources can be concentrated for development, and development benefits can be improved. In the process of making development plan, technical adaptability, development effect and economy are comprehensively considered, and dynamic optimization is carried out through multi-method coupling (numerical simulation, experimental analysis, comprehensive index method, etc.) to ensure the feasibility and economy of development plan.

4.2.5. Basic research and technological innovation

The formation mechanism, reservoir characteristics and fluid occurrence state of tight reservoirs are deeply studied, which provides theoretical basis for the optimization of development technology.

Encourage the development and application of new technologies, new materials and new processes, promote the innovation and integration of tight reservoir development technology, and improve the development technology level. Enhance collaboration among universities, research institutions, and enterprises to establish an integrated industry-university-research innovation model. This approach aims to accelerate the practical application of technological advancements and drive continuous improvement in the development technologies for tight reservoirs.

5. CONCLUSION

Through the systematic analysis of the geological characteristics of tight reservoirs, this study reveals the reservoir-forming mechanism, reservoir characteristics and fluid occurrence state. Tight reservoirs are characterized by low porosity and permeability, strong heterogeneity and complex pore structure, and the formation pressure is high, abnormal pressure is common, and the properties of crude oil are quite different. The temperature field is controlled by burial depth and geothermal gradient. The adaptability of development technology in tight reservoirs is evaluated, and it is found that the existing development technology has some limitations in reservoir evaluation, fracturing transformation, displacement, numerical simulation and real-time monitoring. In order to improve the development effect, a series of improvement suggestions are put forward, including optimizing reservoir reconstruction technology, improving displacement technology, strengthening real-time monitoring and dynamic regulation, optimizing development scheme, and basic research and technological innovation. The research shows that the combination of nano-material modified fracturing fluid, multi-stage fracturing and staged fracturing, gas flooding and water flooding cooperative displacement, real-time monitoring and intelligent control system can effectively improve the oil recovery and economic benefits of tight reservoirs. At the same time, it is the key to realize the efficient development of tight reservoirs to establish a multi-field coupled numerical simulation model, accurately identify the dessert area, comprehensively consider the technical adaptability, development effect and economy, and conduct dynamic optimization.

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