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Perspective

Digital rock physics and resistivity well logging interpretation in unconventional reservoirs: Advances and prospects

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Abstract:
Unconventional hydrocarbon reservoirs, characterized by multiscale and complex pore architectures, diverse mineralogical compositions, and pronounced heterogeneity, present significant limitations to conventional saturation estimation and reservoir evaluation methods, with resistivity well logging data based on classic models such as Archie's equations. Digital rock physics technology, integrating multi-scale imaging, three-dimensional reconstruction, and numerical simulation, enables the precise characterization of pore structures and conductive mechanisms, markedly enhancing the accuracy of electrical response simulations and well logging evaluations in complex reservoirs. Through this perspective, this study systematically compares the application limitations and associated impacts of conventional resistivity logging in unconventional reservoirs of various lithologies and evaluates the applicability and merits of distinct rock physics numerical simulation approaches, highlighting existing constraints and challenges. Furthermore, this work outlines future directions for integrating digital rock physics with well logging evaluation.

1. Introduction

With the advancement of petroleum exploration, unconventional hydrocarbon reservoirs have become a focal point of related international research. In contrast to conventional reservoirs, unconventional systems exhibit heterogeneous pore types, intricate pore structures, and complex hydrocarbon distributions, presenting significant challenges for evaluating unconventional reservoirs. In-situ coring is both technically demanding and expensive, and existing core analysis techniques remain suboptimal for capturing the full complexity of these systems. Therefore, to better characterize and understand unconventional reservoirs, digital rock physics has emerged as a rapidly growing and increasingly essential methodology.

Despite rapid progress in this field, a persistent disconnect remains between digital rock physics and practical well logging evaluation. To date, studies of electrical conduction in digital rocks and their applications in well logging interpretation have largely followed independent tracks. While the former field of research has primarily emphasized the refinement of numerical simulation methodologies and the elucidation of electrical conduction mechanisms, with the aim of revealing conductive behavior at the pore scale, the latter has mainly focused on leveraging conventional approaches and sparse datasets to develop interpretation models that better reflect reservoir conditions. The resulting gap has two key implications: first, findings from digital rock electrical studies have been slow to translate into practical tools for log interpretation, reducing the value of pore-scale physics in field applications; second, well logging evaluation, lacking pore-scale mechanistic support, exhibits limited accuracy and

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generalizability in complex reservoirs.

To bridge the above research gap, this study establishes an integrative framework that unites digital rock physics and well logging evaluation, yielding value in two principal aspects. First, deep insights into pore-scale conductive mechanisms afforded by digital rock analysis can provide the theoretical underpinnings for constructing rock-physics models, thereby facilitating the optimization of model parameters to more accurately capture the realities of complex reservoirs. Second, the application scenarios of well logging evaluation can guide the research trajectory of digital rock technology, driving the development of more targeted simulation methods and analytical approaches. This integrative framework can be operationalized through a systematic workflow: first, a static digital twin multiscale imaging and mineral mapping can be performed; second, pore-scale conductivity can be elucidated by conductivity numerical simulations; third, these microscopic insights can be translated into macroscopic, log-compatible model parameters using abstract modeling and upscaling techniques; and finally, continuous calibration with actual well logging data can ensure practical relevance and accuracy. This closed-loop process addresses a previously unfilled gap in the combined domain of these two fields. The typical workflow from digital rock physics to well logging interpretation, including digital core reconstruction, simulation, and interpretation, is presented in Fig. 1.

2. Application limitations of the resistivity logging method

Conventional approaches to saturation evaluation predominantly employ Archie's equations or its variants in conjunction with well logging data. However, in unconventional reservoirs such as shales, organic matter and clay minerals exert a pronounced influence on resistivity logging responses, rendering Archie's model less effective. Accurately identifying multiple pore-system types and quantitatively characterizing reservoir parameters under complex pore structures has become a key challenge in well logging interpretation (Cai et al., 2017). Traditional assessments based on Archie's equations and its derivatives rely on simple empirical relationships suitable for clean, homogeneous sandstones. Archie's model, however, lacks a rigorous theoretical foundation and assumes a unique saturation-resistivity relationship, a constant saturation exponent, and the absence of electrically ineffective porosity (Mungan and Moore, 1968). Hence, these assumptions fail in unconventional reservoirs such as tight sandstones and shales where microporosity, clay-associated pores and fractures disrupt conductive pathways, creating anisotropy and non-unique saturation-resistivity behavior (Wang et al., 2025). Clay minerals and irreducible water further complicate conduction via introducing additional conductive pathways and non-conductive dead-end porosity (Nie et al., 2020). Table 1 summarizes the limitations of applying conventional resistivity logging to unconventional reservoirs.

In view of the above, traditional Archie-based models yield substantial errors when applied to unconventional reservoirs with complex pore architectures and multiple conductive mechanisms. Improving evaluation accuracy requires models that explicitly integrate microstructural geometry, mineral composition, and multiphase conductive behavior. In this regard, digital rock technology provides a transformative tool, enabling pore-scale simulations that couple structure, composition, and conduction mechanisms, thereby offering a robust foundation for advancing electrical-response modeling beyond the limits of empirical approaches.

3. Digital rock physics for studying rock conductivity

(1) From imaging to mechanism

Saturation estimation by using well logs is constrained in precision by conventional core experiments (full-diameter or plug cores), which fail to accurately capture the microscopic pore architecture and conductive properties of unconventional reservoirs. In essence, conventional experiments provide only statistical averages, while the mechanisms governing electrical conduction are inherently controlled by pore-scale geometry, highlighting a structural mismatch between actually and optimally measured data. To bridge this gap, multi-scale imaging and quantitative mineral composition analysis within the framework of digital rock experimentation have become essential tools for characterizing rock structures and pore features, such as organic matter distribution, mineral content, grain support and size distribution, pore-throat radius distribution and connectivity, as well as fluid-flow characteristics. This technology enables the construction of physical models approximating actual cores and the reconstruction of complex internal pore networks without damaging samples, hence it has emerged as one of the key methods for investigating the rock-physics properties of unconventional reservoirs (Zhou et al., 2024).

Digital rock physics has shifted from being merely a "descriptive imaging tool" to a "mechanistic vision" capable of revealing how electrical pathways emerge, evolve and respond to fluid distributions. In recent years, digital rock studies of electrical properties have primarily concentrated on the numerical simulation of electrical behavior and the investigation of reservoir rock conduction mechanisms, analyzing the coupled relationships among pore-fluid distributions, mineral composition and conductive networks to elucidate pore-scale mechanisms of conduction. In addition, digital rock physics provides substantial value for well logging evaluation: by simulating logging responses under varying fluid saturations, it enables the development of interpretation models that more faithfully represent actual reservoirs, and by reconstructing digital rocks to analyze electrical anisotropy, it provides a mechanistic basis for evaluating complex reservoirs, thereby improving the accuracy and reliability of quantitative reservoir assessment.

In complex unconventional reservoirs, uncertainties in rock electrical responses hinder fine-scale reservoir evaluation. To better simulate the electrical behavior of rock, it is crucial to integrate data on its microscopic pore architecture and mineral composition. High-resolution X-ray computed tomography (CT) and focused ion beam-scanning electron microscopy

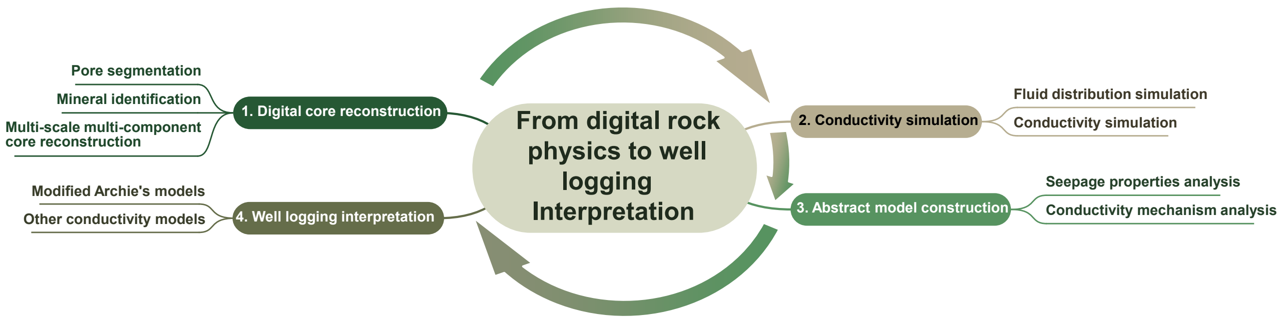

Fig. 1. Workflow diagram of digital core reconstruction, simulation and interpretation.

Table 1. Limitations of resistivity logging in unconventional reservoirs.

Lithology	Limitation	Influence
Shales	Clay mineral content, spatial distribution, additional conductivity; bedding-induced electrical anisotropy	Inapplicability of Archie's law
Tight sandstones	Low resistivity resolution caused by low porosity; microfracture development	Fracture-water-induced low resistivity response
Natural gas hydrates	Heterogeneous hydrate distribution; effects of hydrate decomposition; unclear resistivity response mechanism	Ineffective identification of reservoir fluid properties
Carbonates	Fracture and cavern development; large variations in shale and mineral composition	Difficulty in evaluating reservoir oil-bearing properties; challenges in saturation calculation
Asphaltenes	Inherent conductivity of asphaltenes; heterogeneous asphaltene distribution	Problems in reservoir identification; challenges in saturation calculation

enable the construction of digital rock models that capture microporosity, providing structural and compositional inputs for numerical simulations, while quantitative mineral content evaluation methods provide the component information (Li et al., 2022a).

(2) Numerical simulation methods

Taking the digital core models containing structural and component information as bases, electrical conductivity simulations can be established. Common simulation approaches, including Kirchhoff network, random-walk, lattice Boltzmann and finite element methods, differ in efficiency and precision. However, the choice of method is no longer merely a computational decision but reflects a deeper scientific stance on what physical mechanisms are prioritized. The Kirchhoff network is efficient for higher-porosity rocks; random-walk is characterized by its mesh-free nature that easily handles complex pore geometries; the lattice Boltzmann method excels in multiphase and micropore-scale conduction; and the finite element method achieves high accuracy and anisotropy analysis. A more nuanced comparison should consider multiple dimensions, such as computational efficiency, the handling of complex pore geometries, capability for multiphase flow simulation, and accuracy in anisotropy analysis. This systematic evaluation provides a clearer decision-making basis for method selection based on specific research objectives and computational resources. Voxel-based meshes cause excessive computational costs, addressed by Xiao et al., 2024 via the adaptive tetrahedral finite element method, while unresolved nanoscale pores introduce errors, mitigated by Saxena et al., 2021 through algorithmic pore reconstruction.

(3) Applications in various unconventional reservoirs

Across reservoir types, multiscale and compositional complexities need to be focused on. In shales, conductivity modeling links composition with resistivity, and multiscale four-dimensional digital rock models enhance nanopore localization and saturation simulation (Li et al., 2022b). Tight sandstones, characterized by low porosity and complex pore networks, have been modeled under high-temperature, high-pressure conditions and through multi-source integration to reveal difficult-to-measure electrical responses (Shang et al., 2023). In gas hydrate reservoirs, digital rocks from CT images or stochastic modeling inform hydrate distribution, while modified empirical equations improve saturation estimation (Zhao et al., 2021). In carbonates, dual-porosity conduction models and studies on asphaltene infilling (Wu et al., 2024) elucidate non-Archie behavior and compositional impacts, advancing the quantitative characterization of complex pore-fluid-matrix interactions. In this way, digital rock physics technology is adapting to the characteristics of unconventional reservoirs and has played an important role in revealing the conduction mechanism.

(4) Challenges in upscaling and applications

Digital rock physics simulation results can provide important insights into the electrical conductivity mechanism, but how to apply them to well logging interpretation through upscaling remains a significant challenge. The representative elementary volume of digital rock simulations is typically at the nanoscale to the microscale, while logging detection operates at the decimeter scale. Achieving seamless and high-precision upscaling from the micro- to the macroscale is a core issue. In unconventional reservoirs, simple averaging methods lose critical geological information, and obtaining high-quality, statistically representative digital rock images is extremely difficult. Whether a tiny core sample can represent the heterogeneity of the entire reservoir interval is questionable. For highly heterogeneous unconventional reservoirs, a large number of samples are required for statistical upscaling, making computational costs and data acquisition extremely challenging. Furthermore, even when the upscaled electrical model with log data is perfectly matched, there is another dilemma of multi-solution in log data inversion. How to strip away environmental influences such as drilling fluid invasion, confining pressure effects, and tool response to achieve a "pure" validation of the electrical model itself is also a critical bottleneck that needs to be resolved in current applications.

4. Conclusions and prospects

Digital rock serves as a key tool for unconventional well logging evaluation. Multiscale imaging combined with simulation non-destructively resolves complex pore and mineral structures, addresses challenges such as in-situ coring, cost and variable control, and clarifies the pore-scale conduction mechanisms. By linking microscale and macroscale responses, digital rock workflows can calibrate saturation-estimation models and improve saturation models and evaluation accuracy.

Despite the aforementioned advances, many factors remain to be studied in the future. For fractured reservoirs, high-fidelity models incorporating varied fracture orientations and traits are needed to simulate fluid-geometry-saturation relationships. As for pore architecture, synthetically prescribed pore attributes (such as pore types and pore-throat geometry) are required to correlate pore-structure indices with micro-features and supply quantitative parameters. In terms of pore tortuosity, CT-based estimation methods require improvements through the enhanced resolution of micropores, microfractures and capillary throats to increase calculation accuracy. Furthermore, for complex formations, the conductive efficiency of pores should be considered as electrical behavior influencing factors.

A particularly promising frontier lies at the intersection of digital rock physics and machine learning/artificial intelligence (Li et al., 2023). Machine learning can serve two transformative roles: first, as a "proxy model" trained on digital rock simulations to predict electrical properties millions of times faster, avoiding the inversion steps and enabling near-real-time log interpretation; second, as a data-mining tool to identify key feature patterns from vast multi-scale image and simulation data, potentially uncovering new physical insights and guiding more efficient modeling strategies.

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Conflict of interest

The authors declare no competing interest.

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