Advances in
Geo-Energy Research

Vol. 14, No. 2, p. 86-89, 2024

Perspective

Integrated rock physics characterization of unconventional shale reservoir: A multidisciplinary perspective

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Keywords:
Shale reservoir
rock physics
fracability
fluid flow

Cited as:
Zhao, L., Zhao, Y., Yan, D., Zhu, J., Cai, J. Integrated rock physics characterization of unconventional shale reservoir: A multidisciplinary perspective. Advances in Geo-Energy Research, 2024, 14(2): 86-89.
https://doi.org/10.46690/ager.2024.11.02

Abstract:
Renowned for its organic richness, unconventional shale presents both unique challenges and opportunities for hydrocarbon extraction and various geo-engineering applications, owing to its complex storage, flow, and stimulation properties. It is essential, from a multidisciplinary perspective, to characterize the rock physics response and construct rock physics model for unconventional shale reservoirs. A maturity-constrained rock physics modeling method for shales, in conjunction with geochemical analyses, is proposed, employing the stepwise homogenization method to quantify the scale-dependent elastic and anisotropic behavior of laminated shales. Considering the complex pore structure of shale, combined with the microscale effects of fluid transport, various forces, and microfracture features, the multiphase fluid flow behavior can be accurately characterized. Then, from the perspective of fracturing performance, it is necessary to develop a new fracability evaluation model for unconventional shale reservoirs. This model integrates fracture mechanics theory, the elastic and mechanical properties of rocks, fracturing operations, reservoir geological characteristics, and in-situ stress to thoroughly evaluate fracability. Unconventional petrophysicists must move beyond traditional hydrocarbon evaluation to embrace interdisciplinary approaches, which requires comprehensive understanding and characterization of the storage, flow, and stimulation capacities, thereby optimizing development strategies and maximize resource utilization.

1. Introduction

Shale, a sedimentary rock rich in organic material, typically forms in low-energy sedimentary environments and is prevalent in global sedimentary basins. A detailed understanding and characterization of shale are critical for various Earth sciences, environmental studies, and geo-engineering applications (Zhao et al., 2023a). The advent of technologies such as hydraulic fracturing and horizontal drilling has facilitated the extraction of oil and gas from low-porosity, low-permeability shale reservoirs. Notably, the United States has achieved energy self-sufficiency through the shale revolution, driving global interest in shale resource exploration. This shift is transforming and will continue to reshape the global energy landscape (Zou et al., 2021).

The characterization of shale is inherently complex. As illustrated in Fig. 1, it is imperative to consider both storage capacity factors, such as porosity, fluid saturation, total organic carbon content, organic matter maturity, and pore pressure, and flow capacity factors, including permeability, pore structure, natural fractures, and fluid viscosity. Additionally, evaluating in-situ stress, rock strength, heterogeneity, and brittleness/fracability is crucial as they reflect the shale's stimulation potential. These factors are interdependent, with each potentially affecting multiple capacities. Therefore, a comprehensive consideration of these aspects is essential for better understanding and characterization of shale, which will, in turn, optimize development strategies and enhance the efficient exploitation of shale reservoirs. Multidisciplinary efforts are evidently required to advance the rock physics characterization of unconventional shale reservoirs.

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Received July 10, 2024; revised August 11, 2024; accepted August 29, 2024; available online September 4, 2024.

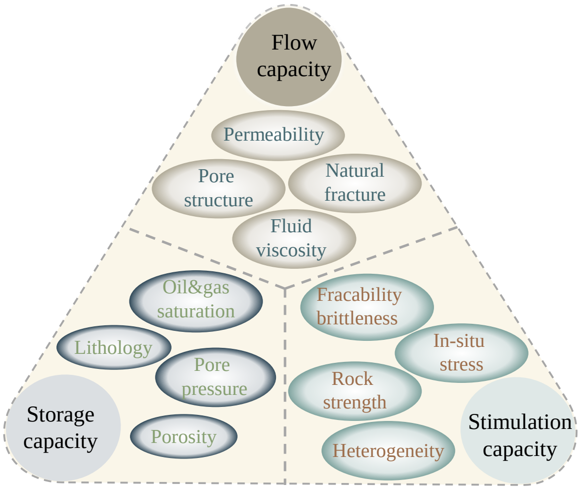

Fig. 1. Three critical aspects considering the efficient development of shale reservoirs.

2. Integrated geochemistry and multi-scale seismic rock physics

Establishing a rock physics relationship is crucial for linking the geological characteristics of unconventional reservoirs with their seismic responses, thus laying the groundwork for seismic characterization of unconventional shale reservoirs. The unique nature of organic shale lies in the fact that it contains various amount of organic matter, the physical properties of which strongly depend on the thermal maturity. Additionally, the presence of multiscale heterogeneous laminar structures, ranging from the micrometer to meter scale, results in elastic and anisotropic responses that are typically scale-dependent (Hart et al., 2013; Mokhtari et al., 2016). Fig. 2 schematically illustrates the rock physics modeling strategy for unconventional shale reservoirs. It is evident that geochemical evolution and step-wise upscaling approaches are crucial for accurately characterizing the multi-scale elastic and anisotropic responses of shale reservoirs.

The evolutionary characteristics of two types of organic matter (kerogen and bitumen), organic porosity during thermal maturation, and the elastic properties of organic matter and fluids have been systematically investigated in Zhao et al. (2023b). A joint geochemistry-rock physics model was proposed to quantify the effects of thermal maturity (Vitrinite reflectance, %Ro) on the elastic signatures the inorganic frame and fluid-filled porous organic matter, as well as their elastic interactions (Fig. 2(a)). Geological factors and reservoir properties at varying maturity levels distinctly impact the elastic and anisotropic behaviors of shale at the microscale, thereby influencing the elastic parameters at the core scale. As shown in Fig. 2(c) and 2(d), under the framework of multiscale homogenization, a rock physics model can be established to characterize the elastic and anisotropic properties of multiscale laminar shales from core scale, well-logging scale, to seismic scale. The elasticity simulation results from the preceding scale serve as elastic inputs for the subsequent scale.

The integration of geochemistry and multiscale methods provides a reliable approach to characterize the scale-dependent elastic responses of shale reservoirs at varying maturity stages.

3. Multi-phase fluid flow

Due to the complex pore structure of shale reservoirs with abundant nano/micropores, the microscale effects on fluid flow within the shale are significant. Microscale effects refer to the phenomena where the fluid flow behavior at the micron scale differs significantly from traditional macroscopic flow, and conventional fluid mechanics equations are inapplicable (Qin et al., 2024). Compared to the macroscopic scale, microscopic interaction forces (such as van der Waals forces and electrostatic forces) are significant at the microscopic scale. The microscale effects of fluid transport are primarily manifested in slip velocity, heterogeneous density and viscosity. Therefore, establishing a relative permeability model that accounts for fluid slip, microscopic oil-water distribution, and heterogeneous viscosity is crucial for characterizing multiphase fluid flow behavior (Wang et al., 2019). Additionally, unlike single-phase fluids, two-phase systems exhibit liquid-liquid interfacial slip velocity in addition to liquid-solid slip, which significantly impacts the flow capacity of two-phase fluids and cannot be ignored (Zhan et al., 2020; Xu et al., 2022). Due to tectonic stress, shale reservoirs are also rich in microfractures. Fracture roughness, fracture shape, and fracture tortuosity could affect the flow behavior of multiphase fluids within the fractures. It is necessary to comprehensively consider the fluid exchange mechanisms within the pore-fracture system.

In addition to microscopic forces, the multiphase fluid flow in shale is influenced by capillary force, elastic driving force, and shear force. The complex pore topology further results in the existence of corner flow, piston-like displacement, and snap-off (Luo et al., 2018; Wang et al., 2018; Xiao et al., 2018). It is necessary to consider microscale effects and the interplay of multiple forces to revise the pore-scale multiphase fluid transport equations. This approach characterizes the multiphase fluid distribution, velocity variations, relative permeability changes, and capillary pressure parameters within multimineral shale formations. This can provide key parameters (such as relative permeability and capillary pressure) for multiphase multiscale macroscopic numerical simulations that couple microscale effects.

4. Fracability evaluation

The assessment of shale reservoir fracability is crucial for identifying candidate zones that ensure optimal post-fracturing productivity and plays a key role in the design of fracturing operations. Traditionally, evaluating reservoir fracability has predominantly relied on brittleness indexes (Meng et al., 2021). These indexes focus primarily on intrinsic rock failure characteristics, offering limited insight into fracture propagation processes and the interactions between fluids and the rock matrix. Consequently, numerous studies have highlighted that brittleness indexes alone may not accurately evaluate fracability.

Hydraulic fracturing aims to create fractures within the

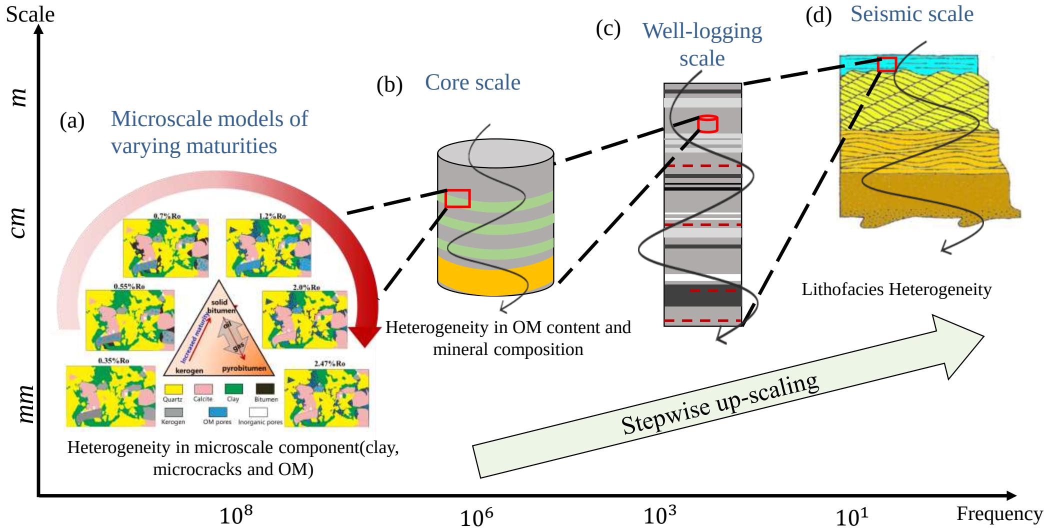

Fig. 2. Three critical aspects considering the efficient development of shale reservoirs.

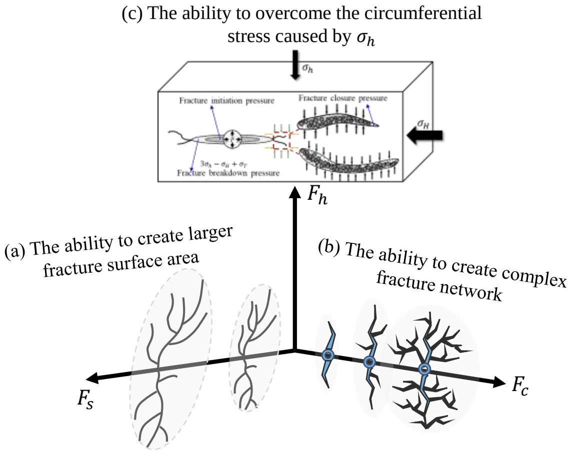

Fig. 3. Suggested fracability model based on fracturing performance. (a): F_s, index representing rock's ability to create larger fracture areas, (b): F_c, index signifying rock's ability to generate complex fracture networks, (c): F_h, index reflecting the influence of minimum in-situ stress on fracturing

formation, induce complex crack networks, and enhance reservoir permeability to release trapped oil and gas resources. Therefore, the evaluation of shale reservoir fracability should be based on ultimate fracturing performance, considering both rock failure and fracture propagation processes. As shown in Fig. 3, the proposed fracability assessment model encompasses three key factors: The rock's capacity to generate fracture surface area during fracturing, the ability to develop a complex fracture network, and the influence of in-situ stress. Integrating these factors allows for a comprehensive evaluation of the reservoir's fracturing potential, offering valuable guidance for optimizing fracturing design.

5. Integrated petrophysics evaluation

Integrated petrophysical evaluation has become a crucial component in the assessment and development of unconventional shale reservoirs. Accurate petrophysical characterization—including maturity constraints, shale mobility assessment, rock mechanics, geomechanical characterization, and reservoir fracability evaluation—is essential. Integrating these factors allows for a comprehensive understanding and characterization of the storage, flow, and stimulation capacities of unconventional reservoirs, thereby optimizing development strategies to address complex challenges and maximize resource utilization. Thus, innovative petrophysical methods and workflows are required, and unconventional petrophysicists must move beyond traditional hydrocarbon evaluation to embrace interdisciplinary approaches.

A multidisciplinary integrated petrophysics evaluation workflow for a typical tight gas reservoir was developed by Spain et al. (2015). This approach emphasizes key petrophysical characterizations, including the reservoir's storage capacity (total porosity, porosity thickness), flow capacity (flow units, effective gas permeability thickness), and stimulation capacity (minimum horizontal stress curve calibrated with after-closure analysis data). By integrating various data types and analytical techniques, this workflow provides a comprehensive understanding of reservoir properties. Such an approach not only improves the accuracy of petrophysical models but also optimizes development and production strategies for unconventional reservoirs.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos. U23B20157 and 42174134).

Conflict of interest

The authors declare no competing interest.

References

Hart, B. S., Macquaker, J. H., Taylor, K. G. Mudstone ("shale") depositional and diagenetic processes: Implications for seismic analyses of source-rock reservoirs. Interpretation, 2013, 1(1): B7-B26.

Luo, W., Tang, C., Zhou, Y., et al. A new semi-analytical method for calculating well productivity near discrete fractures. Journal of Natural Gas Science and Engineering, 2018, 57: 216-223.

Meng, F., Wong, L. , Zhou, H. Rock brittleness indices and their applications to different fields of rock engineering. A review. Journal of Rock Mechanics and Geotechnical Engineering, 2021, 13(1): 221-247.

Mokhtari, M., Honarpour, M. M., Tutuncu, A. N., et al. Characterization of elastic anisotropy in eagle ford shale: Impact of heterogeneity and measurement scale. SPE Reservoir Evaluation & Engineering, 2016, 19(3): 429-439.

Qin, X., Wu, J., Xia, Y., et al. Multicomponent image-based modeling of water flow in heterogeneous wet shale nanopores. Energy, 2024, 298: 131367.

Spain, D. R., Merletti, G. D., Dawson, W. Beyond volumetrics: Unconventional petrophysics for efficient resource appraisal (example from the Khazzan field, Sultanate of Oman). Paper SPE-172920-MS Presented at the SPE Middle East Unconventional Resources Conference and Exhibition, Muscat, Oman, 26-28 January, 2015.

Wang, F., Yang, K., Cai, J. Fractal characterization of tight oil reservoir pore structure using nuclear magnetic resonance and mercury intrusion porosimetry. Fractals, 2018, 26(2): 1840017.

Wang, H., Su, Y., Wang, W., et al. Relative permeability model of oil-water flow in nanoporous media considering multi-mechanisms. Journal of Petroleum Science and Engineering, 2019, 183: 106361.

Xiao, J., Cai, J., Xu, J. Saturated imbibition under the influence of gravity and geometry. Journal of Colloid and Interface Science, 2018, 521: 226-231.

Xu, J., Zhan, S., Wang, W., et al. Molecular dynamics simulations of two-phase flow of n-alkanes with water in quartz nanopores. Chemical Engineering Journal, 2022, 430: 132800.

Zhan, S., Su, Y., Jin, Z., et al. Study of liquid-liquid two-phase flow in hydrophilic nanochannels by molecular simulations and theoretical modeling. Chemical Engineering Journal, 2020, 395: 125053.

Zhao, L., Cai, Z., Qin, X., et al. An empirical elastic anisotropy prediction model in self-sourced reservoir shales and its influencing factor analysis. Geophysics, 2023a, 88(3): MR117-MR126.

Zhao, L., Zhu, J., Qin, X., et al. Joint geochemistry-rock physics modeling: Quantifying the effects of thermal maturity on the elastic and anisotropic properties of organic shale. Earth-Science Reviews, 2023b, 247: 104627.

Zou, C., Zhao, Q., Cong, L., et al. Development progress, potential and prospect of shale gas in China. Natural Gas Industry, 2021, 41(1): 1-14. (in Chinese)