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From Micro-Pore Structure to Macro-Logging Response: Integrated Mechanisms of Low-Resistance Oil and Gas Reservoir Formation and Precise Identification

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Abstract

Low-resistance oil and gas reservoirs, characterized by their high concealment and significant exploration potential, are specialized reservoirs whose identification accuracy directly impacts the efficiency of hydrocarbon resource exploration and development. This paper systematically elucidates the core genesis mechanisms of low-resistance reservoirs by examining the intrinsic characteristics of micro-pore structures, revealing the coupling relationship between intrinsic factors such as micro-pore systems and mineral composition and macro-logging responses. It comprehensively reviews response patterns of conventional logging, array logging, and nuclear magnetic resonance logging techniques, summarizing core methodologies such as Fisher diagramming, intersection mapping, and neural network identification. This establishes an integrated technical framework linking "genetic mechanisms – logging responses – identification models." Research indicates that at the microscopic scale, high bound water saturation, additional conductivity from clay minerals, and complex pore structures are the primary internal factors governing low-resistance formation. Macro-scale manifestations include reduced resistivity and weakened differentiation in logging curve responses. Multi-technique integration and identification methods guided by dominant genesis mechanisms can significantly enhance recognition accuracy. This paper provides theoretical support and technical references for the precise evaluation of low-resistance hydrocarbon reservoirs, holding significant implications for expanding the scope of oil and gas exploration.

Keywords

low-resistance Oil and Gas Reservoirs; Micro-pore Structure; Genesis Mechanism; Logging Response; Precise Identification; Integrated Technology.

1. Introduction

Low-resistance oil and gas reservoirs refer to hydrocarbon-bearing reservoirs with resistivity comparable to adjacent water layers, a resistivity increase rate ≤3 (typically 3Ω·m~1000Ω·m), and minimal resistivity difference from surrounding rock. Such reservoirs are widely distributed in major Chinese oil and gas production areas such as the Junggar Basin, Dagang-Banqiao, and Jidong Coastal Plain. Due to their strong concealment, complex genesis, and atypical logging response characteristics, they are often misinterpreted as water layers, leading to resource loss. As oil and gas exploration extends into low-porosity, low-permeability reservoirs with complex lithologies, the exploration value of low-resistivity oil and gas layers has become increasingly prominent. Their genesis mechanisms and precise identification techniques have emerged as research hotspots in petroleum geology and logging engineering.

Traditional studies have predominantly focused on isolated aspects such as genesis analysis or single logging identification methods, lacking a systematic interpretation of the intrinsic relationship between "micro-pore structure and macro-logging response." This results in identification models with poor adaptability and accuracy that fails to meet practical demands. Building upon recent core research achievements worldwide, this paper adopts a micro-pore structure approach to establish a logical chain linking “micro-genesis – macro-response – integrated identification.” It systematically reviews the formation mechanisms, logging response patterns, and precise identification techniques for low-resistance oil and gas layers, constructing a multidimensional, multi-level integrated evaluation system to provide scientific basis for the exploration and development of complex reservoirs. [1-3]

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2. Mechanisms of Low-Resistance Reservoir Formation: Micro-Essence and Macro-Manifestation

The formation of low-resistance reservoirs results from the combined effects of intrinsic factors—such as micro-pore structure and mineral composition—and extrinsic conditions—including depositional environment and drilling fluid intrusion. The evolution of micro-pore system characteristics constitutes the core mechanism driving resistivity reduction, while macro-geological conditions indirectly influence reservoir conductivity by regulating micro-parameters.

2.1. Microscopic Mechanisms: Core Control by Pore Structure and Mineral Composition

2.1.1. Complex Pore Structure and High Bound Water Saturation

The complexity of microscopic pore structure is the primary intrinsic factor in low-resistance reservoir formation. Low-resistance reservoirs predominantly develop a dual pore system of “flooding pores - micropores,” where micropores (radius < 0.1 μm) significantly increase in proportion. Mercury porosity analysis reveals a bimodal distribution of throat radii (peaking around 0.1 μm and 2.0–10.0 μm). This structure increases the reservoir's specific surface area and significantly elevates bound water saturation. While vast quantities of bound water in micropores cannot participate in fluid flow, they form continuous conductive pathways, enhancing the reservoir's overall electrical conductivity and reducing its resistivity. Studies indicate that when bound water saturation exceeds 40%, reservoir resistivity can decrease by over 30%. This low-resistance characteristic becomes more pronounced as the proportion of microporosity increases.

2.1.2. Additional Conductivity Effect of Clay Minerals

The type and content of clay minerals critically influence reservoir conductivity. Low-resistance reservoirs typically exhibit high clay content, with expansive clay minerals like montmorillonite and illite dominating. These minerals possess high cation exchange capacity (CEC), and their exchangeable surface cations form additional conductive pathways under electric fields, significantly reducing reservoir resistivity. For instance, when montmorillonite content exceeds 15%, cation exchange capacity can reach 10–20 meq/100g, with additional conductivity contributions surpassing 40%. Furthermore, the distribution morphology of clay minerals affects conductivity efficiency—dispersed clay forms continuous conductive networks more readily than film-like or bridged distributions, intensifying low-resistance effects.

2.1.3. Enrichment of Conductive Autogenous Minerals

Certain low-resistance reservoirs develop conductive autogenous minerals like pyrite and siderite due to unique depositional environments. These minerals exhibit excellent conductivity, significantly reducing reservoir resistivity even at trace concentrations. For example, in certain low-resistance oil layers of the Junggar Basin, pyrite content ranges from

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just 2% to 5%, yet it reduces reservoir resistivity by over 50%, making it a key factor in low-resistance formation. The distribution characteristics of conductive minerals are equally important: dispersed or thin-film distributions readily form conductive pathways, while patchy distributions have a relatively weaker impact. [2-6]

2.2. Macro-Control Factors: Indirect Influence of Geological Environment and External Conditions

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2.2.1. Sedimentary and Diagenetic Environments

Low-resistance hydrocarbon reservoirs predominantly form in weakly hydrodynamic sedimentary environments, such as shallow lakes, semi-deep lakes, and the foredunes of river deltas. In these settings, sediments consist of fine-grained particles (predominantly silt) with high clay content, providing the material basis for the development of microporosity and the enrichment of clay minerals. During diagenesis, compaction reduces porosity and increases microporosity, while cementation may promote clay mineral cement formation, further intensifying low-resistance effects. Moderate dissolution, however, can create secondary porosity that mitigates low-resistance characteristics.

2.2.2. Formation Water and Drilling Fluid Conditions

Highly mineralized formation water is a key external factor in low-resistance formation—increased mineralization reduces fluid resistivity, enhancing overall reservoir conductivity. This effect is particularly pronounced in microporous reservoirs, where highly mineralized bound water exhibits significant conductive properties. Additionally, under saline drilling fluid conditions, borehole collapse and mud filtrate intrusion alter near-wellbore fluid properties, causing logging response distortion manifested as abnormal resistivity decreases, thereby increasing identification difficulty.

2.2.3. Thin Sandstone-Shale Interbedding Effect

In zones with thin sandstone-shale interbedding, where sand layers are thinner than the logging resolution, logging curves are influenced by the high conductivity of shales. This leads to underestimation of sandstone reservoir resistivity, creating a “false low-resistivity” phenomenon. Identifying such low-resistivity oil and gas layers requires combining high-resolution logging techniques with sequence stratigraphic analysis to eliminate interference from thin interbedding.

3. Macro-Logging Response Patterns of Low-Resistance Oil and Gas Zones

Differences in micro-pore structure and mineral composition ultimately manifest in macro-logging curves. The core logging response characteristics of low-resistance oil and gas zones are “reduced resistivity and weakened response differentiation.” However, reservoirs of different genesis types still exhibit specific patterns across various logging suites.

3.1. Conventional Logging Response Characteristics

3.1.1. Resistivity Logging

The most prominent feature of low-resistivity oil and gas layers is that both the lateral deep resistivity (LLD) and induced deep resistivity (ILD) are lower than those of conventional oil and gas layers, with minimal difference from adjacent water layers. The resistivity increase rate is ≤3. Response variations exist among reservoirs with different fluid types: water layers exhibit significantly lower ILD than LLD, with pronounced negative array-induced resistivity anomalies; gas layers exhibit near-equal deep lateral and deep induced resistivity values, sometimes even showing positive anomalies. Furthermore, resistivity curves for low-resistivity oil and gas layers display diverse morphologies, commonly including stepped, “mountain-

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shaped," and uniform patterns. Quantitative parameters such as the fullness coefficient (RAD) and ellipticity (RAT) can assist in their identification.

3.1.2. Triple Porosity Logging

Acoustic time difference (AC) exhibits moderate to elevated values, reflecting reduced rock matrix compactness due to microporosity development. Density porosity (DEN) increases while neutron porosity (CNL) decreases, forming a characteristic combination of "high acoustic-density porosity and low neutron porosity." In natural gas layers, P-wave velocity decreases significantly while S-wave velocity remains largely unaffected. This causes the S/P time difference ratio to deviate from the constant range, serving as a key indicator for gas layer identification.

3.1.3. Self-Potential (SP) and Gamma Ray (GR)

Natural potential typically exhibits small positive or negative anomalies, particularly under saline mud conditions where anomaly amplitudes further diminish. Optimizing mud properties is essential to enhance the interpretive value of natural potential data. Natural gamma values range from moderate to elevated, reflecting high clay content in the reservoir. These values correlate positively with clay content, allowing calculation of clay parameters from natural gamma curves to assist in identifying causes of low resistivity.

3.2. Special Logging Response Characteristics

3.2.1. Array Induced Polarization Logging

Array IP logging effectively distinguishes fluid properties and intrusion characteristics through multi-depth curve combinations. Low-resistance water layers exhibit a distinct negative gradient where deep, intermediate, and shallow induced resistivity values decrease sequentially. Low-resistance oil layers show smaller resistivity differences with relatively flat curves. Gas layers may display a positive gradient, where deep induced resistivity is slightly higher than intermediate and shallow values. This technique effectively mitigates interference from intrusions in conventional resistivity logging, enhancing fluid identification accuracy.

3.2.2. Nuclear Magnetic Resonance Logging (NMR)

By exploiting differences in polarization time and diffusion coefficients between natural gas and water, low-resistance gas layers can be identified using dual-time-of-wait (TW) or differential spectroscopy methods. Theoretically, differential spectroscopy can cancel water signals while preserving gas signals; however, due to noise effects, quantitative evaluation requires integration with time-domain analysis (TDA) technology. For low-resistance oil layers with highly confined water, NMR logging directly provides confined water saturation data, offering core parameter support for identification. Additionally, NMR logging distinguishes contributions from flow pores and micro-pores, revealing micro-pore structure characteristics and providing evidence for genesis mechanism analysis.

3.2.3. Dipole Shear Wave Logging (XMAC)

Low-resistance gas layers can be effectively identified through cross-plots of P-wave and S-wave velocities or Poisson's ratio versus Young's modulus. Low-resistance gas layers exhibit significantly reduced Poisson's ratios and moderate Young's moduli, clearly distinguishing them from oil and water layers. Conversely, low-resistance oil layers display Poisson's ratios and Young's moduli intermediate between gas and water layers, requiring comprehensive interpretation alongside other logging curves. This technique offers unique advantages for fluid identification in complex lithological low-resistance reservoirs.

3.3. Coupling Relationships in Logging Responses

Macroscopic logging responses of low-resistance oil and gas layers reflect the combined effects of microscopic pore structure and mineral composition:

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- Microscopically: Microporosity development → Increased bound water saturation → Enhanced conductivity → Reduced macroscopic resistivity; clay mineral enrichment → increased cation exchange capacity → additional conductivity → further reduced resistivity. This "micro-parameter - macro-response" coupling relationship provides the theoretical foundation for genesis mechanism inversion and identification model construction. Specifically, macro-log responses are used to infer micro-genesis, followed by selecting targeted identification methods based on the identified genesis type. [7-11]

4. Precision Identification Techniques for Low-Resistance Hydrocarbon Reservoirs

Precise identification of low-resistance hydrocarbon reservoirs requires a clear understanding of genesis mechanisms. Adopting an integrated approach of "genetic-driven orientation + multi-technique fusion," appropriate identification methods should be selected based on geological conditions and logging data characteristics.

4.1. Conventional Identification Methods

4.1.1. Curve Morphology Analysis

Preliminary identification of low-resistance reservoirs is achieved by analyzing resistivity curve morphology (step-like, mountain-shaped, uniform) and quantitative parameters (RAD, RAT), combined with composite characteristics from natural gamma and triple porosity curves. For example, low-resistance oil layers in the Dongying Formation of the Gudu East Oilfield often exhibit uniform resistivity curves with RAD > 0.7 and RAT < 1.2. Combined with moderately high GR and elevated AC characteristics, this enables preliminary identification. While operationally simple, this method is highly subjective and requires validation against regional geological context.

4.1.2. Crossplot Method

Quantitative identification is achieved by constructing pairwise crossplots of logging parameters to amplify differences between oil and water layers. Common crossplots include: 1)Sonic Time-Differential vs. Deep-Induced Resistivity: Oil data points cluster in the "high time-differential - medium-low resistivity" zone, while water layers distribute in the "low time-differential - low resistivity" zone; 2) Neutron porosity versus density porosity cross-plot: gas layers exhibit a distinct "low neutron porosity - high density porosity" separation pattern; 3) LLD-SPR (Low-Lateral-Direction resistivity - Self-Potential) normalized cross-plot: low-resistivity oil layer data points deviate from the water layer clustering zone. In the Youquanzi Oilfield of the Qaidam Basin, using crossplots of lateral-to-sensing resistivity ratio versus acoustic traveltime, oil layers exhibit ratios <1.4 while water layers show ratios >1.6, achieving over 85% identification accuracy.

4.1.3. Fisher Diagram Method

Projecting multi-dimensional logging data (such as resistivity, acoustic travel time, neutron porosity, etc.) onto optimal linear directions enables multi-parameter integrated identification by maximizing separation between oil and water samples through variance analysis. This method is suitable for blocks with abundant logging data and complex reservoir types, requiring calibration of projection directions based on extensive well testing data to establish region-specific identification criteria. Following its implementation at Shinan Oilfield, the identification accuracy of low-resistance oil layers increased from 68% to 82%.

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4.2. Advanced Identification Techniques

4.2.1. Reservoir Parameter Interpretation Model Method

Based on regional geological characteristics, establish quantitative relationship models between reservoir parameters (e.g., clay content, porosity, confined water saturation) and logging data. Determine reservoir oil potential by applying parameter thresholds. For example, the Dangang Banqiao low-resistance reservoir established a three-dimensional model linking “shale content - bound water saturation - oil saturation.” Reservoirs meeting the criteria of 15%-30% shale content, 40%-60% bound water saturation, and >25% oil saturation were classified as effective low-resistance reservoirs. In the Jidong Coastal Oilfield, empirical equations linking model parameters m and n to clay content and pore structure index were derived from rock-electrical experiments. This optimizes Arch model calculations for oil saturation, enhancing evaluation accuracy for low-resistance reservoirs.

4.2.2. Quantitative Identification via Nuclear Magnetic Resonance Logging

Based on the T2 spectrum distribution characteristics from NMR logging, signals from mobile oil, confined water, and natural gas are differentiated. Low-resistance oil layers exhibit a “bimodal distribution” in the T2 spectrum: the confined water peak (T2 < 10 ms) accounts for 40%–60%, while the mobile oil peak (T2 = 10–100 ms) accounts for 20%–40%. Low-resistance gas layers exhibit a rightward shift in the T2 spectrum, with a prominent gas signal peak (T2 > 100 ms). Through dual-delay logging data processing and TDA analysis techniques, light hydrocarbon identification and quantitative oil saturation calculation are achievable. Application of this method in the Tabei area of Xinjiang achieved a 90% accuracy rate in identifying low-resistance gas layers.

4.2.3. Machine Learning Identification Method

Machine learning algorithms such as grey relational analysis and BP artificial neural networks integrate multi-source logging data to construct nonlinear identification models. BP neural networks learn logging response patterns of oil and water layers through training samples, automatically extracting feature parameters—suitable for geologically complex low-resistance reservoirs. The Quti Oilfield employed a “GR-AC-LLD-CNL” four-parameter BP neural network model, achieving 88% accuracy in low-resistance oil layer identification—significantly outperforming traditional methods. The Huzhuangji Oilfield combined grey correlation analysis with clustering algorithms to resolve identification challenges in thin interbedded sandstone-shale low-resistance oil layers.

4.3. Integrated Identification Technology System

Establish an integrated identification workflow: “Genetic Mechanism Analysis → Log Series Optimization → Parameter Modeling → Multi-method Validation”: 1)Determine micro-genetic mechanisms (e.g., high-bound water type, clay-enhanced conductivity type) through core experiments and thin section identification; 2) Optimize logging suites based on genesis type (e.g., NMR logging for high-bound water types, natural gamma and cation exchange capacity logging for clay types); 3) Develop targeted interpretation models (e.g., dual-water models for high-CEC reservoirs); 4) Employ cross-validation methods (intersection mapping, machine learning) to mitigate misidentification risks. Applied to Cretaceous low-resistance reservoirs in the Junggar Basin, this system elevated identification accuracy from 75% (traditional methods) to 92%, effectively confirming reserve volumes. [12-13]

5. Discussion

5.1. Core Technical Bottlenecks and Resolution Pathways

Current low-resistance reservoir identification faces three major bottlenecks: 1)Unclear quantitative coupling between micro-scale genesis and macro-scale response, leading to poor model adaptability; 2) Significant stacking effects in thin interbedded reservoirs with insufficient vertical resolution; 3) Fluid property identification is challenging under complex mineralization conditions. To address these issues, future breakthroughs should focus on three aspects: First, strengthen the integrated analysis of core experiments and logging data to establish a quantitative characterization model linking "micro-parameters and logging responses," enhancing model universality; Second, promote high-resolution array logging and imaging logging technologies combined with pre-stack inversion methods to improve vertical resolution for thin interbedded reservoirs; 3) Optimize differential spectral techniques and time-domain analysis methods for NMR logging to mitigate mineralization interference and enhance fluid signal identification.

5.2. Optimizing Identification Strategies for Reservoirs of Different Genesis Types

The genesis of low-resistance oil and gas layers exhibits significant regional variation, necessitating differentiated identification strategies tailored to dominant genesis mechanisms: 1)High-bound water type (e.g., Dagang Banqiao): Emphasize NMR logging-based bound water saturation calculations combined with mobile water analysis. Classify as effective reservoirs when mobile water saturation < 30% and oil saturation > 25%. 2) Clay-enhanced conductivity type (e.g., Liaohe Tanhai): Prioritize analysis of natural gamma and cation exchange capacity data, employing the W-S model to calculate oil saturation to avoid underestimation errors from the Archimedes model; 3) Thin sandstone-shale interbedding type (e.g., North Jiangsu Basin): Utilize high-resolution logging stratification techniques, integrating micro-layer plan views with regional structural correlation to eliminate shale interference.

5.3. Technological Development Trends

Future identification of low-resistance oil and gas reservoirs will evolve toward "multidisciplinary integration, intelligent upgrading, and integrated evaluation": 1)Deep integration of geological, logging, and laboratory data to construct three-dimensional visualization evaluation models; 2) Advanced application of artificial intelligence technologies, such as deep learning-based automatic extraction of logging curve features and intelligent classification of genesis types to enhance identification efficiency; 3) WDM and real-time interpretation technologies will enable rapid field identification of low-resistance reservoirs and sweet spot optimization, reducing exploration risks.

6. Conclusion

1. The formation of low-resistance hydrocarbon layers results from the combined effects of micro-pore structure and macro-geological conditions: Microscopically, high bound water saturation due to complex dual-pore systems and additional conductivity from clay minerals are core intrinsic factors; Macroscopically, depositional environments, highly mineralized formation water, and thin sandstone-shale interbedding are key controlling factors, often manifesting as multi-factor coupling dominated by primary genesis.

2. Macro-logging responses of low-resistance hydrocarbon reservoirs exhibit distinct characteristics: conventional logging shows reduced resistivity, weakened natural potential anomalies, and abnormal tri-porosity curve combinations. Specialized logging techniques—such as differential features in array induction logging, T2 spectrum distribution in nuclear

magnetic resonance logging, and the P/S ratio in dipole shear wave logging—effectively distinguish fluid properties, providing critical identification criteria.

3. Establishing an integrated identification system based on "genetic orientation and multi-technique fusion" is central to enhancing accuracy: Conventional methods (curve morphology analysis, intersection diagram analysis) are suitable for preliminary identification, while advanced techniques (quantitative NMR analysis, machine learning) improve recognition accuracy in complex reservoirs. Combining region-specific strategies with multi-method validation significantly reduces misidentification risks.

Future research should focus on: - Quantitative coupling of micro- and macro-parameters - Application of high-resolution logging techniques - AI-driven advancements These efforts will further refine the integrated evaluation system, providing more reliable technical support for efficient exploration and development of low-resistance oil and gas reservoirs.

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