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Mechanism and Application of Electrical Resistivity Responses in Annular

Adsorbed Water Films: Insights From Capillary Theory

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Abstract: In strongly water-wet low-resistivity oil reservoirs, hydrocarbons can displace most free water, but residual water may still remain as continuous or semi-continuous films on pore walls. These adsorbed water films, together with electrical double-layer and surface-conduction effects, may form effective conductive pathways and cause conventional Archie models to overestimate water saturation. However, the quantitative contribution of adsorbed film water to the resistivity response remains difficult to characterize. This study investigates low-resistivity oil reservoirs in the Lunnan area and develops a pore-scale constrained rock-electrical model for water-saturation evaluation. Lithological, clay-mineral, conductive-mineral, and wettability analyses show that the low-resistivity response is not mainly controlled by clay minerals or conductive minerals. Instead, the evidence points to connected bound-water films developed under strongly water-wet conditions as a major contributor to the anomalous conductivity. On this basis, a thermodynamic relationship between water-film thickness and pore-throat radius is established by balancing Young–Laplace capillary pressure with thin-film disjoining pressure. A coupled high-pressure mercury intrusion and nuclear magnetic resonance method is developed to separate capillary-bound water in fine pore throats from adsorbed film water retained on the walls of larger pores. High-pressure mercury intrusion constrains the pore-throat structure and the capillary-controlled immobile-water volume, whereas nuclear magnetic resonance provides the total bound-water saturation after centrifugation. The difference between the NMR-derived total bound water and the HPMI-constrained capillary-bound water is then used to quantify the adsorbed film-water content and invert an interfacial thermodynamic constant. Dynamic resistivity experiments are further incorporated to establish an electrical-double-layer-enhanced dual-network conductivity model and

determine the conductivity enhancement ratio and cutoff exponent. The proposed model explains the persistently low resistivity index observed at low water saturation and shows good agreement with oil-test interpretations when applied to logging data. This study provides a physically constrained approach for water-saturation evaluation in strongly water-wet low-resistivity reservoirs.

Keywords: low-resistivity oil reservoir; annular adsorbed water film; capillary theory; resistivity index; saturation correction

Highlights

1. A HPMI–NMR coupling method is established to quantitatively separate capillary-bound water in fine pore throats from adsorbed film water retained on strongly water-wet pore walls.
2. An interfacial thermodynamic constant is inverted from the quantified adsorbed film-water content, linking pore-throat structure, film-water thickness, and solid–liquid interaction strength.
3. An EDL-enhanced dual-network rock-electrical model is developed to incorporate adsorbed film-water conduction into water-saturation evaluation for low-resistivity reservoirs.

1 Introduction

The spatial distribution of multiphase fluids in porous media and its influence on macroscopic electrical transport properties constitute a fundamental problem in geophysics, seepage mechanics, and porous materials science (*Soldi et al., 2024; Markova et al., 2024*). In strongly water-wet rock systems characterized by micro- to nanoscale pore throats, interfacial effects, including capillary forces, van der Waals interactions, disjoining pressure, and electrical double-layer effects, can exert a profound control on the configuration of pore fluids (*Derjaguin et al., 1987; Hirasaki,*

1991; Yuan *et al.*, 2021; Norouzisadeh *et al.*, 2024; Amadu & Miadonye, 2024). When nonwetting phases such as oil and gas enter the pore space and displace formation water, the wetting-phase water is not completely expelled. Instead, it commonly remains in the pore system in two principal forms: one fraction is retained within fine pore throats as capillary-bound water, whereas another adheres to the walls of larger pores under the control of solid–liquid interfacial interactions, forming continuous or semi-continuous water films (Yuan *et al.*, 2021; Amadu & Miadonye, 2024; Wang & Revil, 2020; Archie, 1942; Waxman, 1968; Clavier *et al.*, 1984). For strongly water-wet rocks, such water films distributed along mineral grain surfaces not only exhibit a high degree of spatial connectivity, but may also be affected by electrical double-layer effects and surface ion enrichment, thereby forming additional conductive pathways distinct from those associated with bulk water (Markova *et al.*, 2024; Qi & Wu, 2022, 2025; Liu *et al.*, 2022). The resulting interfacial conduction can substantially modify current transmission paths within the pore network and cause the macroscopic resistivity response to deviate from predictions based on conventional rock-electrical models (Soldi *et al.*, 2024; Markova *et al.*, 2024; Qi & Wu, 2022, 2025; Liu *et al.*, 2022).

Accurately characterizing film-water-dominated electrical responses in strongly water-wet porous media remains a major challenge in contemporary rock-physics modeling. The classical Archie equation and its derivative models are fundamentally based on volumetric conduction through pore fluids and are generally applicable to conventional reservoirs with low clay contents, relatively simple pore structures, and weak interfacial conduction effects (Wang *et al.*, 2012). However, in strongly water-

wet fine-grained reservoirs or low-resistivity oil reservoirs with well-developed micro- to nanoscale pore throats, the connected conduction associated with pore-wall water films and bound water cannot be neglected. Conventional models therefore tend to underestimate the bulk electrical conductivity of the rock, resulting in an overestimation of water saturation. To address this issue, models such as the Waxman–Smits model and the dual-water model incorporate cation exchange capacity or clay-bound water conductivity terms to correct for the additional conductive effects induced by clay minerals (*Zhu et al., 2021; Xia et al., 2024*). In recent years, some studies have further attempted to integrate fractal geometry, characteristic pore-structure length scales, or effective medium theory to describe electrical transport behavior in complex pore systems. These approaches have, to some extent, improved rock-electrical interpretation in unconventional or structurally complex reservoirs. Nevertheless, their parameters often remain strongly empirical, and they lack an explicit representation of the geometric occurrence of film water, the interfacial thermodynamic controls, and the associated conductivity enhancement under strongly water-wet conditions. Therefore, quantitatively describing the contribution of film water to the macroscopic resistivity index, from the perspective of microscopic pore-throat structure and solid–liquid interfacial interactions, remains an important problem requiring further investigation.

These theoretical challenges are manifested most prominently in the difficulty of identifying low-resistivity oil reservoirs during deep hydrocarbon logging evaluation (*Li et al., 2007; Wang et al., 2023; Changwei et al., 2025; Deng, 2024; Hamada et al., 2001; Wang et al., 2024*). Extensive exploration practice has shown that some low-

resistivity oil-bearing intervals exhibit favorable hydrocarbon potential, yet display anomalously low resistivity responses and reduced resistivity indices. On conventional electrical logs, such intervals can therefore be easily confused with water-bearing zones or high-water-saturation layers, leading to missed or erroneous identification of hydrocarbon reservoirs. Previous studies have attributed the development of low-resistivity oil reservoirs to a range of factors, including fine-grained sedimentation, complex pore structures, clay-related excess conduction, conductive minerals, mud-filtrate invasion, and variations in formation-water salinity. However, for strongly water-wet reservoirs, even when the contents of clay minerals and highly conductive minerals are limited, residual water films along pore walls may still form an effective conductive network under favorable pore-throat connectivity, causing the reservoir to exhibit anomalously low resistivity under oil-bearing conditions. Conventional rock-electrical models based primarily on volumetric averaging are unable to adequately capture this microscopic conduction mechanism and may therefore misinterpret low-resistivity responses induced by film water and electrical double-layer conduction as high water saturation. Accordingly, re-examining the occurrence and conductive contribution of film water from the perspectives of microscopic capillary physics and interfacial thermodynamics provides an important pathway for explaining electrical anomalies in strongly water-wet, low-resistivity oil reservoirs. In this study, strongly water-wet, low-resistivity oil reservoirs in the Lunnan area are selected as the research target. On the basis of systematically evaluating potential low-resistivity controls, including lithology, clay minerals, conductive minerals, and wettability, particular

emphasis is placed on the microscopic occurrence of film water under strongly water-wet conditions and its influence on the electrical response of rocks. First, under the assumptions of equivalent capillaries and equilibrium water films, an interfacial thermodynamic expression relating water-film thickness to pore-throat radius is established based on the equilibrium between Young–Laplace capillary pressure and thin-film disjoining pressure. Second, high-pressure mercury intrusion and nuclear magnetic resonance measurements are integrated to distinguish the volumetric contributions of capillary water in fine pore throats and film water along macropore walls, and to invert a comprehensive surface physicochemical coefficient that characterizes the strength of solid–liquid interfacial interactions. Furthermore, dynamic resistivity measurements during core displacement are used to construct a dual-network rock-electrical response model that incorporates additional conduction associated with the electrical double layer, through which key parameters such as the conductivity enhancement ratio and cutoff structural exponent are inverted. Finally, the proposed model is embedded into the logging interpretation workflow to calculate water saturation in low-resistivity oil reservoirs and to compare the results with oil-test interpretations (*Wang et al., 2023; Changwei et al., 2025; Hamada et al., 2001; Wang et al., 2024; Guo et al., 2026*).

This study aims to establish a rock-electrical evaluation framework for low-resistivity oil reservoirs that is jointly constrained by pore-throat architecture, the occurrence state of bound water, and interfacial conductivity enhancement. By linking anomalous resistivity responses to microscopic fluid occurrence and solid–liquid

interfacial interactions, the proposed method provides a physically constrained basis for water-saturation estimation and quantitative logging evaluation in complex low-resistivity reservoirs.

2 Geological Setting and Origin of Low-Resistivity Responses

The Lunnan Oilfield is located on the Lunnan low uplift in the eastern part of the Tabei Uplift, within the central segment of the Lunnan fault-block belt. Characterized by complex structural deformation and strong reservoir heterogeneity, it represents one of the typical deep hydrocarbon exploration areas in the Tarim Basin (Figure 1) (Yang & Han, 2008; Zeng-Li et al., 2004). The oil-bearing intervals in the Lunnan well area are deeply buried, exhibit relatively favorable petrophysical properties, and contain comparatively high hydrocarbon abundance. Nevertheless, low-resistivity responses are widely developed in certain local intervals, where conventional logging crossplots and interpretation charts show limited effectiveness in distinguishing oil-bearing zones from water-bearing zones (Song et al., 2008; Changwei et al., 2025). To clarify the principal causes of the low-resistivity responses in the study area, this study integrates reservoir petrophysical properties, mineralogical composition, wettability measurements, oil-test results, and core experimental data to evaluate the potential influences of lithology, clay minerals, conductive minerals, and wettability on the observed resistivity anomalies. It should be noted that low-resistivity oil reservoirs are commonly controlled by multiple coupled factors. Therefore, the screening analysis presented here is intended primarily to assess the relative contribution of each factor

and to provide a geological basis for the subsequent investigation of film-water conduction mechanisms.

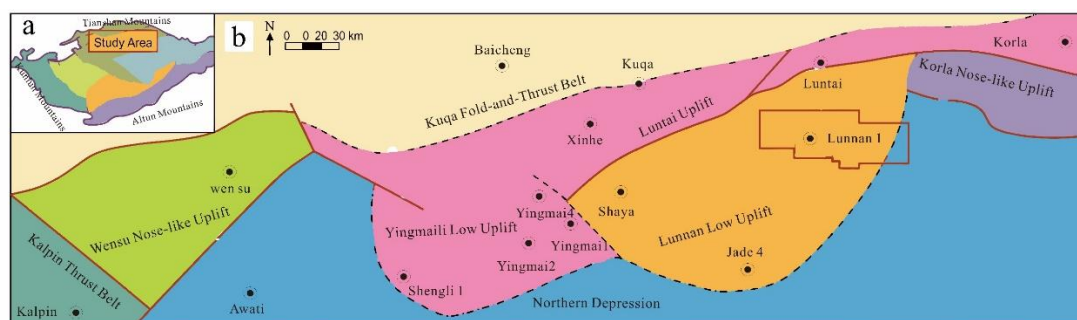


Figure 1 Geological Distribution Map of the Study Area

2.1 Lithological Characteristics

In general, the microscopic characteristics of reservoirs exert an important control on low-resistivity phenomena. Based on statistics from cored wells in the study area, a total of 13,749 core samples from 11 wells were collected and analyzed. The reservoir lithology is dominated by siltstone, with minor occurrences of fine sandstone and inequigranular conglomerate in local intervals.

Core analysis results indicate that reservoir porosity ranges from 10.9% to 26.9%, with a median value of 21.8%, a mean value of 21.31%, and a standard deviation of 3.91%. Overall, the reservoir exhibits moderate to relatively high porosity, although a certain degree of heterogeneity remains evident. Horizontal permeability ranges from 1.11 to 2653 mD, with a median value of 225 mD, a mean value of 384.82 mD, and a standard deviation of 504.82 mD. The mean permeability is markedly higher than the median value, indicating a right-skewed permeability distribution and substantial variability in reservoir flow capacity. Rock density ranges from 1.91 to 2.39 g/cm³, with a median value of 2.05 g/cm³, a mean value of 2.08 g/cm³, and a standard deviation of 0.11 g/cm³, suggesting a relatively concentrated distribution. Taken together, these

results indicate that the reservoirs in the study area are characterized by well-developed pore systems and relatively stable rock-matrix properties, but also by pronounced heterogeneity in flow capacity (Figure 2).

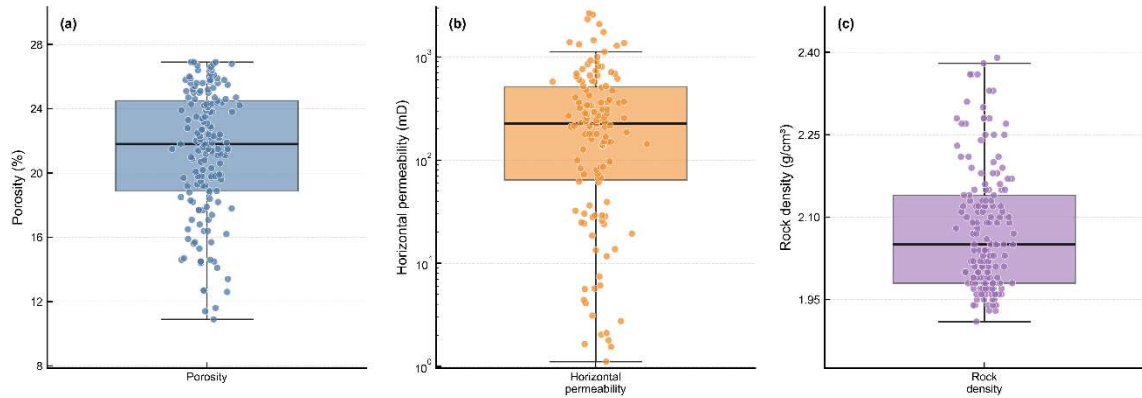


Figure 2 Core analysis diagram of the research area

2.2 Influence of Clay Mineral Content

Clay minerals can influence reservoir electrical properties by increasing the specific surface area of mineral grains, enhancing bound-water content, and introducing surface conduction. X-ray diffraction analysis of clay minerals (Figure 3) indicates that the overall clay mineral content in the studied intervals is relatively low, with an average total content of approximately 3.44%. Among these minerals, the mixed-layer C/S phase has the highest abundance, with an average content of 1.27%, whereas chlorite and illite have average contents of 1.03% and 1.02%, respectively. The mixed-layer I/S phase is the least abundant, with an average content of only 0.12%.

From the perspective of mineral composition, the clay mineral content in the study area is insufficient to independently account for the widely developed low-resistivity responses. Nevertheless, the surface-conduction capacity of clay minerals is also controlled by their spatial distribution, specific surface area, cation exchange capacity, and formation-water salinity. Therefore, interfacial conduction is still

considered as a potential source of excess conductivity in the model formulation presented below.

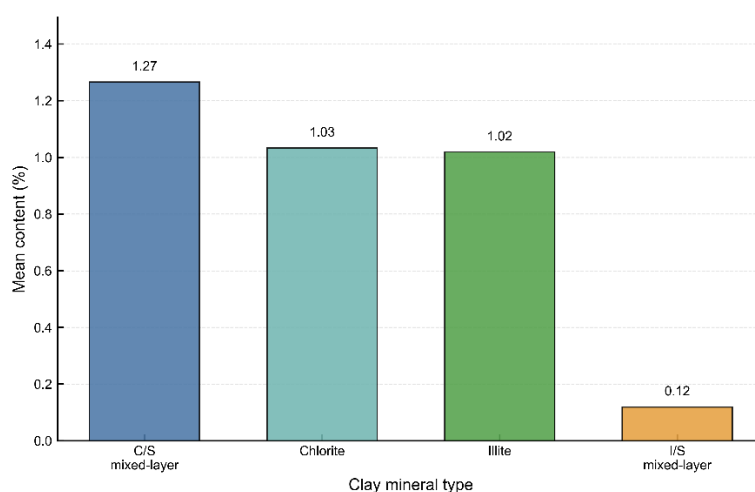


Figure 3 Histogram of clay mineral content distribution

2.3 Influence of Conductive Mineral Content

Conductive minerals possess a certain degree of electronic conductivity. When present in sufficiently high abundance and forming continuous networks at grain contacts or within pore spaces, they may enhance the bulk electrical conductivity of the reservoir and reduce logging resistivity. Heavy-mineral analysis results (Figure 4) show that the studied intervals are dominated by stable heavy minerals such as garnet, epidote, and zircon, with average contents of 26.37%, 17.32%, and 16.34%, respectively.

By contrast, minerals with strong electrical conductivity occur in relatively low abundance. The average contents of magnetite and pyrite are 1.79% and 0.89%, respectively. Although both are typical conductive minerals, their overall concentrations are limited and are unlikely to independently form regionally continuous conductive networks. Ilmenite has an average content of 11.35%; however, it generally exhibits weakly conductive or semiconductive behavior and is not regarded as a typical highly conductive mineral.

Overall, the abundance of strongly conductive minerals in the study area is relatively low. Although these minerals may exert localized effects on low-resistivity responses, they should not be considered the primary controlling factor responsible for the widespread low-resistivity characteristics observed in the study area.

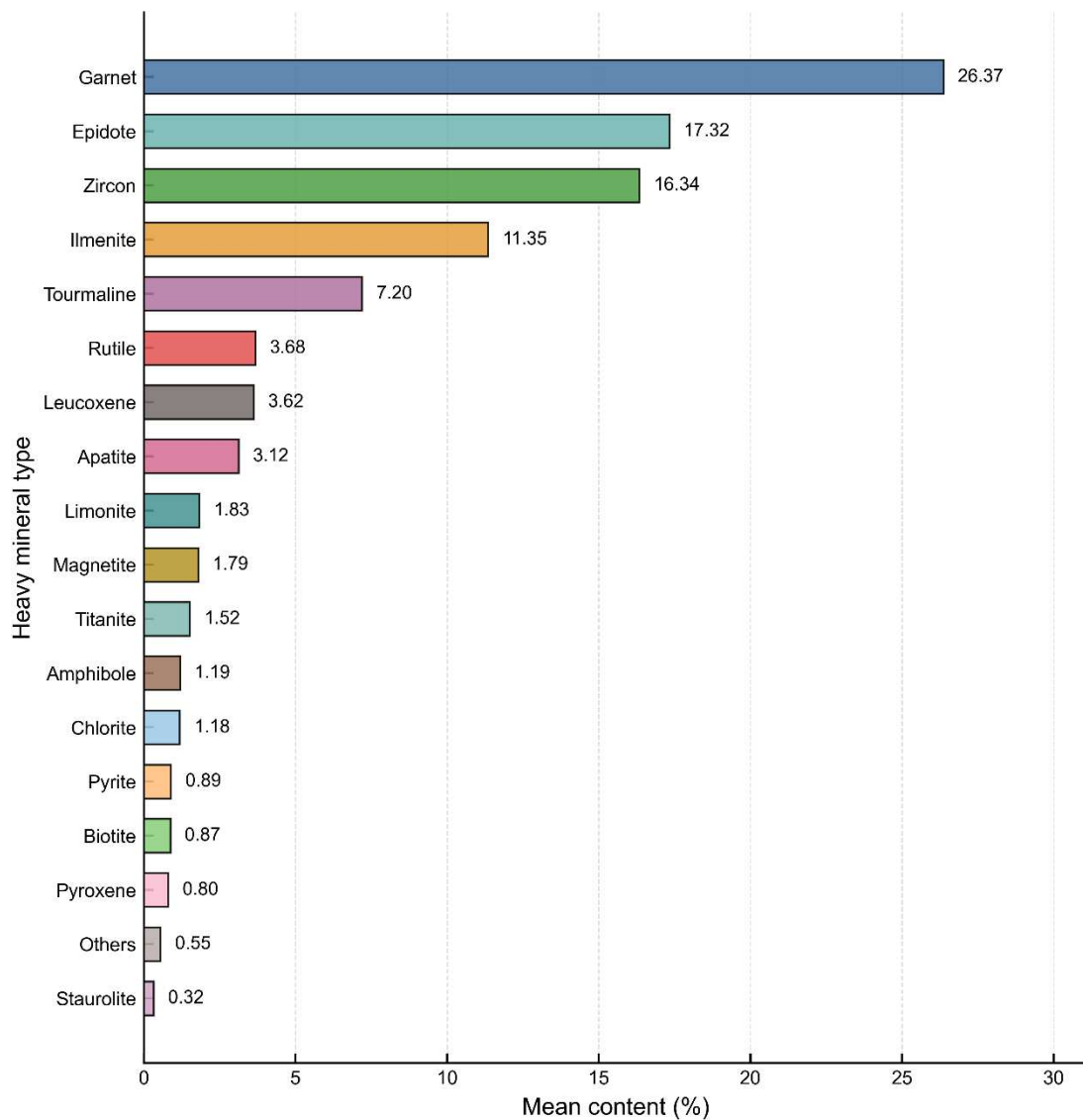


Figure 4 Histogram of Heavy Mineral Content Distribution

2.4 Influence of Rock Wettability

Rock wettability and pore structure exert important controls on the distribution of bound water and the conductive mechanisms of reservoirs. In water-wet to strongly water-wet rocks, the aqueous phase preferentially adheres to mineral grain surfaces and,

under favorable pore-throat connectivity, may form continuous or semi-continuous water-film networks. Such networks provide a potential pathway for excess conduction under low water-saturation conditions.

The E interval in the study area exhibits overall favorable reservoir properties, with pore systems and flow conditions that are conducive to the spatial connectivity of residual water films. Wettability analysis results (Table 1) show that the relative wettability indices of the rock samples from this interval are generally positive, indicating an overall water-wet to strongly water-wet character. This suggests a strong affinity of the mineral surfaces for the aqueous phase. Therefore, strong water wettability may constitute an important prerequisite for the low-resistivity responses observed in the study area.

Table 1 Report on Reservoir Wettability

Sample ID	Sampling Depth (m)	Stratigraphic Unit	Water-Wet Index	Oil-Wet Index	Relative Wettability Index	Wettability Type
W044	3473	E	0.94	0.1	0.84	Strongly water-wet
W047	3473.72	E	0.47	0	0.47	Water-wet
W048	3474.12	E	0.54	0	0.54	Water-wet
W050	3474.54	E	0.78	0	0.78	Strongly water-wet
W051	3474.82	E	0.92	0	0.92	Strongly water-wet
W052	3475.1	E	0.74	0	0.74	Strongly water-wet
W053	3475.24	E	0.79	0	0.79	Strongly water-wet
W054	3475.52	E	0.72	0	0.72	Strongly water-wet
W055	3475.88	E	0.21	0	0.21	Weakly water-wet
W056	3476.13	E	0.42	0	0.42	Water-wet

W057	3476.4	E	0.79	0.06	0.73	Strongly water-wet
W058	3476.64	E	0.97	0	0.97	Strongly water-wet
W059	3477.01	E	0.79	0	0.79	Strongly water-wet
W061	3478.2	E	0.32	0	0.32	Water-wet
W063	3478.65	E	0.94	0	0.94	Strongly water-wet

In summary, the low-resistivity response in the study area is not controlled by a single lithological factor. Analyses of lithological characteristics, clay mineral content, and conductive mineral abundance indicate that the contributions of these factors to the observed low-resistivity responses are relatively limited and are insufficient to independently explain the widespread low-resistivity characteristics of the reservoir. By contrast, the E interval exhibits pronounced water-wet to strongly water-wet behavior, implying a strong affinity of mineral grain surfaces for the aqueous phase. After substantial displacement of free water by hydrocarbons, a portion of bound water may still remain in the pore system as capillary water within fine pore throats and as film water along the walls of larger pores. These residual water phases may form continuous or semi-continuous conductive networks along mineral surfaces. Therefore, it is necessary to further examine the spatial distribution of bound water from the perspective of microscopic fluid occurrence and to evaluate its controlling effect on rock electrical conductivity.

3 Microscopic Fluid Occurrence and Conductive Mechanisms

3.1 Microscopic Occurrence State of Formation Water

The microscopic occurrence state of formation water has been extensively investigated in previous studies (Mu et al., 2023; Zou et al., 2020; Liu et al., 2025). At

present, fluids in rock pores are generally classified into three categories: free water, bound water, and hydrocarbons. Among them, bound water mainly occurs in two forms: capillary water and film water. Film water is typically adsorbed on mineral grain surfaces as an ultrathin water layer, whereas capillary water is controlled by capillary forces and commonly occurs as water columns within pores or fractures.

This study focuses on the oil-bearing state after free water has been sufficiently displaced by hydrocarbons. Under this condition, the content of free water is substantially reduced, and the residual water in the pore system is mainly present as capillary-bound water in fine pore throats and adsorbed film water along the walls of larger pores (Figure 5). Accordingly, the subsequent model formulation focuses on the volumetric contributions and conductive effects of these two types of bound water.

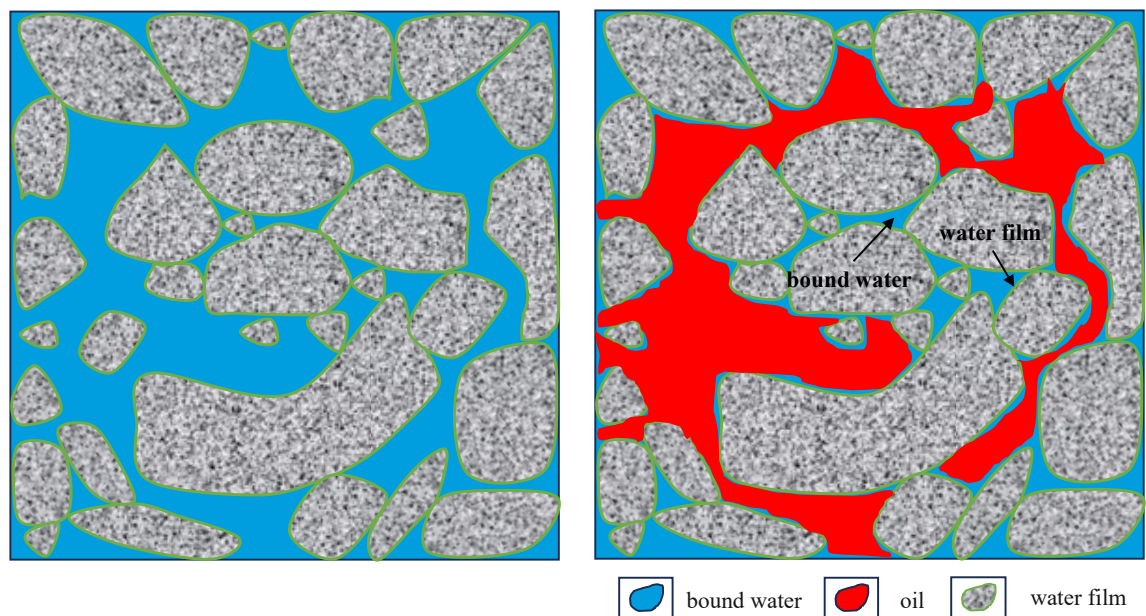


Figure 5 Diagram illustrating the storage state of subsurface fluids

3.2 Construction of a Single-Capillary Physical Model

The electrical properties of rocks can be regarded as the result of equivalent current pathways jointly composed of the rock matrix, pore fluids, and argillaceous

components (Glover, 2010). Given the overall low clay mineral content in the study area (Figure 3), this study, as a first-order approximation, focuses primarily on the parallel conductive relationship between the rock matrix and pore fluids (A P W J G et al., 2000). The effects of argillaceous materials or surface conduction are subsequently represented equivalently through a film-water conductivity enhancement term (Revil & Glover, 1998). Within this simplified framework, the equivalent parallel conductive pathways of the rock are illustrated in Figure 6, and the total conductance can be expressed as the superposition of the conductance contributions from individual components:

$$\frac{1}{R_t} = \frac{1}{R_{ma}} + \frac{1}{R_f} \quad (1)$$

where R_t is the total rock resistance, Ω ; R_{ma} is the resistance of the rock matrix, Ω ; and R_f is the resistance of the pore fluid, Ω .

According to classical electrical theory, for a conductor with known geometry, its resistance is determined by its resistivity, length, and cross-sectional area as follows:

$$R = \rho \frac{L}{A} \quad (2)$$

where ρ is the electrical resistivity of the medium, $\Omega \cdot \text{m}$; L is the actual length of the current conduction path, m; and A is the effective conductive cross-sectional area, m^2 .

For sandstone reservoirs dominated by nonmetallic minerals such as quartz and feldspar, the resistivity of the rock matrix is generally much higher than that of pore water. The rock matrix can therefore be treated, as an engineering approximation, as a weakly conductive or nearly insulating medium. Consequently, the bulk electrical

conductance of the rock is primarily controlled by pore fluids and their associated interfacial conductive pathways. By neglecting the conductive contribution of the rock matrix, the relationship between equivalent rock conductance and resistance can be simplified as follows:

$$R_t \approx R_f \quad (3)$$

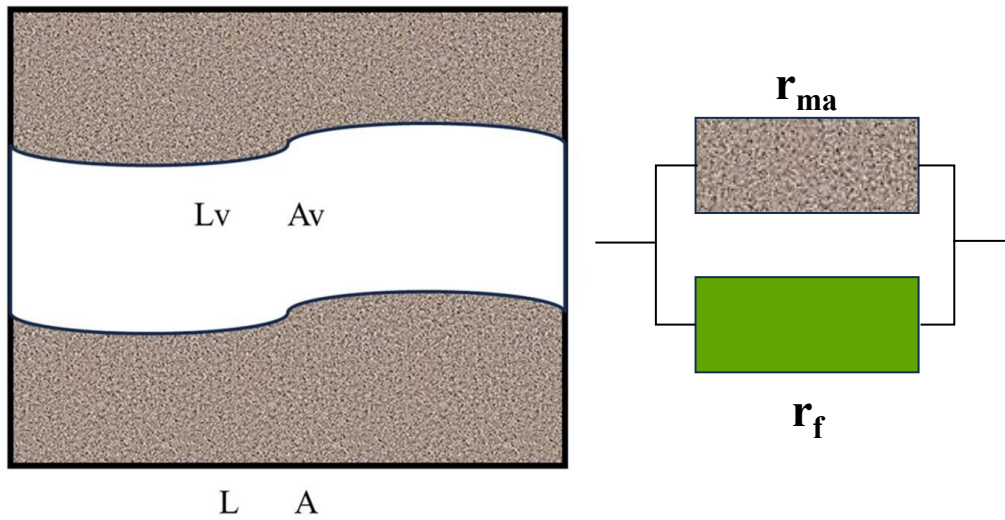


Figure 6 Schematic Diagram of Rock Conductivity Model

3.3 Geometric Analysis of Conductive Characteristics

To quantitatively characterize the enhancement of rock resistivity under oil-bearing conditions, the electrical responses of a single equivalent capillary under different fluid occurrence states are first analyzed for strongly water-wet conditions. The single-capillary model used here is not intended to fully reproduce the actual pore geometry, but rather serves as an equivalent representation for describing the relationships among pore-throat length scale, water-film thickness, and effective conductive cross-sectional area (Rostron, 2018).

During the invasion of a nonwetting phase, namely crude oil, the wetting-phase water preferentially remains along the pore wall, whereas oil tends to occupy the central

portion of the pore space (Lenormand et al., 1983). This process leads to an idealized topological configuration consisting of an annular water film surrounding a central oil phase (Mason & Morrow, 1991). The corresponding schematic representation of microscopic fluid occurrence is shown in Figure 7.

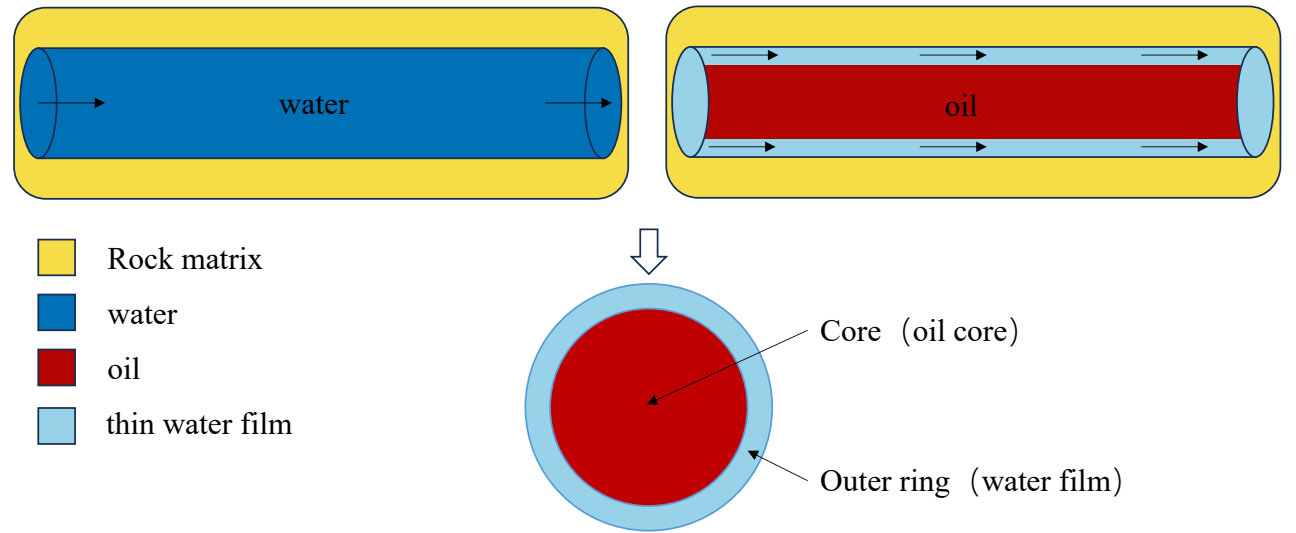


Figure 7 Schematic Diagram of Fluid Distribution in Capillary Management Theory

For a single capillary with an absolute radius r and length L when the capillary is completely saturated with water, its effective conductive cross-sectional area is πr^2 . According to Ohm's law, its conductance can be expressed as:

$$G_0 = \frac{1}{R_w} \frac{\pi r^2}{L} \quad (4)$$

where G_0 is the conductance of a single capillary, and R_w is the resistivity of formation water.

During the displacement process associated with the invasion of the nonwetting phase, namely crude oil, the strong water-wet nature of the rock surface causes oil to occupy only the central region of the capillary, while a continuous annular water film with a thickness of X remains on the pore wall. Under this condition, the effective

conductive cross section can be approximated as an annular region, and the effective conductive area of the annular water film is given by:

$$A_{film} = \pi[r^2 - (r - X)^2] \quad (5)$$

where A_{film} is the effective conductive cross-sectional area; r is the pore-throat radius, μm ; and X is the thickness of the film water, μm .

Under this oil-bearing condition, the capillary conductance, $G_t(r, X)$, is reduced to:

$$G_t(r, X) = \frac{1}{R_w} \frac{\pi(2rX - X^2)}{L_0} \quad (6)$$

The resistivity index (RI) is essentially defined as a resistance ratio, and equivalently as the reciprocal of the corresponding conductance ratio. For a single capillary, when tortuosity effects are neglected, the purely geometric resistivity index, RI_{geo} , can be expressed as:

$$RI_{geo} = \frac{G_0(r)}{G_t(r, X)} = \frac{r^2}{2rX - X^2} \quad (7)$$

where r is the radius of the single capillary, μm ; and X is the thickness of the continuous water film adhering to the microscopic pore-wall surface, μm .

Based on numerical simulations of the single equivalent-capillary model, the response of the resistivity index (RI) to water-film thickness X and capillary radius r can be quantified. Figure 8 shows that, for a fixed capillary radius, RI decreases markedly with increasing water-film thickness. Figure 9 further indicates that, for a fixed water-film thickness, RI increases as the capillary radius becomes larger. This behavior can be physically explained by the change in effective conductive cross-

sectional area. A thicker water film enlarges the annular conductive region, thereby enhancing electrical conduction and reducing RI. In contrast, an increase in capillary radius enlarges the proportion of the nonconductive central region occupied by oil, which weakens the conductive capacity per unit pore cross section and consequently increases RI. It should be emphasized that these results represent the fundamental trend under equivalent geometric conditions. In real rocks, tortuosity, pore-throat connectivity, and wall-roughness effects may further influence electrical transport and will be equivalently incorporated into the macroscopic model through the pore-size distribution and structural parameters.

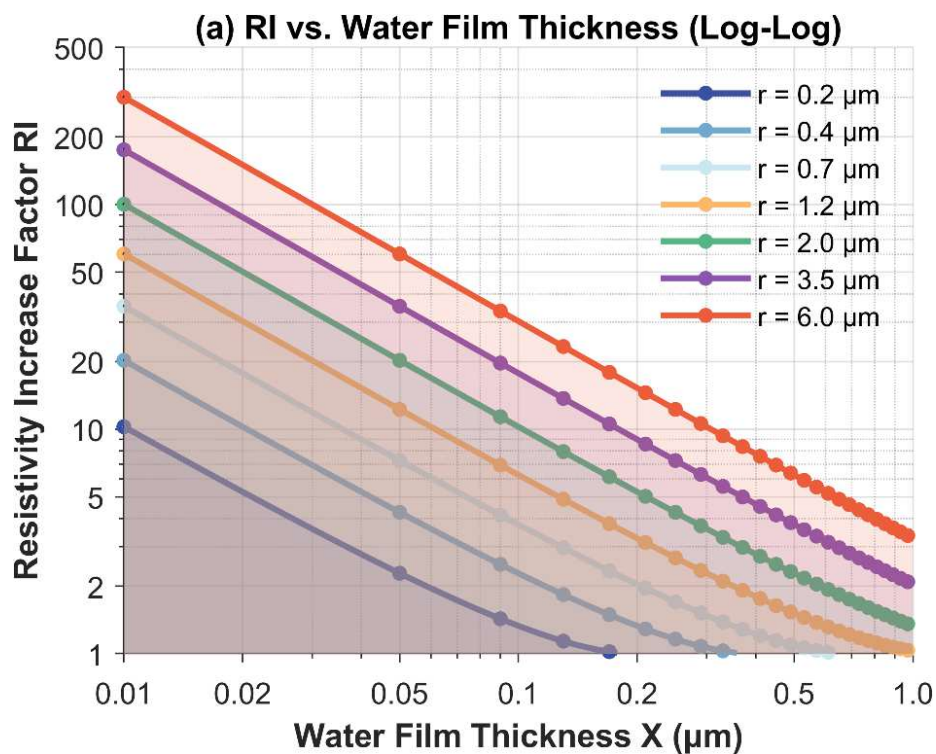


Figure 8 Relationship between resistivity increase coefficient and water film thickness

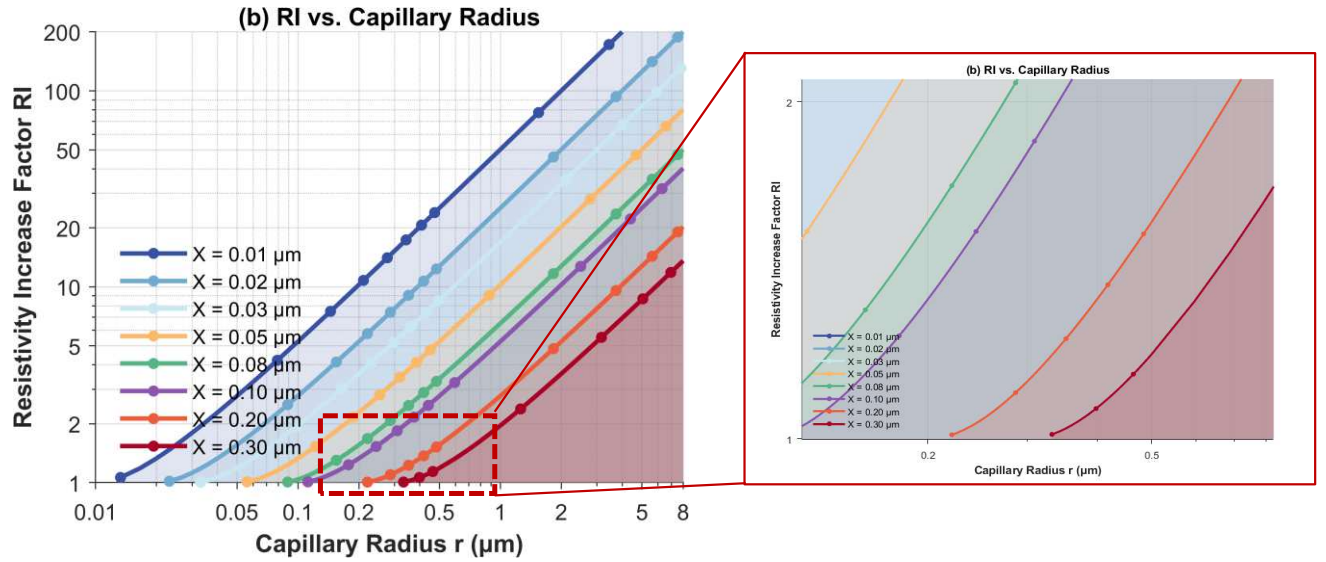


Figure 9 Relationship between resistivity increase coefficient and capillary radius

Figure 10 further shows that RI exhibits a pronounced nonlinear distribution in the bivariate space defined by water-film thickness X and capillary radius r . In general, under conditions of small pore throats or relatively thick water films, film water occupies a larger proportion of the pore-throat cross section, thereby providing more effective conductive pathways and resulting in lower RI values. Conversely, under conditions of large pore throats or thin water films, the nonconductive central region expands rapidly with increasing r , reducing the areal proportion of the conductive annular zone and consequently increasing RI. This relationship indicates that the resistivity response is not governed by a single geometric parameter, but is jointly controlled by pore-throat scale and water-film thickness. The above analysis provides a geometric basis for subsequently linking pore-throat radius distribution, water-film thickness evolution, and macroscopic rock-electrical response.

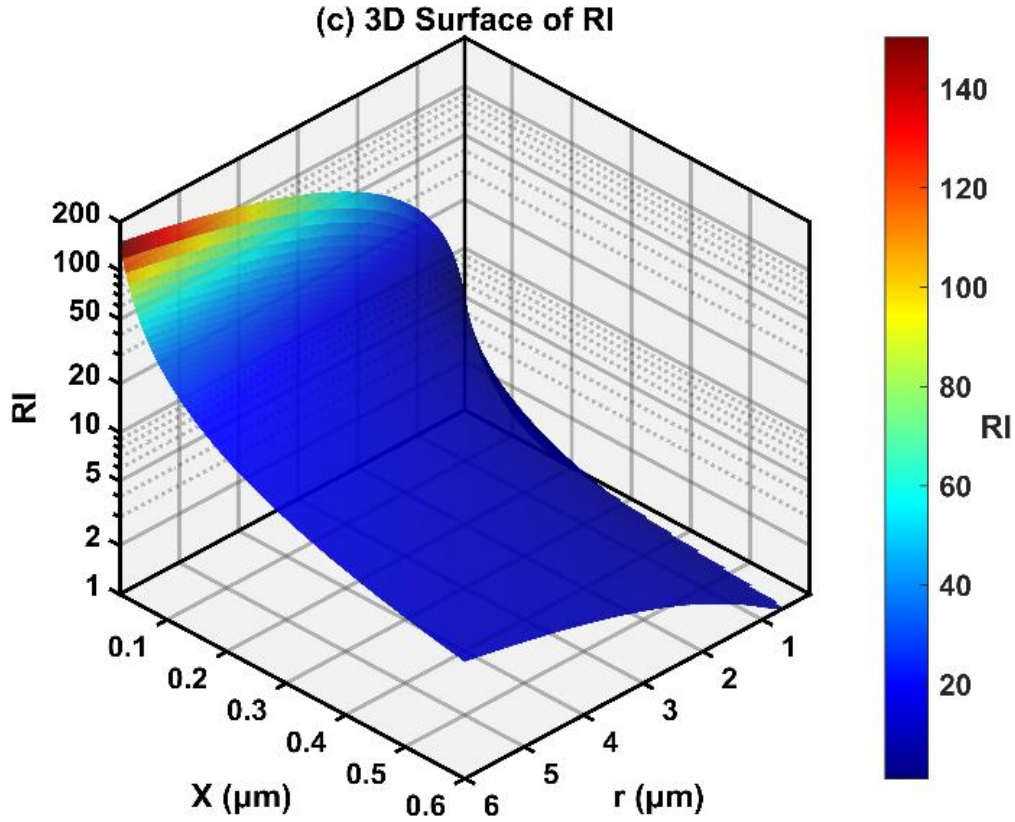


Figure 10 Three-dimensional relationship between the resistivity increase coefficient and the water film thickness and capillary radius

3.4 Single-Capillary Conductive Model Incorporating Electrical Double-Layer Enhancement

In the pore network of strongly water-wet rocks, mineral surfaces such as silicates are commonly negatively charged. Cations in the pore fluid may therefore become enriched near the solid–liquid interface, forming an electrical double layer (EDL). Because the EDL spatially overlaps substantially with the adsorbed water film, the film water may exhibit an effective conductivity higher than that of the bulk water occupying the pore center. To characterize this interfacial conductivity enhancement, the intrinsic conductivity of bulk water is defined as σ_{bulk} , and the effective conductivity of film water is defined as σ_{film} . These two quantities satisfy $\sigma_{film} = E\sigma_{bulk}$. It should be noted that E is introduced as an integrated effective parameter that accounts for EDL conduction, surface ion enrichment, and the

connectivity of film water. This parameter will be inverted subsequently using rock-electrical experimental data.

Under fully water-saturated conditions, the fluid within a single capillary can be approximately divided into two conductive components: pore-wall film water and central bulk water. These two components jointly constitute parallel conductive pathways. The initial conductance can therefore be expressed as:

$$G_0^* = \frac{\pi}{L} \left[E\sigma_{bulk} (r^2 - (r - X)^2) + \sigma_{bulk} (r - X)^2 \right] \quad (8)$$

Under the oil-bearing condition after free water has been sufficiently displaced by the nonwetting phase, the central bulk-water region is occupied by the insulating oil phase, and only the annular pore-wall film water and immobile water in fine pore throats remain. For a single equivalent capillary, the residual conductance can be expressed as:

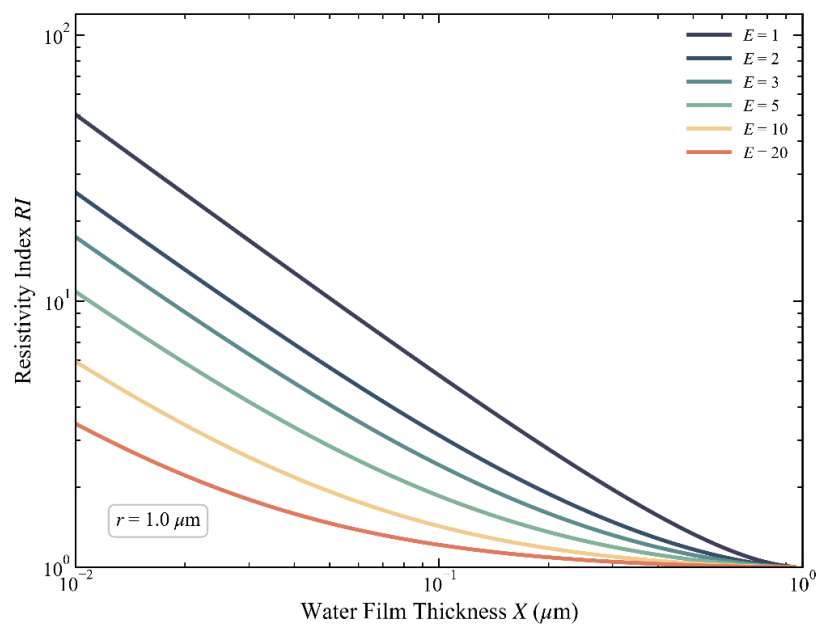
$$G_t^* = \frac{\pi}{L} \left[E\sigma_{bulk} (r^2 - (r - X)^2) \right] \quad (9)$$

Accordingly, at the microscopic scale, the true resistivity index incorporating electrical double-layer enhancement can be modified as:

$$RI = \frac{G_0^*}{G_t^*} = 1 + \frac{(r - X)^2}{E[r^2 - (r - X)^2]} \quad (10)$$

According to Equation (10), Figure 11 illustrates the corresponding relationships, where Figure 11a shows the variation of RI with water-film thickness X under a fixed capillary radius, and Figure 11b shows the variation of RI with capillary radius r under a fixed water-film thickness. Both figures indicate that the conductivity enhancement ratio E exerts a significant control on pore-scale electrical conduction.

When $E=1$, the film water exhibits no additional conductivity enhancement and can therefore be regarded as the purely geometric conduction baseline. When $E>1$, the effective conductivity of film water becomes higher than that of ordinary formation water due to the effects of the electrical double layer, interfacial ion enrichment, and surface conduction. With increasing E , the curves shift systematically toward lower RI values, indicating that enhanced film-water conduction can weaken the increase in resistivity caused by the reduced geometric volume of the water phase. This effect is particularly pronounced under conditions of thin water films or large pore throats. If strong interfacial conductivity enhancement is present, the rock may still exhibit a relatively low-resistivity response even when the geometric proportion of water is limited. Therefore, the occurrence of continuous or semi-continuous film water in strongly water-wet reservoirs, together with its conductivity enhancement effect, represents an important microscopic mechanism for explaining low-resistivity responses.



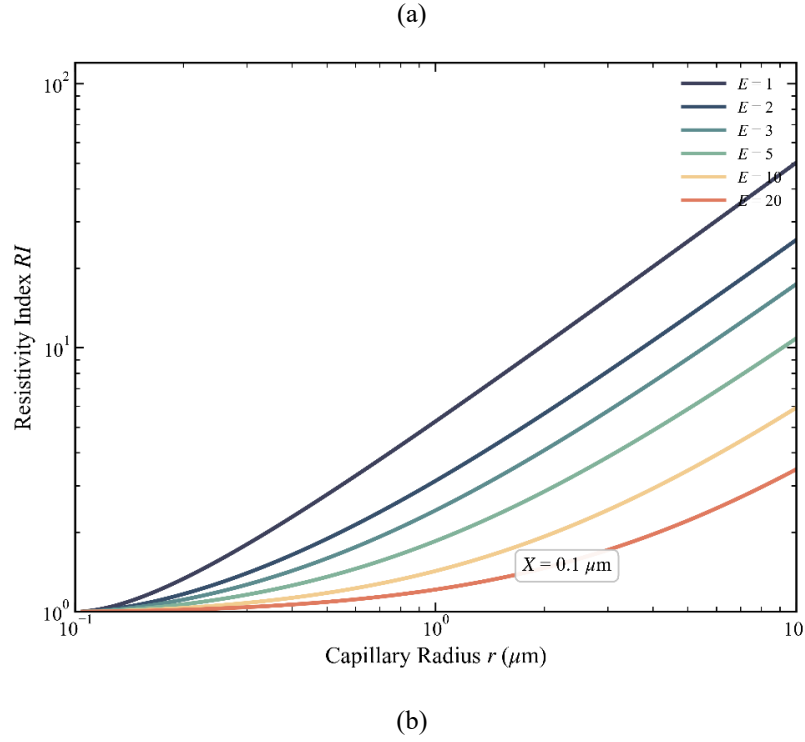


Figure 11 Regulation Laws of the Coefficient of Resistivity Increase Based on Different Conductivity Enhancement Ratios

4 Macroscopic Rock-Electrical Model Based on Micro-Interfacial Thermodynamics and Electrical Double-Layer Conductivity Enhancement

4.1 Solid–Liquid Interfacial Thermodynamic Equilibrium and Film-Evolution Equation

In strongly water-wet porous media, the stable distribution of fluid phases is jointly controlled by macroscopic capillary forces and microscopic interfacial interactions (Gerhard et al., 1997; Alexander et al., 1997) (Figure 12). Under the equivalent-capillary assumption, for a pore throat with radius r , the capillary pressure at the oil–water interface can be approximately described by the Young–Laplace equation as follows:

$$P_c = \frac{2\gamma \cos \theta}{r} \quad (11)$$

where P_c is the capillary pressure at the oil–water interface, Pa; γ is the oil–water interfacial tension under reservoir temperature and pressure conditions, N/m; θ is

the contact angle between the rock mineral surface and the oil–water interface, θ , which characterizes the microscopic wettability of the rock; and r is the equivalent radius of the capillary, or pore throat, expressed in m or μm .

Meanwhile, polar water molecules adjacent to mineral surfaces are affected by multiple interfacial forces, including van der Waals interactions, electrostatic forces, and surface hydration. These interactions can generate a disjoining pressure that resists further thinning of the water film. To preserve analytical tractability, this study adopts the van der Waals form of disjoining pressure from Derjaguin thin-film thermodynamics as a first-order approximation, in which the disjoining pressure exhibits a nonlinear inverse relationship with the thickness of the adsorbed water film:

$$\Pi = \frac{A_H}{6\pi X^3} \quad (12)$$

where Π is the disjoining pressure at the solid–liquid interface, Pa; A_H is the Hamaker constant, J, which represents the van der Waals interaction energy between rock minerals, such as quartz or clay, and water molecules, and is highly dependent on the mineral composition of the rock; and X is the absolute thickness of the water film adsorbed on the inner pore wall, expressed in m or μm .

Under quasi-static conditions following long-term hydrocarbon accumulation and displacement in the reservoir, the pore system can be approximately regarded as having reached interfacial mechanical equilibrium; that is, the capillary pressure and disjoining pressure are balanced in order of magnitude. By combining Equations (11) and (12), one obtains:

$$\frac{2\gamma \cos \theta}{r} = \frac{A_H}{6\pi X^3} \quad (13)$$

By algebraically rearranging Equation (13) and taking the cube root, the theoretical expression describing the variation of water-film thickness with pore-throat radius can be obtained as follows:

$$X(r) = \left(\frac{A_H}{12\pi\gamma \cos \theta} \right)^{1/3} \cdot r^{1/3} \quad (14)$$

Defining the comprehensive surface physicochemical coefficient as $k = (A_H / 12\pi\gamma \cos \theta)^{1/3}$, the microscopic water-film thickness function can be expressed as:

$$X(r) = k \cdot r^{1/3} \quad (15)$$

To determine the comprehensive surface physicochemical coefficient k of the rock, it is necessary to quantitatively characterize the volumetric contributions of capillary-bound water in fine pore throats and film water along the walls of larger pores. In this study, this constraint is achieved by integrating high-pressure mercury intrusion and nuclear magnetic resonance measurements (Liu et al., 2022; Mu et al., 2023; Liu et al., 2025; Jing-Qiang et al., 2016; Purcell, 1949; Swanson, 1981). First, mercury intrusion data are used to determine the pore-throat radius corresponding to 99.99% of the cumulative permeability contribution for each core sample, which is taken as the critical seepage cutoff radius. This threshold is used to distinguish fine pore throats with negligible contributions to flow from larger pore throats that can be invaded by the nonwetting phase. It should be noted that 99.99% is an engineering threshold selected in this study based on the cumulative permeability contribution, and its stability should be further evaluated through sensitivity analysis in subsequent applications. When the

pore-throat radius is smaller than the critical seepage cutoff radius, this portion of the pore space can be approximately regarded as being occupied by capillary-bound water, and its volumetric fraction can be expressed as:

$$S_{w1} = \int_{r_{min}}^{r_{cut}} f(r) dr \quad (16)$$

where S_{w1} is the saturation of immobile capillary water in micropores, dimensionless and expressed as a fraction; and r_{cut} is the effective seepage cutoff radius, with units of μm .

For the macropore network ($r \geq r_{cut}$), the nonwetting phase can invade the central region of the pores, whereas the water film adsorbed on the inner pore walls can be approximately represented as an annular distribution (Roman et al., 2017; Abu-Al-Saud et al., 2016; Bernard et al., 2010). For a pore with a cross-sectional area of πr^2 , the cross-sectional area occupied by the pore-wall water film is $\pi r^2 - \pi(r - X)^2$. Therefore, the relative volumetric proportion of film water for a given pore radius, $V_{film}(r)$, can be expressed as:

$$V_{film}(r) = \frac{\pi r^2 - \pi(r - X(r))^2}{\pi r^2} = \frac{2rX(r) - X(r)^2}{r^2} = 2 \frac{X(r)}{r} - \left(\frac{X(r)}{r} \right)^2 \quad (17)$$

Substituting Equation (15) into Equation (17) yields the expression for the volumetric fraction of water film within any macropore:

$$V_{film}(r) = 2k \cdot r^{-2/3} - k^2 \cdot r^{-4/3} \quad (18)$$

By performing weighted integration over the bulk volume-frequency function $f(r)$ within the macropore interval, the total volume of dynamic film water in the macropore network can be obtained as:

$$S_{w2} = 2k \int_{r_{cut}}^{r_{max}} f(r) r^{-2/3} dr - k^2 \int_{r_{cut}}^{r_{max}} f(r) r^{-4/3} dr \quad (19)$$

To solve for the comprehensive surface physicochemical coefficient k , a macroscopic fluid-volume conservation constraint must be introduced. The total bound-water saturation calibrated from nuclear magnetic resonance (NMR) measurements can be used to estimate the macroscopic bound-water content of the reservoir after sufficient displacement. According to volume conservation, the amount of film water along macropore walls can be expressed as:

$$S_{w2} = S_{wb} - S_{w1} \quad (20)$$

Defining two integral constants, I_1 and I_2 , that are uniquely determined from the mercury intrusion data:

$$I_1 = \int_{r_{cut}}^{r_{max}} f(r)r^{-2/3} dr, \quad I_2 = \int_{r_{cut}}^{r_{max}} f(r)r^{-4/3} dr \quad (21)$$

where I_1 and I_2 are integral constants determined by the mercury-derived pore-throat radius distribution and can characterize the geometric heterogeneity of the macropore interval. Substituting these constants into the preceding film-water volume equation reduces the original integro-differential formulation to a quadratic equation in k :

$$I_2 \cdot k^2 - 2I_1 \cdot k + S_{w2} = 0 \quad (22)$$

According to the physical boundary condition that the water-film thickness must be smaller than the pore radius, the physically admissible solution of this quadratic equation can be extracted as follows:

$$k = \frac{I_1 - \sqrt{I_1^2 - I_2 \cdot S_{w2}}}{I_2} \quad (23)$$

where k is the comprehensive surface physicochemical coefficient inverted under the constraints of the mercury-derived pore-throat radius distribution, NMR-

derived bound-water saturation, and the equilibrium film assumption. This parameter provides an integrated characterization of the strength of rock–fluid interfacial interactions and the capacity for film-water retention, rather than representing a single mineral-specific physical constant.

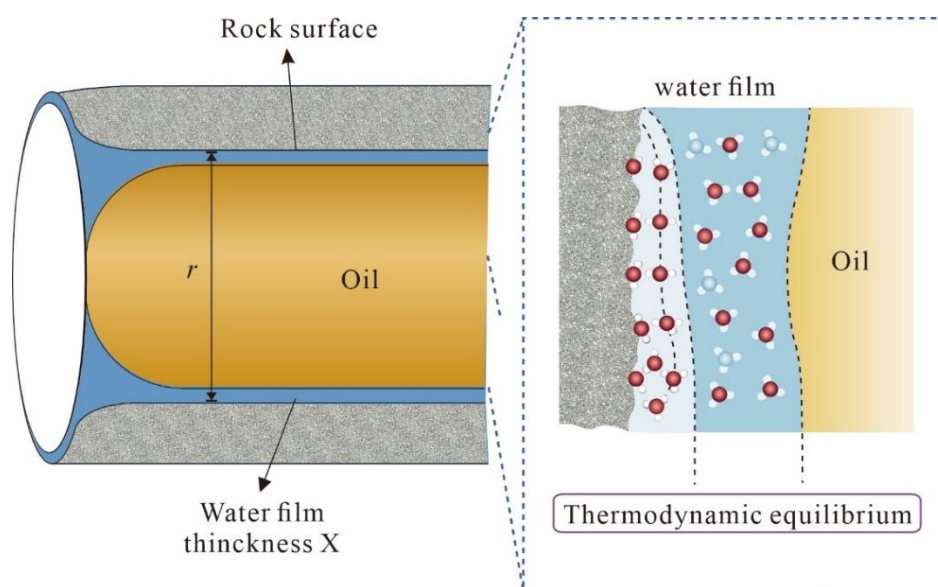


Figure 12 Schematic diagram of water storage in strongly hydrophilic pores and interface mechanical equilibrium

4.2 Dual-Network Conductive Model

In the pore network of strongly water-wet rocks, the negatively charged mineral surfaces may induce the enrichment of cations near the solid–liquid interface, thereby forming an electrical double layer (EDL). Because the EDL is spatially concentrated mainly within or adjacent to the adsorbed water film, the effective conductivity of film water may exceed that of the bulk water in the pore center. Combined with the previously derived water-film thickness evolution relationship, a larger comprehensive surface physicochemical coefficient k generally implies a thicker water film retained along macropore walls, as well as a greater volume of water phase and more abundant

ionic charge-carrier pathways participating in interfacial conduction. Based on the difference in conductive capacity between film water and bulk water, this study develops a dual-network conductive model, in which the pore-fluid conductive pathways are divided into a highly conductive pore-wall film-water network and a conventional conductive central mobile-water network.

According to the principle of parallel conduction, the macroscopic total conductivity of a porous medium can be approximately expressed as the volume-weighted superposition of the conductivities of the connected fluid networks. Let the intrinsic conductivity of the central bulk water be C_w , and the macroscopic effective conductivity of film water be C_{wb} . The following relationship is then defined: $C_{wb} = E \cdot C_w$, where E is the conductivity enhancement ratio of film water.

(1) Reference state: conductivity modeling for a 100% water-saturated formation

When the rock is fully saturated with formation water, that is, when the water saturation is $S_w = 1.0$, the highly conductive film-water network occupies a pore-volume fraction of S_{wb} , whereas the conventional bulk-water network occupies the remaining pore space. Under this condition, the reference total effective conductivity of the rock can be expressed as the linear superposition of the conductive contributions from the two networks:

$$C_o = C_{wb} \cdot S_{wb} + C_w \cdot (1 - S_{wb}) \quad (24)$$

(2) Displacement state: conductivity modeling for an oil- or gas-bearing formation

As insulating hydrocarbon fluids, including oil or gas, invade the pore network, the water saturation decreases to S_w . During displacement, the conductive cross section of the fluid network is reconfigured. Constrained by capillary forces and interfacial interactions, pore-wall film water is difficult to completely remove under conventional displacement pressures; therefore, its conductive contribution can be approximately retained. In contrast, the volume of mobile water in the pore center decreases as water saturation declines. Meanwhile, in heterogeneous porous media, the loss of conductive connectivity in the central water network generally occurs faster than the reduction in its volume. To characterize the effects of oil-phase segmentation, water-phase isolation, and increased tortuosity on the conductive capacity of the central water network, the remaining mobile-water volume is normalized, and a cutoff structural exponent β is introduced to nonlinearly describe the rate at which the mobile water phase loses its continuous conductive capability.

By incorporating the evolution of these two conductive networks under oil- or gas-bearing conditions, the total effective formation conductivity predicted by the model can be expressed as:

$$C_t = C_{wb} \cdot S_{wb} + C_w \cdot (S_w - S_{wb}) \cdot \left[\frac{S_w - S_{wb}}{1 - S_{wb}} \right]^\beta \quad (25)$$

According to the reciprocal relationship between rock resistivity and conductivity, the formation resistivity index I can be derived from the ratio between Equations (24) and (25).

$$I = \frac{R_t}{R_o} = \frac{C_o}{C_t} = \frac{E \cdot S_{wb} + 1.0 \cdot (1 - S_{wb})}{E \cdot S_{wb} + (S_w - S_{wb}) \cdot \left(\frac{S_w - S_{wb}}{1 - S_{wb}} \right)^\beta} \quad (26)$$

5 Parameter Inversion and Model Validation Based on Multiscale Experiments

In the preceding sections, a rock-electrical response model applicable to strongly water-wet, low-resistivity reservoirs was established from the perspective of pore-scale interfacial thermodynamics and conductive mechanisms. The key feature of this model is the introduction of the comprehensive surface physicochemical coefficient k , which is used to characterize the variation in film-water thickness along macropore walls as a function of pore-throat radius. This parameter further enables quantification of the contribution of the film-water conductive network, enhanced by electrical double-layer effects, to the bulk electrical conductivity of the rock. To evaluate the applicability of the proposed model and determine its key parameters, natural core samples from typical strongly water-wet, low-resistivity oil reservoirs were selected for integrated high-pressure mercury intrusion, nuclear magnetic resonance, and rock-electrical experiments. These three types of experiments provide constraints at different scales, namely pore geometry, bound-fluid occurrence, and macroscopic electrical response. Specifically, high-pressure mercury intrusion was used to characterize the pore-throat radius distribution of the cores and to establish the pore-throat radius frequency function $f(r)$. Nuclear magnetic resonance was employed to identify the volumetric contributions of immobile water and film water in pores of different sizes. Rock-electrical experiments were conducted to obtain the resistivity evolution of the rocks under different water-saturation states. By coupling the multiscale experimental results with the theoretical model, closed-loop inversion and validation of the model parameters can be achieved.

5.1 Pore-Structure Characterization and Cutoff-Radius Determination Based on Mercury Intrusion Experiments

The macroscopic electrical properties of rocks are fundamentally governed by the geometry and connectivity of their microscopic pore networks. For the model developed in this study, the pore-throat radius distribution function serves as a fundamental input parameter linking pore-scale geometric characteristics to the macroscopic volume-conservation and electrical-conduction equations. Therefore, quantitative characterization of the core pore-throat structure using mercury intrusion experiments is required as a first step.

To minimize potential interference from original pore fluids and salts on pore-structure measurements, the natural core samples were subjected to oil washing, desalination, and drying pretreatments prior to the experiments. Mercury intrusion tests were then performed. The mercury intrusion capillary pressure curves are shown in Figure 13, and the pore-throat radius distribution characteristics are presented in Figure 14. As shown in Figure 13, the mercury injection and withdrawal curves differ markedly among the core samples, indicating pronounced heterogeneity in their pore-throat structures. The capillary pressure levels corresponding to the initial stage of mercury intrusion vary among samples, suggesting substantial differences in the dominant pore-throat radii of different cores. In addition, as mercury saturation increases, the curves of some samples continue to advance within the high-capillary-

pressure range, implying the development of abundant fine pore throats within these samples. Figure 14 further presents the pore-throat radius frequency distributions of the core samples. Overall, the cores from this type of low-resistivity oil reservoir exhibit broad distributions dominated by micron-scale pore throats, with extensions toward smaller pore-throat radii. This indicates that the samples contain both relatively large pore throats that dominate fluid flow and a certain proportion of submicron- to micron-scale fine pore throats.

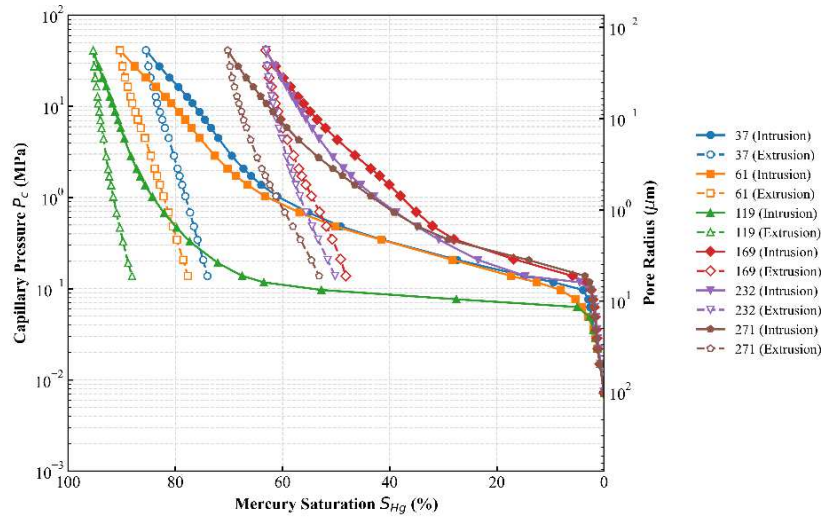


Figure 13 Mercury Intrusion Capillary Pressure Curve Chart

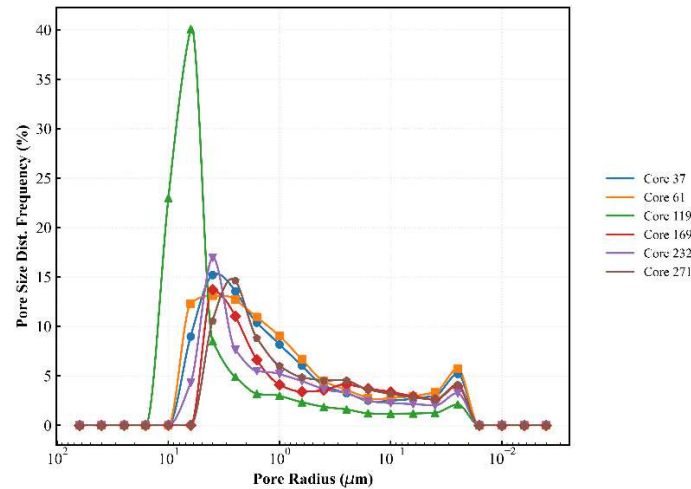


Figure 14 Distribution Characteristics Chart of Pore Radius

When incorporating the mercury intrusion results into the macroscopic volume-conservation equation, the critical seepage cutoff radius must first be determined. In this study, based on the cumulative permeability contribution derived from mercury intrusion data, the pore-throat radius corresponding to 99.99% of the cumulative permeability contribution is defined as the critical seepage cutoff radius. This criterion originates from the Purcell permeability-contribution analysis of mercury intrusion data, and previous studies have commonly used the pore-throat size corresponding to 99.99% of the cumulative permeability contribution as the critical flow pore-throat size or the minimum flow pore-throat radius.

The physical implication of this classification is as follows: when the pore-throat radius is smaller than this threshold, its contribution to the overall seepage pathways is nearly negligible, and the corresponding entry pressure is relatively high, making it difficult for the nonwetting phase to effectively invade during actual displacement. By contrast, when the pore-throat radius is larger than this threshold, the nonwetting phase is more likely to occupy the central region of the pore space, while a certain thickness of adsorbed film water may still be retained on the strongly water-wet mineral surfaces.

On this basis, the pore system of the core can be divided into two components with distinct physical meanings. When $r \leq r_{cut}$, the pore space corresponds to a fine pore-throat system and can be approximately regarded as being occupied by capillary-bound water. When $r \geq r_{cut}$, it corresponds to a relatively large and connected pore network, where nonwetting-phase invasion can occur while pore-wall film water is retained. The seepage cutoff radii obtained using this method are shown in Figure 15.

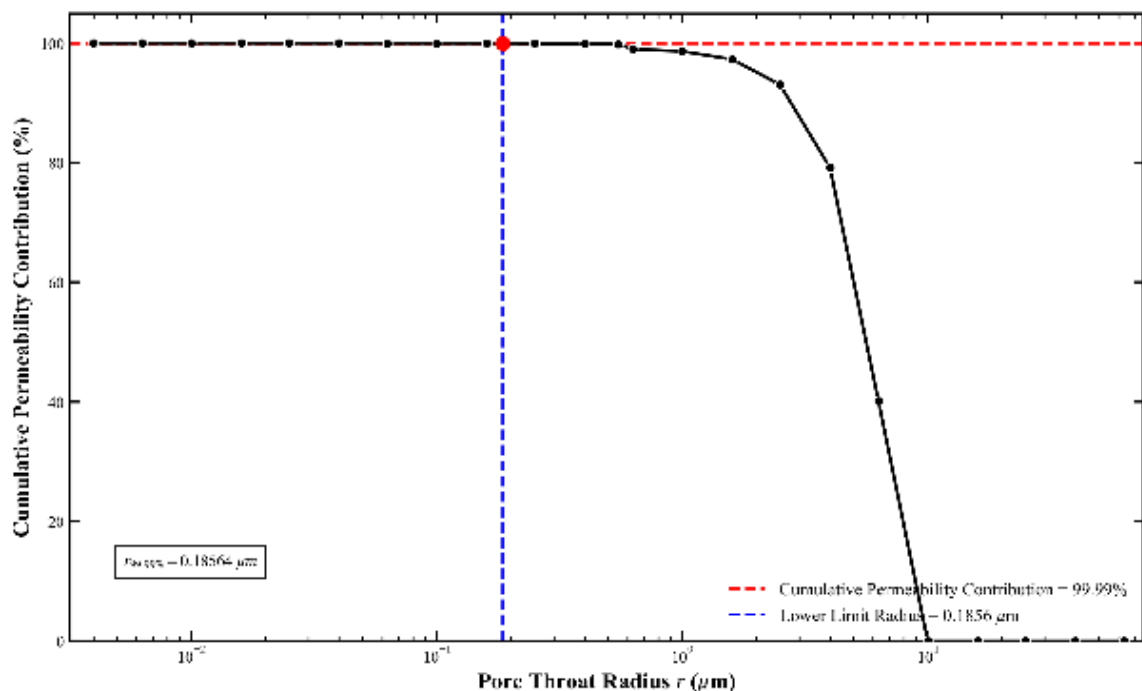


Figure 15: Schematic diagram of the truncation radius of fluid flow under different core conditions

5.2 Determination of Core Bound-Water Saturation Based on NMR Experiments

Bound water in the rock pore system constitutes an important component of the low-resistivity conductive network. To distinguish the volumetric contributions of bound water in different occurrence states and to provide constraints for the inversion of microscopic thermodynamic parameters, nuclear magnetic resonance (NMR) experiments were introduced in this study. The NMR T2 relaxation spectrum can nondestructively and continuously reflect the amount and mobility of fluids residing in

pores of different sizes, making it suitable for identifying fluid variations between the fully water-saturated state and the post-centrifugation bound-water state.

In the experiments, natural core samples fully saturated with formation water were first subjected to NMR measurements to obtain the complete initial T2 spectra. The saturated cores were then centrifuged, with the centrifugal pressure set as close as possible to the effective displacement pressure experienced during hydrocarbon accumulation or displacement in the study area. After centrifugation, NMR measurements were conducted again to obtain the bound-water T2 spectra. Figure 16 shows a comparison between the saturated-water and bound-water T2 relaxation spectra for representative core samples. As shown in Figure 16, the signal on the right side of the T2 spectrum, corresponding to larger pores, decreases significantly after centrifugation, indicating that a large proportion of free water in the centers of larger pores has been displaced. In contrast, the signal associated with fine pores on the left side remains relatively stable, suggesting that this portion of fluid is constrained by capillary forces and is difficult to mobilize. By calibrating the intersection point of the cumulative porosity curves before and after centrifugation, the T2 cutoff value can be determined, thereby allowing the macroscopic total bound-water saturation to be estimated. The corresponding calculation formula for determining bound-water saturation based on NMR T2 cutoff calibration is given in Figure 17.

According to the dual-network fluid distribution model established in this study, the total bound water can be divided into two components: immobile water controlled by capillary forces in fine pore throats, and adsorbed film water along the inner walls of larger pores. The former can be constrained by the mercury-derived cutoff radius, whereas the latter can be obtained by subtracting the capillary water in fine pore throats from the total bound-water saturation determined by NMR. Figure 18 illustrates the distribution characteristics of bound water under different pore-throat radius conditions, where the red region represents capillary-bound water in fine pore throats, the green region represents film water along macropore walls, and the blue region represents the mobile-fluid volume.

By combining the geometric heterogeneity constants obtained from numerical integration of the mercury-derived pore-size distribution and substituting them into the analytical solution, the comprehensive surface physicochemical coefficient k can be inverted. The basic petrophysical properties, NMR-derived bound-water classification parameters, and inverted k values for representative core samples are summarized in Table 2. Based on the data in Table 2, the relationship between k and porosity–permeability parameters can be further analyzed, as shown in Figure 19.

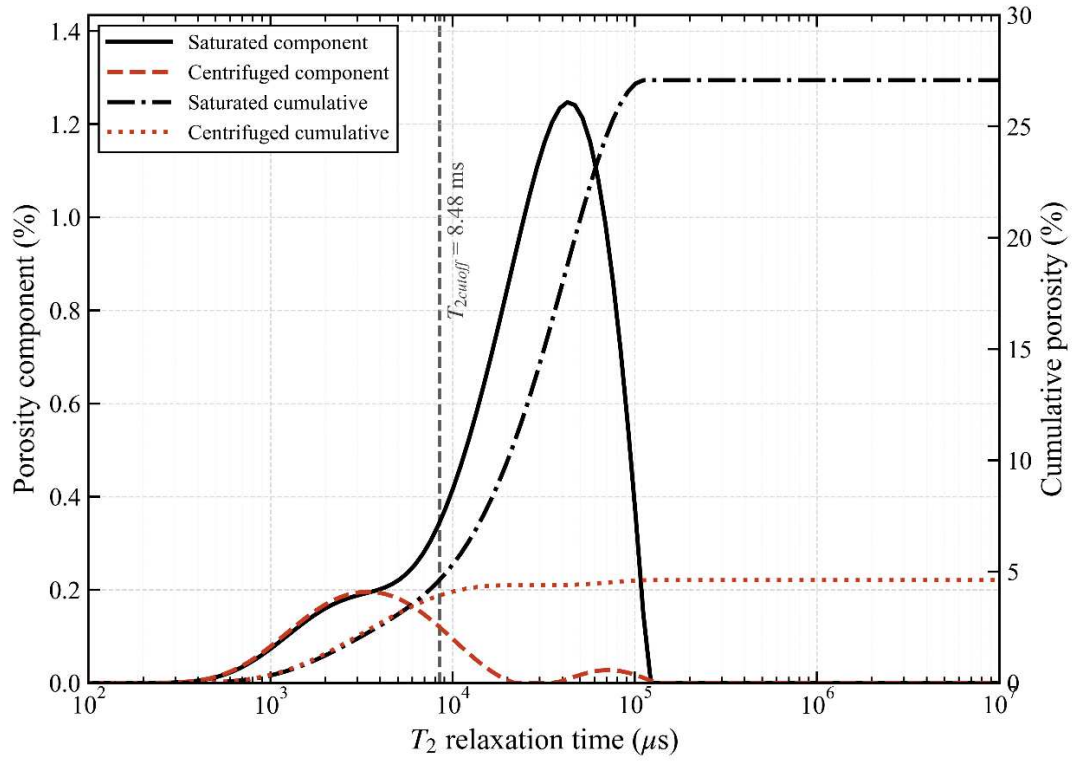
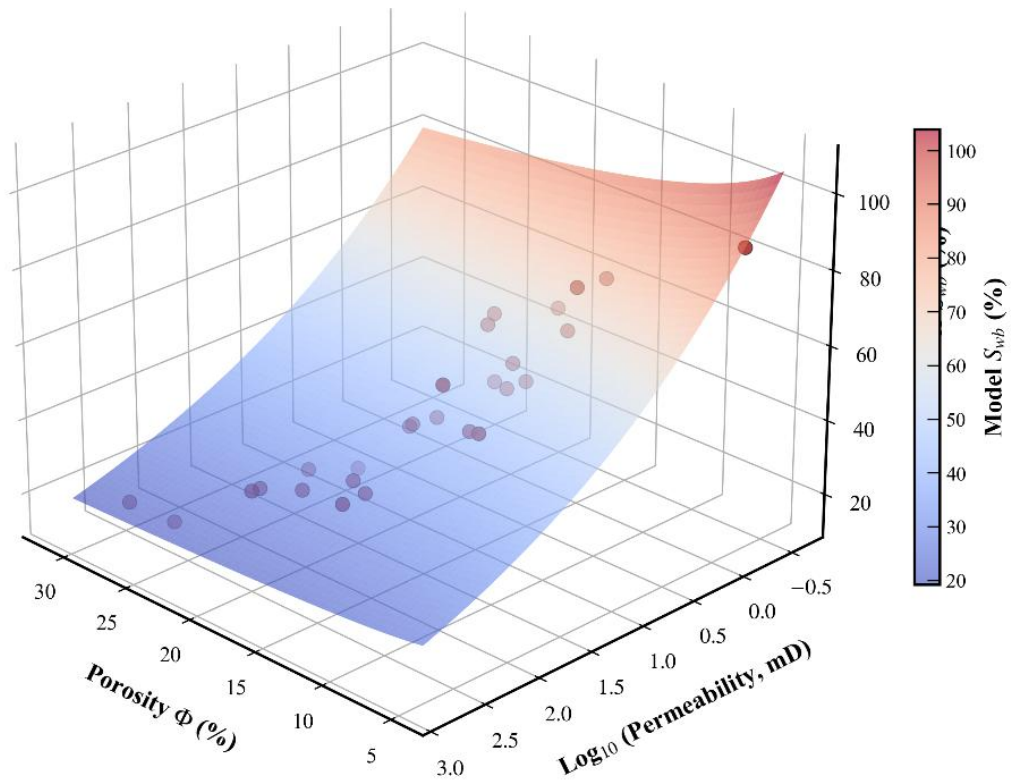
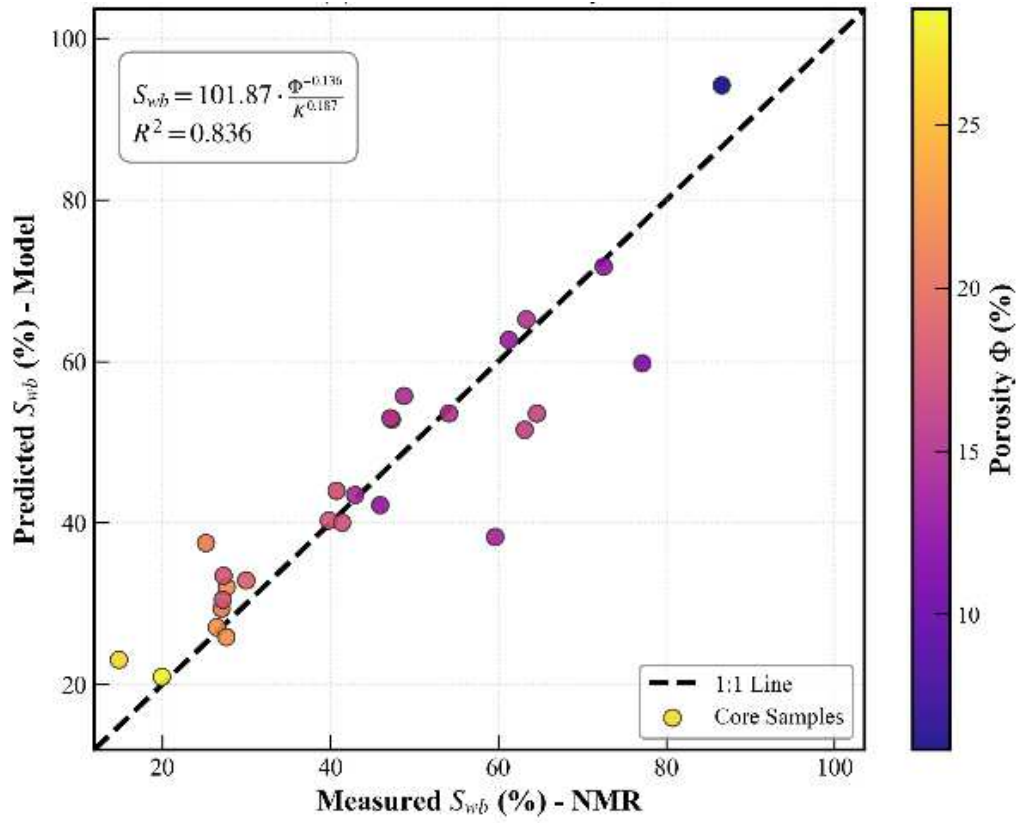


Figure 16 Comparison of T₂ relaxation spectra of saturated water and bound water in a typical core sample



(a)



(b)

Figure 17 Schematic diagram of the calculation formula for bound water based on nuclear magnetic resonance calibration

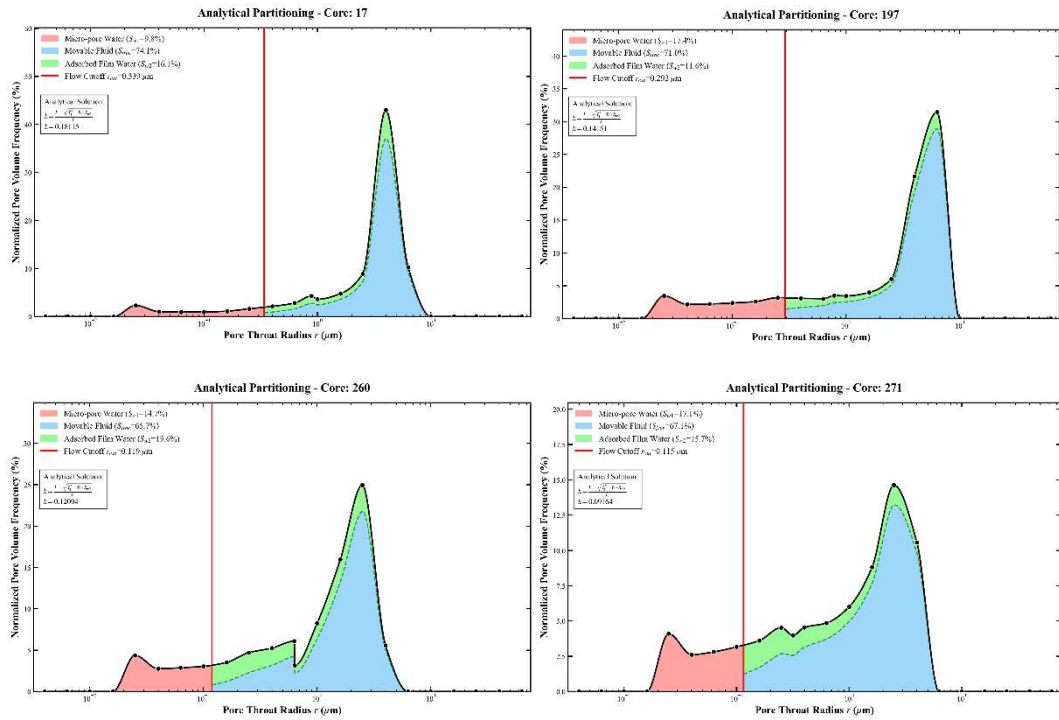


Figure 18 Distribution characteristics of bound water for different pore throat radii
Table 2 Joint Inversion Results Table

Core ID	Porosity (%)	K (mD)	r _{cut} (um)	Sw1 (%)	Sw2 (%)	k
17	24.1	151	0.34	0.34	9.79	16.10
37	22.9	80.7	0.19	0.19	18.23	11.07
61	22.1	82.9	0.20	0.20	19.67	9.63
113	15.6	310	0.07	0.07	15.13	8.88
72	20.8	1390	0.21	0.21	13.99	3.45
119	24.3	693	0.59	0.59	11.79	7.66
133	22.3	211	0.34	0.34	15.28	9.30
169	16.3	48.4	0.07	0.07	12.86	20.91
179	20.4	250	0.38	0.38	14.44	9.66
197	17.6	104	0.29	0.29	17.37	11.59
206	18.4	82.1	0.17	0.17	20.37	9.72
221	20.7	81	0.11	0.11	17.38	12.30
232	22.6	117	0.16	0.16	17.30	10.09
251	22.2	95.3	0.12	0.12	18.06	10.47
260	19.1	39.6	0.12	0.12	14.75	19.56
271	18.9	50.2	0.11	0.11	17.14	15.73

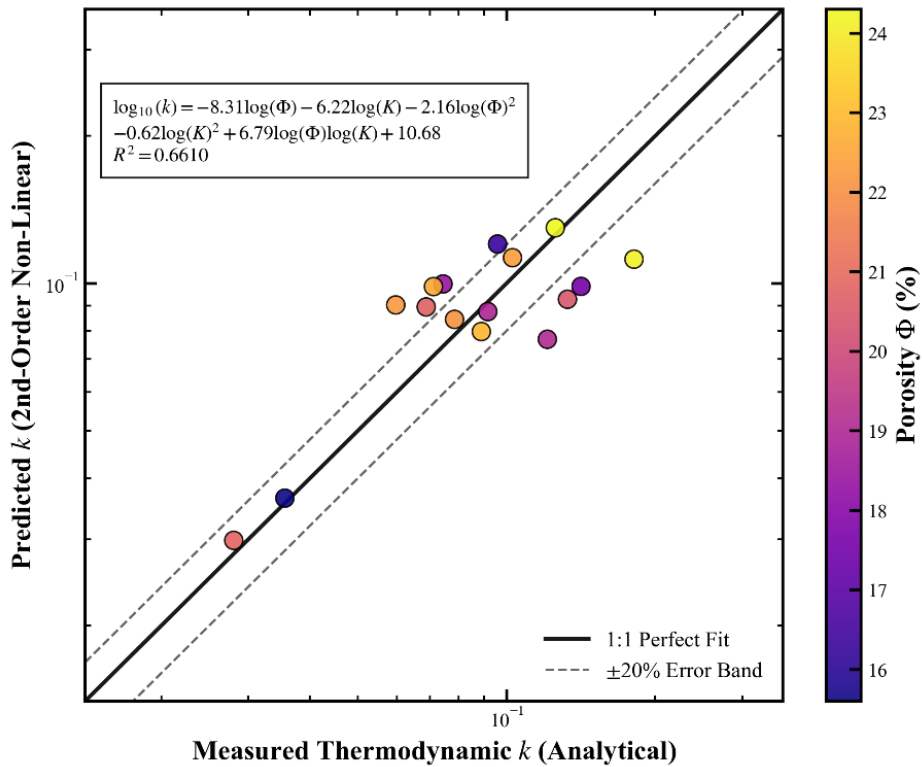


Figure 19 Relationship between thermodynamic parameters and pore permeability

5.3 Rock-Electrical Experiments and Multi-Parameter Joint Inversion With Released Bound-Water Degrees of Freedom

After the comprehensive surface physicochemical coefficient k was jointly inverted from NMR and high-pressure mercury intrusion data, dynamic resistivity measurements obtained during core displacement were further used to analyze the

relationships among the dynamic rock-electrical response, the conductivity enhancement ratio E , and the cutoff structural exponent β . For strongly water-wet, low-resistivity oil reservoirs, residual water mainly occurs as capillary water in fine pore throats and film water along pore walls. Both the spatial boundaries of these residual water components and the additional conductive capacity of film water can substantially influence the electrical response of rocks. Therefore, conventional rock-electrical models are unable to adequately characterize the dynamic variation of the resistivity index with water saturation during hydrocarbon displacement. On this basis, dynamic resistivity data from core displacement experiments were introduced to optimize and invert the parameters of the dual-network rock-electrical response model.

According to the microscopic fluid occurrence and conductive mechanisms established above, this study constructed an objective function for the resistivity index that incorporates additional electrical double-layer conduction, as expressed in Equation (26). Constrained by this objective function, nonlinear least-squares fitting was performed independently on the dynamic resistivity data of each core sample, yielding the optimal conductivity enhancement ratio E and cutoff structural exponent β for the corresponding core. Representative fitting results are shown in Figure 20. The results indicate that, compared with the conventional Archie model, the proposed dual-network model more effectively captures the relatively low resistivity index observed at low water saturations. This finding suggests that connected film-water conduction and electrical double-layer-induced excess conduction exert an important influence on the resistivity response of strongly water-wet reservoirs. To further enhance the credibility of the model, subsequent analysis should provide fitting errors for each core, confidence intervals of the inverted parameters, and quantitative comparisons with conventional models.

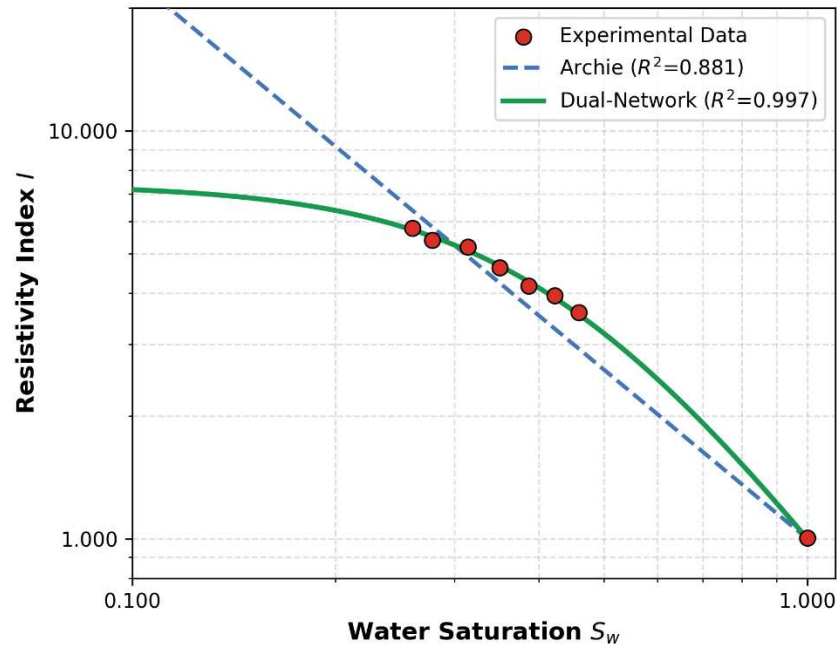


Figure 20: Comparison Chart of Measured Rock-Electricity Data and Archie Model

The fitted results further allow the conductivity enhancement ratio E and the cutoff structural exponent β to be extracted for each core sample. Among them, E

characterizes the effective conductivity enhancement of the film-water conductive network relative to the conventional bulk-water network, and may be jointly controlled by factors such as pore-surface wettability, electrical double-layer effects, formation-water salinity, and film-water thickness. In contrast, β reflects the rate at which the conductive connectivity of the central mobile-water network declines during hydrocarbon displacement. In order to extend these laboratory-derived electrical parameters to full-well logging evaluation, this study further investigates their relationships with macroscopic rock petrophysical properties and microscopic interfacial parameters.

A cross-analysis was conducted between the conductivity enhancement ratio E inverted for each core and the comprehensive surface physicochemical coefficient k obtained from the joint NMR–mercury intrusion inversion. The results indicate the existence of a functional relationship between the two parameters, suggesting that the conductivity enhancement effect of film water may be closely related to the strength of rock–fluid interfacial interactions. By fitting the relationship between E and k (Figure 21), a predictive function for the conductivity enhancement ratio applicable to strongly water-wet reservoirs in the study area can be established, thereby providing a parameter basis for subsequent water-saturation evaluation of low-resistivity reservoirs based on pore structure and interfacial thermodynamic parameters. Meanwhile, the cutoff structural exponent β also exhibits a certain mapping relationship with the petrophysical

index T ($\sqrt{Perm / Por}$) (Figure 22). The petrophysical index T comprehensively reflects the combined effects of porosity, permeability, and pore-structure connectivity, whereas β characterizes the attenuation behavior of the effective conductive water-network connectivity during hydrocarbon displacement. Establishing an empirical relationship between β and T therefore provides a basis for transferring β from the core-experiment scale to the continuous logging-evaluation scale.

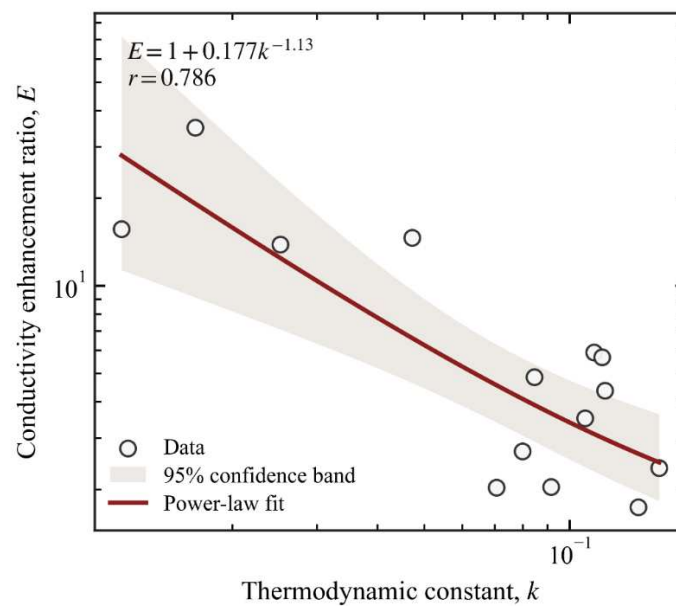


Figure 21 Relationship between Conductivity Enhancement Ratio and

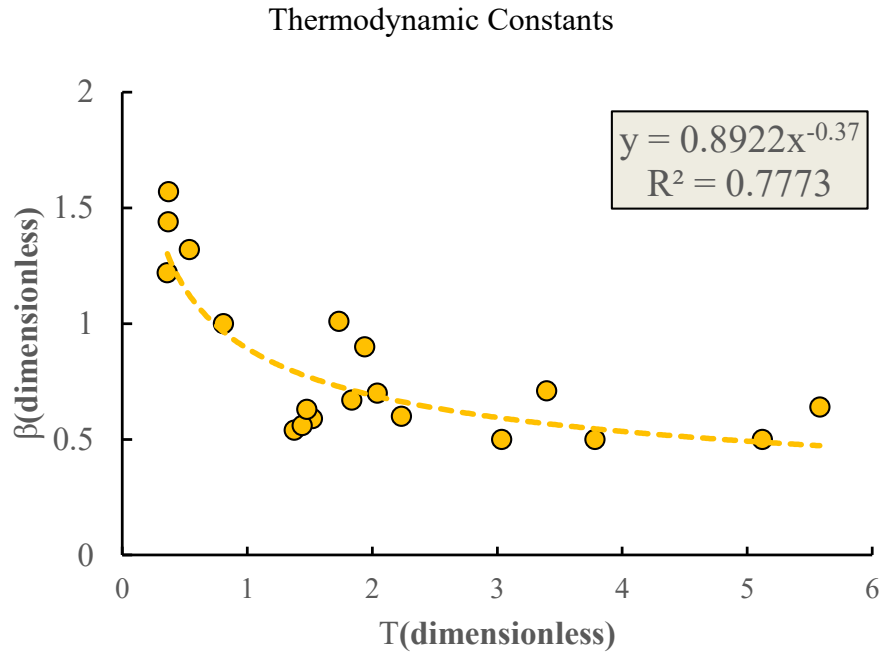


Figure 22: Relationship between the truncated index and the physical property index

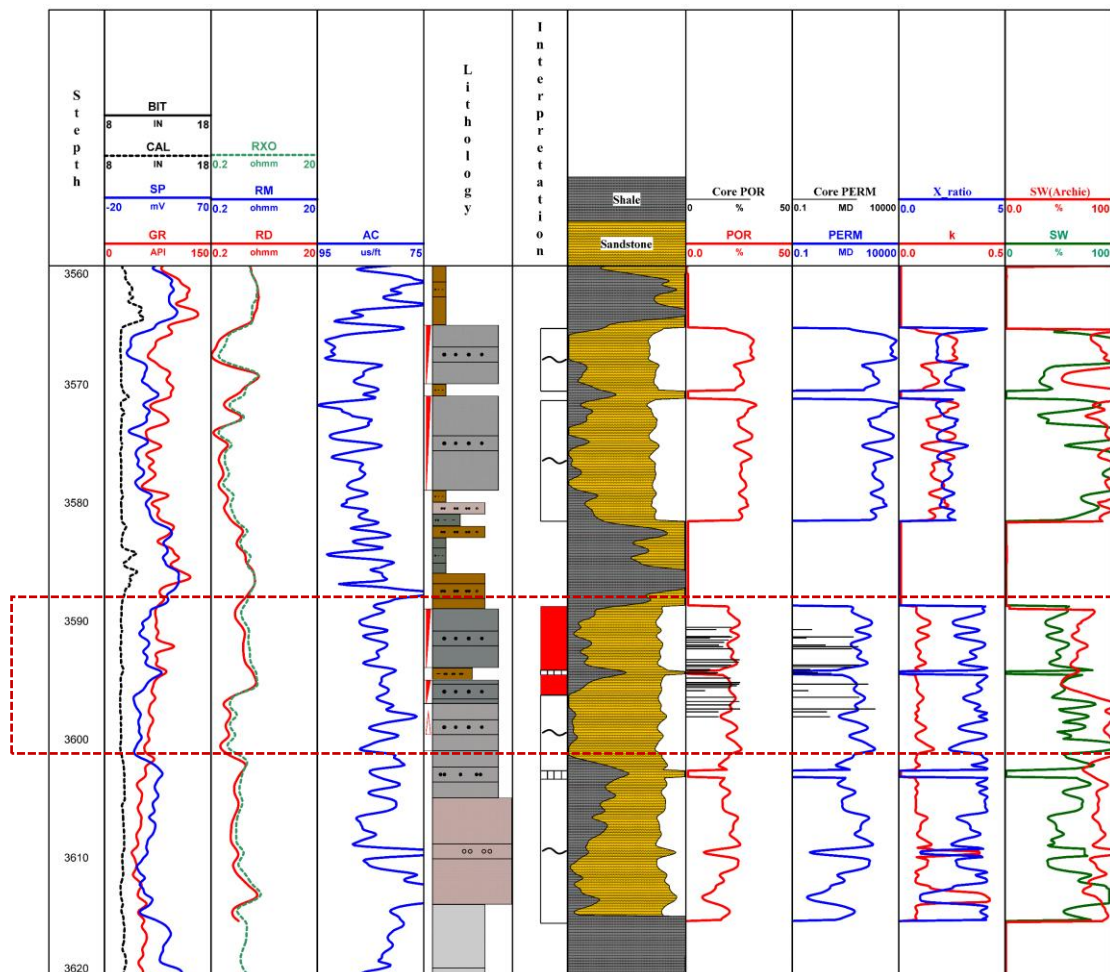
6 Application and Validation of the Model Using Logging Data

Based on high-pressure mercury intrusion, nuclear magnetic resonance, and rock-electrical experiments, the preceding sections established a water-saturation evaluation model for low-resistivity reservoirs jointly constrained by pore-throat structure, bound-water occurrence, and film-water conductivity enhancement, and completed the experimental inversion of key parameters. However, core experimental results represent reservoir characteristics only at discrete depth points. To achieve continuous identification and quantitative evaluation of low-resistivity oil reservoirs, it is necessary to establish relationships between model parameters and conventional logging responses and to incorporate the model into the logging interpretation workflow. Therefore, in this section, the pore-throat-structure-constrained saturation model developed above is applied to actual logging data and compared with oil-test results to preliminarily evaluate its applicability for wellbore-scale identification of low-resistivity oil reservoirs.

In field application, porosity, permeability, and related pore-throat structural parameters are first inverted from conventional logging curves. Then, based on the relationships established from core experiments among k and porosity–permeability parameters, E and k , and β and the petrophysical index T , continuous model parameters are obtained along the well interval. Finally, the pore-throat-structure-constrained model is embedded into the water-saturation calculation workflow to generate a continuous S_w profile. This workflow can, to some extent, extend discrete core-scale experimental understanding to the logging scale. Nevertheless, its reliability still depends on the accuracy of porosity–permeability interpretation, the stability of parameter-fitting relationships, and the degree of core–logging scale matching.

Figure 23 presents the integrated logging interpretation results for the 3590 m interval of the study well. From left to right, the figure shows conventional logging curves, including spontaneous potential (SP), resistivity (RT), acoustic transit time (AC), and density (DEN); lithological interpretation and stratigraphic subdivision results; and the porosity (POR), permeability (PERM), and water-saturation (Sw) profiles calculated using the proposed method. This interval generally exhibits a low-resistivity response, with $RT < 1 \text{ } \Omega \cdot \text{m}$ in some sections. If the conventional Archie model is applied, such low resistivity is likely to be interpreted as high water saturation, thereby increasing the risk of misclassifying low-resistivity oil-bearing intervals as water layers or poor oil zones.

By contrast, the proposed model jointly considers the pore-throat radius distribution, the lower seepage limit, and the additional conductive contribution of bound water films under strongly water-wet conditions. The calculated results still identify relatively low water-saturation responses within low-resistivity intervals, showing good consistency with oil-test interpretations. In future work, multi-well and multi-layer comparisons should be further expanded, and quantitative differences between the proposed model and the Archie model should be evaluated in terms of water saturation, interpretation conclusions, and oil-test results.



production test result

In May 1993, an oil test was conducted in this interval (3587.0–3596.5 m). The test results showed an oil production rate of 4.14 m³/d and a water production rate of 0.43 m³/d, indicating a water-bearing oil layer. In February 1999, another oil test was conducted, yielding an oil production rate of 31.73 m³/d with no water production; the interval was therefore interpreted as an oil layer.

Figure 23 Logging processing diagram and oil testing conclusion

7 Conclusions

This study focuses on strongly water-wet, low-resistivity oil reservoirs in the Lunnan area and investigates the origin of low-resistivity responses, microscopic fluid occurrence, film-water conduction mechanisms, and quantitative water-saturation evaluation. By integrating lithology, clay mineralogy, conductive mineral analysis, wettability measurements, nuclear magnetic resonance, high-pressure mercury intrusion, and rock-electrical experiments, a water-saturation evaluation model for low-resistivity reservoirs was established that incorporates microscopic pore-throat structural constraints and additional electrical double-layer conduction. The model was further applied to actual logging interpretation. The main conclusions are as follows.

(1) The low-resistivity response in the study area is not primarily controlled by lithology, clay minerals, or conductive minerals. Lithological analysis indicates that the reservoirs are dominated by sandstone and generally exhibit favorable pore structures. The overall clay mineral content is low, suggesting limited clay-related excess conduction. In addition, strongly conductive minerals such as pyrite occur in low abundance and are unlikely to form continuous and effective conductive networks. Therefore, conventional lithological factors and conductive minerals are not the dominant controls on the low-resistivity responses in the study area.

(2) Wettability analysis shows that the rocks in the E interval are generally water-wet to strongly water-wet, with strongly water-wet samples being dominant. Under strongly water-wet conditions, formation water tends to adsorb onto pore-wall surfaces as film water and may form continuous or semi-continuous conductive networks where pore-throat connectivity is favorable. Even after substantial displacement of free water during hydrocarbon charging, a portion of bound water can remain as capillary water in micropores and film water along pore walls. This residual bound-water network significantly enhances rock conductivity and constitutes an important microscopic basis for the low-resistivity response in the study area.

(3) Based on interfacial thermodynamic equilibrium theory, this study established an equilibrium relationship between oil–water capillary pressure and film-water disjoining pressure in strongly water-wet pores, and derived a functional expression describing the variation of water-film thickness X with pore-throat radius r . The results indicate that film-water thickness is controlled by the strength of rock–fluid interfacial interactions and can be characterized by the comprehensive surface physicochemical coefficient k . This parameter provides a physical link between microscopic interfacial thermodynamic processes and macroscopic rock-electrical responses.

(4) Joint inversion using high-pressure mercury intrusion and nuclear magnetic resonance experiments enabled quantitative partitioning of bound water into different occurrence states. Mercury intrusion data were used to determine the critical seepage cutoff radius and the volume of capillary-immobile water in fine pores, whereas the NMR T2 spectra were used to calibrate the macroscopic total bound-water saturation. By combining these two constraints, the volume of film water along macropore walls

was further determined, and the microscopic thermodynamic coefficient k was inverted. This approach provides a closed constraint linking pore-throat structure, bound-water occurrence, and interfacial thermodynamic parameters.

(5) Dynamic resistivity experiments during core displacement demonstrate that the conventional Archie model cannot accurately describe the dynamic variation of the resistivity index with water saturation in strongly water-wet, low-resistivity oil reservoirs. The dual-network rock-electrical model developed in this study incorporates capillary water in micropores, pore-wall film water, and additional electrical double-layer conduction, and can better explain the persistence of relatively low resistivity indices under low water-saturation conditions. The fitting results further show a clear functional relationship between the conductivity enhancement ratio E and the microscopic thermodynamic coefficient k , while the cutoff exponent β also exhibits a favorable mapping relationship with the reservoir petrophysical index T . These relationships provide a basis for extending model parameters from the core-experiment scale to the continuous logging-evaluation scale.

(6) After application to actual logging data, the proposed model yielded results that are broadly consistent with oil-test interpretations. Compared with the conventional Archie model, the proposed method can effectively reduce the risk of misclassifying low-resistivity oil reservoirs as high-water-saturation zones or water-bearing layers. It remains capable of identifying oil-bearing intervals under a low-resistivity background. These results indicate that a saturation evaluation method incorporating pore-throat structural constraints, strongly water-wet film-water occurrence, and conductivity enhancement effects has good applicability in the logging interpretation of strongly water-wet, low-resistivity oil reservoirs.

Although the proposed model can effectively explain the anomalous conductive mechanism of strongly water-wet, low-resistivity oil reservoirs in the study area and has been preliminarily validated using logging data, several aspects still require further improvement.

(1) Film-water thickness and its conductivity enhancement effect require more direct experimental constraints. In this study, film-water parameters were indirectly inverted based on interfacial thermodynamic equilibrium and multiscale experimental data. However, under real reservoir conditions, film-water thickness, electrical double-layer structure, and the degree of surface ion enrichment may be affected by multiple factors, including mineral composition, formation-water salinity, temperature, and pressure. Future studies may combine low-field NMR, micro- to nanoscale CT, atomic force microscopy, and interfacial electrochemical measurements to more directly characterize film-water occurrence and surface-conduction capacity.

(2) Continuous inversion of model parameters at the logging scale still requires further optimization. Core experiments provide detailed information on pore-throat structure and rock-electrical responses, whereas logging data are limited by vertical resolution, and the responses of different logging curves to pore structure and fluid properties are often nonunique. Future work may integrate machine learning,

multimineral inversion, NMR logging, electrical imaging logging, and array induction logging to improve the continuous inversion accuracy of pore-throat structural parameters, film-water conductivity parameters, and water saturation.

(3) The application of the model to production dynamics deserves further investigation. This study mainly validated the model using static logging interpretation and core experimental data. In the future, the model could be integrated with production performance, oil testing and trial production, water-cut evolution, and remaining-oil distribution prediction to explore its potential applications in low-resistivity reservoir identification, remaining-oil evaluation, and injection–production adjustment during field development.

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Conflict of Interest Disclosure

The authors declare no conflicts of interest relevant to this study.

References

- Abu-Al-Saud, M. O., Riaz, A., & Tchelepi, H. A. (2016). Multiscale level-set method for accurate modeling of immiscible two-phase flow with deposited thin films on solid surfaces. *Journal of Computational Physics*, 333, 297–320. <https://doi.org/10.1016/j.jcp.2016.12.038>
- Amadu, M., & Miadonye, A. (2024). Effect of equilibrium contact angle on water equilibrium film thickness for the carbon dioxide–brine–mineral system based on surface force theory. *Journal of Petroleum Exploration & Production Technology*, 14(7). <https://doi.org/10.1007/s13202-024-01793-9>
- A P W J G, A M J H A, & B J P. (2000). A modified Archie's law for two conducting phases. *Earth and Planetary Science Letters*, 180(3–4), 369–383. [https://doi.org/10.1016/S0012-821X\(00\)00168-0](https://doi.org/10.1016/S0012-821X(00)00168-0)
- Archie, G. E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the AIME*, 146(1), 54–62. <https://doi.org/10.2118/942054-G>
- Bernard, N., Soullaine, C., & Roman, S. (2010). Impact of wetting films on the stability of two-phase flow in porous media: A pore-doublet perspective. *Advances in Water Resources*, 204, 14. <https://doi.org/10.1016/j.advwatres.2025.105060>

- Changwei, C., Baozhi, P., Xuechun, L., et al. (2025). Evaluation of low-resistivity reservoirs based on the new three-water model and comprehensive identification of fluid properties using a committee machine—A case study of the Dongying Formation Member 1 Reservoir in the Gangdong Fault Zone. *Journal of Geophysics and Engineering*, 2025(2), 2. <https://doi.org/10.1093/jge/gxaf022>
- Clavier, C., Coates, G., & Dumanoir, J. (1984). Theoretical and experimental bases for the dual-water model for interpretation of shaly sands. *Society of Petroleum Engineers Journal*, 24(2), 153–168. <https://doi.org/10.2118/6859-PA>
- Deng, R. (2024). Saturation calculation for low-resistivity reservoirs caused by pyrite conductivity. *Processes*, 12. <https://doi.org/10.3390/pr12122682>
- Derjaguin, B. V., Churaev, N. V., & Muller, V. M. (1987). *Surface Forces*. Consultants Bureau. <https://doi.org/10.1007/978-1-4757-6639-4>
- Du, Z.-L., et al. (2004). 3D seismic prospecting of Ordovician buried hill in Sangtamu Area, Tarim Basin. *Xinjiang Petroleum Geology*.
- Gerhard, H., Findenegg, et al. (1997). Wetting: Statics and dynamics. *Current Opinion in Colloid & Interface Science*. [https://doi.org/10.1016/S1359-0294\(97\)80039-8](https://doi.org/10.1016/S1359-0294(97)80039-8)
- Glover, P. W. J. (2010). A generalized Archie's law for n phases. *Geophysics*, 75(6). <https://doi.org/10.1190/1.3509781>
- Guo, Y. H., Wang, W. Y., Pan, B. Z., et al. (2026). Study on the conductive mechanism and saturation model of continental shale oil reservoirs with complex mineral composition. *Petroleum Science*, 23(1), 143–156. <https://doi.org/10.1016/j.petsci.2025.08.021>
- Hamada, G. M., et al. (2001). Petrophysical evaluation of low-resistivity sandstone reservoirs with nuclear magnetic resonance log. *Journal of Petroleum Science & Engineering*. [https://doi.org/10.1016/S0920-4105\(01\)00095-X](https://doi.org/10.1016/S0920-4105(01)00095-X)
- Hirasaki, G. J. (1991). Wettability: Fundamentals and surface forces. *SPE Formation Evaluation*, 6(2), 217–226. <https://doi.org/10.2118/17367-PA>
- Jinglan, L., Yaquan, D., Division, T. F. P. R., et al. (2007). Analysis of depositional system and paleocurrent on Chang 6 and Chang 8 of the Yanchang Formation in the Southwestern Ordos Basin. In *The IPACES 6th Annual Meeting*.
- Jing-Qiang, L., Chao-Mo, Z., & Zhansong, Z. (2016). Combine the capillary pressure curve data with the porosity to improve the prediction precision of permeability of sandstone reservoir. *Journal of Petroleum Science and Engineering*. <https://doi.org/10.1016/j.petrol.2015.12.018>
- Lenormand, R., Zarcone, et al. (1983). Mechanisms of the displacement of one fluid by another in a network of capillary ducts. *Journal of Fluid Mechanics*. <https://doi.org/10.1017/S0022112083003110>
- Liu, C., Ma, L., Liu, C., et al. (2025). Quantitative study of microscopic formation water distribution in tight gas reservoirs based on the thermogravimetric method. *Frontiers in Earth Science*, 13, 1627768. <https://doi.org/10.3389/feart.2025.1627768>
- Liu, J., Xie, R., Guo, J., et al. (2022). Novel method for determining irreducible water saturation in a tight sandstone reservoir based on the nuclear magnetic resonance T₂ distribution. *Energy & Fuels*. <https://doi.org/10.1021/acs.energyfuels.2c02507>

- Markova, I., Markov, M., & Jarillo, G. R. (2024). Effective medium approximation for the electromagnetic properties of rocks with surface conductivity. *Journal of Applied Geophysics*, 229. <https://doi.org/10.1016/j.jappgeo.2024.105497>
- Mason, G., & Morrow, N. R. (1991). Capillary behavior of a perfectly wetting liquid in irregular triangular tubes. *Journal of Colloid & Interface Science*, 141(1), 262–274. [https://doi.org/10.1016/0021-9797\(91\)90321-X](https://doi.org/10.1016/0021-9797(91)90321-X)
- Mu, Y., Hu, Z., Guo, Q., et al. (2023). Water distribution in marine shales: Based on two-dimensional nuclear magnetic resonance and low-temperature nitrogen adsorption. *Energy & Fuels*. <https://doi.org/10.1021/acs.energyfuels.3c00029>
- Norouzisadeh, M., Leroy, P., & Soulaïne, C. (2024). A lubrication model with slope-dependent disjoining pressure for modeling wettability alteration. *Computer Physics Communications*, 298. <https://doi.org/10.1016/j.cpc.2024.109114>
- Oron, A., Stephen, et al. (1997). Long-scale evolution of thin liquid films. *Reviews of Modern Physics*. <https://doi.org/10.1103/RevModPhys.69.931>
- Purcell, W. (1949). Capillary pressures—Their measurement using mercury and the calculation of permeability therefrom. *Journal of Petroleum Technology*, 1, 39–48. <https://doi.org/10.2118/949039-G>
- Qi, Y., & Wu, Y. (2022). Electrical conductivity of clayey rocks and soils: A non-linear model. *Geophysical Research Letters*, 49(10). <https://doi.org/10.1029/2021GL097408>
- Qi, Y., & Wu, Y. (2025). Revisiting the relationship between induced polarization and surface conductivity: Ratios from laboratory to field. *Journal of Geophysical Research: Solid Earth*, 130(4). <https://doi.org/10.1029/2024JB030406>
- Revil, A., & Glover, P. W. J. (1998). Nature of surface electrical conductivity in natural sands, sandstones, and clays. *Geophysical Research Letters*, 25(5), 691–695. <https://doi.org/10.1029/98GL00296>
- Roman, S., Abu-Al-Saud, M. O., Tokunaga, T., et al. (2017). Measurements and simulation of liquid films during drainage displacements and snap-off in constricted capillary tubes. *Journal of Colloid & Interface Science*, 279. <https://doi.org/10.1016/j.jcis.2017.07.092>
- Rostron, B. J. (2018). Multiphase flow in permeable media: A pore-scale perspective. *Groundwater*, 56(5), 688–689. <https://doi.org/10.1111/gwat.12812>
- Soldi, M., Guarracino, L., Rembert, F., et al. (2024). Electrical conductivity model for reactive porous media under partially saturated conditions with hysteresis effects. *Advances in Water Resources*, 193. <https://doi.org/10.1016/j.advwatres.2024.104815>
- Song, F., et al. (2008). Origin of low resistivity reservoirs in low angle drape structure in Lunnan, Tarim Basin. *Petroleum Exploration and Development*, 35(1), 108–112.
- Swanson, B. F. (1981). A simple correlation between permeabilities and mercury capillary pressures. *Journal of Petroleum Technology*, 33(12), 2498–2504. <https://doi.org/10.2118/8234-PA>
- Wang, H., & Revil, A. (2020). Surface conduction model for fractal porous media. *Geophysical Research Letters*. <https://doi.org/10.1029/2020GL087553>

- Wang, S., Xie, R. H., Jin, G. W., et al. (2024). A new method for fluid identification and saturation calculation of low contrast tight sandstone reservoir. *Petroleum Science*, 21(5), 3189–3201. <https://doi.org/10.1016/j.petsci.2024.07.005>
- Wang, X., Zhu, X., & Zhang, X. (2023). Genetic mechanisms and multiparameter logging identification of low-resistivity oil pay: A case study of the Triassic Chang 6 Member, Zhidan Area, Ordos Basin, China. *ACS Omega*, 8, 23425–23445. <https://doi.org/10.1021/acsomega.3c00120>
- Waxman, M. H. (1968). Electrical conductivities in oil-bearing shaly sands. *Society of Petroleum Engineers Journal*, 8(8), 107–122. <https://doi.org/10.2118/1863-A>
- Xia, X., Xia, Y., Zhao, F., et al. (2024). Evaluating the surface relaxivity and movable fluid of low-permeability sandstones based on low-field nuclear magnetic resonance. *Physics of Fluids*, 36(11), 116619. <https://doi.org/10.1063/5.0238003>
- Xiaomei, W., Jingzhou, Z., & Xinshe, L. (2012). Occurrence state and production mechanism of formation water in tight sandstone reservoirs of Sulige area, Ordos Basin. *Petroleum Geology & Experiment*, 34(4), 400–405.
- Yang, H. J., & Han, J. F. (2008). Accumulation characteristics and the main controlling factors of Lunnan multilayer oil province, Tarim Basin, China. *Science China Earth Sciences*, S1, 12. <https://doi.org/10.1007/s11430-008-5015-z>
- Yuan, L., Habibi, A., & Dehghanpour, H. (2021). Liquid imbibition in tight rocks: The role of disjoining pressure. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 127037. <https://doi.org/10.1016/j.colsurfa.2021.127037>
- Zhu, C., Guo, W., Li, Y., et al. (2021). Effect of occurrence states of fluid and pore structures on shale oil movability. *Fuel*, 288, 119847. <https://doi.org/10.1016/j.fuel.2020.119847>
- Zou, G., Zhu, W., Liu, W., et al. (2020). Research on the movable water in the pores of tight sandstone gas reservoirs. <https://doi.org/10.1002/9781119593324.ch21>