Advances in Geo-Energy Research
Vol. 17, No. 2, p. 91-94, 2025

Perspective

Evaluation of the cross-scale mechanical behavior and fracability of deep shales: How innovations benefit the exploitation of deep resources

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Keywords:
Multi-scale rock mechanics
brittleness
fracability
machine learning

Cited as:
Zhao, G., Guo, Y., Yang, C., Chang X., Zhang X. Evaluation of the cross-scale mechanical behavior and fracability of deep shales: How innovations benefit the exploitation of deep resources. Advances in Geo-Energy Research, 2025, 17(2): 91-94.
https://doi.org/10.46690/ager.2025.08.01

Abstract:
Deep/ultra-deep oil and gas resources are abundant at vertical depths of more than 3,500 m, which is an important succeeding field for future oil and gas exploitation. However, a lack of understanding of the multi-scale mechanical behavior of deep reservoirs under in situ conditions, as well as an insufficiently accurate prediction of engineering sweet spots, restricts the effectiveness of hydraulic fracturing in deep shale gas exploitation. In this study, the application of cross-scale rock mechanics, digital rock core modeling, and machine learning in characterizing reservoir geomechanical properties and assessing engineering sweet spots was summarized. The challenges and future development directions of the above research elements were explored. To achieve efficient deep-resource exploitation, it's essential to clarify the mechanical behavior of shales with different mineral compositions at micro- and macro-scales. Numerical models incorporating mineral spatial heterogeneity were developed to analyze the multifactorial synergistic mechanism influencing shale brittle failure. Finally, intelligent fracability prediction methods for deep shale were proposed to accurately identify engineering sweet spots. The research findings have identified the key research and development directions for deep-resources development from a rock mechanics perspective.

1. Introduction

In engineering practice, deep shale formations often experience both high temperatures and high pressures. These conditions significantly alter their mechanical and brittleness properties, setting them apart from shallow to medium-depth shales (Cheng et al., 2023; Wu et al., 2025). Laboratory research methods for rock brittleness evaluation, which focus on modelling to characterize rock brittleness based on experimental results, are advanced (Rickman et al., 2008; Zhao et al., 2022). However, the physical connotations behind the brittleness index are unknown. Insufficient research into the multi-scale fracture mechanisms of shale under high-temperature and high-pressure conditions limits the precision of engineering sweet spot assessments in shale reservoirs (Hajiabdolmajid and Kaiser, 2003). Many deep shale gas wells and fracking candidates in the Sichuan Basin have been improperly deployed and have not produced enough gas or have even failed to come on stream (Zeng et al., 2023). It is crucial to develop a comprehensive fracability evaluation model for deep shales. Such a model would enhance the accuracy and reliability of assessing the fracability of deep shale reservoirs and offer theoretical support for reservoir modification efforts.

Yandy Scientific Press

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Received June 6, 2025; revised June 22, 2025; accepted July 1, 2025; available online July 4, 2025.

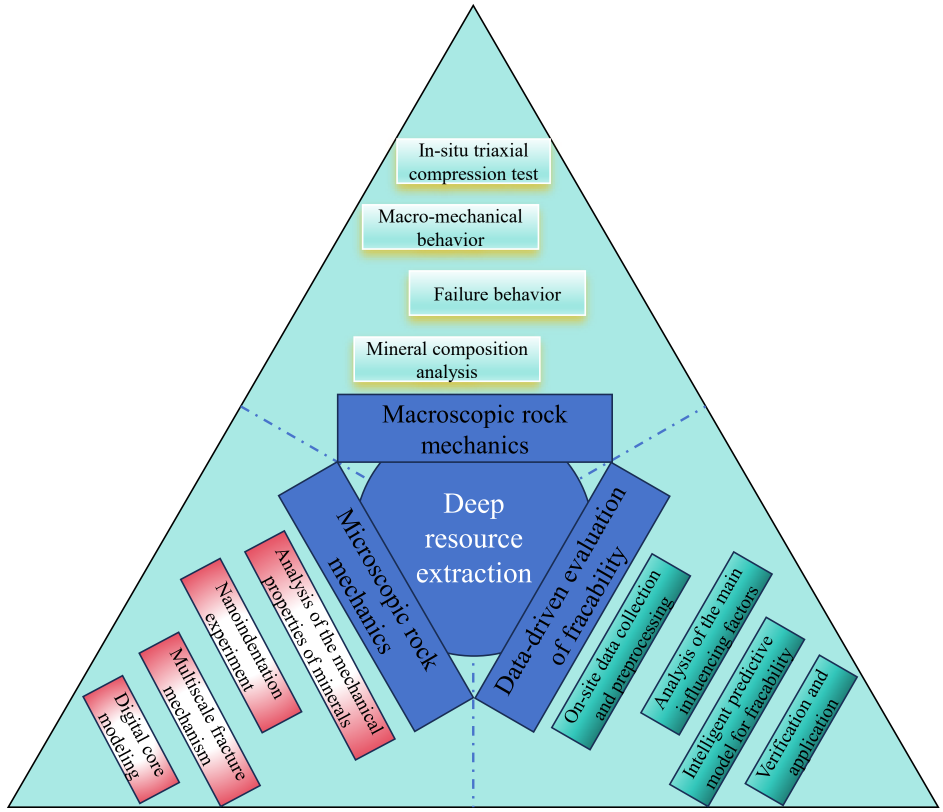

Fig. 1. Workflow for the evaluation of cross-scale mechanical behavior and fracability of shales.

Additionally, the mechanical behavior of shales with different mineral compositions varies under high temperatures and high-pressure conditions. This brings more challenges to the mechanical property evaluation of shale reservoirs. It is crucial to conduct systematic experimental investigations into the multi-scale mechanical properties of shales exhibiting diverse mineralogical compositions. This work is based on the actual problems of deep and ultra-deep shale gas exploitation in the Sichuan Basin of China. It aims to deepen the understanding of multidisciplinary integration of rock mechanics, cross-scale mechanics, and artificial intelligence to provide theoretical support for deep resource development, as presented in Fig. 1.

2. Multiscale insight into the mechanical behavior

Accurately obtaining rock mechanics information is essential for deep underground projects, such as efficiently extracting shale gas and geothermal energy. The mineral composition of shale, together with the microscale mechanical properties and distribution characteristics of each mineral, has a significant impact on its macroscale mechanical behavior (Feng et al., 2020). In recent years, the effects of temperature and confining pressure on the mechanical parameters, failure characteristics, and brittle-ductile transition behavior have been reported. However, conventional macro-scale mechanical tests on rocks can only capture their macro-scale mechanical behavior, while struggling to reflect the effects of the heterogeneous and multi-scale characteristics of samples. The internal microstructure of shale, including mineral inhomogeneities and intrinsic microdefects, has important implications for its nonlinear mechanics and cracking behavior (Jin et al., 2015; Ding et al., 2024). It is important to accurately characterize the effect of the actual microstructure inside the rock on the nonlinear mechanical behavior and damage evolution. The nanoindentation technique can help to gain insights into the local mechanical properties of different minerals in rocks, which is essential for accurate numerical modelling of rocks and analysis of damage mechanisms.

From the experimental point of view, it is difficult to select rock samples with different mineral components and different mineral spatial distribution characteristics to meet the requirements of a large number of experimental studies. Numerical modelling methods have the unique advantage of providing information on rock deformation and damage processes that are difficult to obtain experimentally. Statistical methods, such as the Weibull distribution function or random generation methods, are commonly used to characterize the non-homogeneous characteristics of rocks. However, the use of assumptions and random elements can lead to the loss of rock microstructural details. As a result, some inaccuracy in the findings is inevitable. Future work should attempt by digital image-processing techniques to obtain detailed information on rock microstructures and the spatial distribution of mineral components. Subsequently, it's essential to develop numerical models that take into account the spatial heterogeneity of actual mineral components. This approach will enhance the analysis of the nonlinear failure characteristics of rocks.

In summary, the percentage of mineral components in shale, the micro-mechanical properties and spatial distribution characteristics of each mineral have a significant impact on its macro-mechanical behavior. However, limited research has been conducted into how temperature and confining pressure affect the mechanical properties of rocks at the micro- and nano-scales. In addition, in terms of upscaled models or digital core modelling, research is often focused on the effective elastic parameters of the rock, while research on the nonlinear mechanical behavior of the rock and the damage process, which is an important guideline for deep reservoir stimulation, is insufficient. The mechanical properties and deformation failure mechanisms of deep rocks at different scales are explored, which can provide a more accurate theoretical basis for numerical modelling and engineering applications. Future work should strengthen the theoretical study of cross-scale mechanics to further understand the scale-upgrading mechanism of mechanical behavior from microscopic to macroscopic.

3. Identification of engineering sweet spots

Sweet spot identification is a key part of fracturing section selection, segmental fracturing design and economic benefit prediction. It has become an indispensable core element in the development of unconventional oil and gas. Currently, reservoir sweet spot identification is often carried out in academia and industry through two methods: reservoir rock brittleness evaluation and fracability evaluation by multi-parameter modelling.

3.1 Brittleness

The research related to brittle-ductile transition and nonlinear deformation damage mechanism of deep rocks is of great significance to promote the scientific and efficient development of the shale gas industry in China and around the world. Currently, the acquisition of brittleness indicators characterizing the brittle-ductile properties of rocks is mostly based on mineral composition, deformation parameters, strength parameters, and energy parameters (Zhao et al., 2024). However, these methods have their limitations in different engineering applications or geological conditions. Energy-based brittleness indices, which contain more information about the deformation and damage processes in rocks, are more promising for characterizing brittle-ductile properties than brittleness indices based on mineral composition and mechanical parameters (Feng et al., 2020). In addition, advanced testing techniques, such as micro-CT scanning and SEM, have been applied to reveal the brittle-ductile transition mechanism of shale at different scales. On this basis, a three-part brittleness index that integrates pre-peak and post-peak stress-strain characteristics was established for brittleness evaluation of deep shales (Zhao et al., 2023). Field practice shows the advantages of the above model in the evaluation of deep shale brittleness in comparison with the existing classical brittleness indices.

In deep shale reservoirs, the constraining effects of high geostress can also result in highly brittle rocks failing to generate complex fracture networks during or post-fracturing (Zeng et al., 2023). In other words, existing studies often focus on how to quantitatively characterize the brittle-ductile properties of rocks. The relationship between the energy-based brittleness index and the complexity of internal fractures after rock rupture is unclear, resulting in a poor selection of sweet spots for deep engineering. Therefore, future work should also focus on the relationship between rock brittleness and non-linear fracture characteristics so that brittleness data from indoor tests can be applied to guide the design of fracture optimization. In addition, the application of machine learning methods in brittleness evaluation should be strengthened, establishing the relationship between log data and energy-based brittleness, to obtain brittleness characteristics of continuous profiles in deep shale reservoirs.

3.2 Fracability

As one of the key assessment indicators prior to reservoir fracture stimulation, fracability can reflect the production and resource exploitation efficiency of a reservoir (Xu et al., 2024). An accurate assessment of fracability is essential for the development of unconventional energy sources such as shale gas and geothermal energy. In the early years, the industry did not make a strict distinction between brittleness and fracability, which may be applicable in shallow shale gas extraction. However, some studies have shown that the brittleness of shale reservoirs is not equivalent to fracability. As mentioned above, reservoirs with high brittleness may not produce complex fracture networks after fracking.

In contrast to North America, where shale gas commercialization has been achieved, China's shale gas reservoirs exhibit unique geological characteristics that slow down the process. The latter consists of multiple developed strata formed over a wide span of geological periods. Additionally, these reservoirs are marked by a high level of structural complexity and a complex stress state. The significant burial depth further results in elevated reservoir temperatures and in-situ stresses. The above factors make fracturing designs for deep reservoirs more challenging, with post-fracturing results varying greatly. Conventional fracability models, which rely on single-parameter proxies like brittleness indices, often overestimate fracability in such settings. There are many factors affecting the fracability of shale in deep-earth engineering. On the one hand, the fracability prediction model based on conventional methods fails to adequately consider the various factors affecting the formation of complex fractures. On the other hand, few existing studies have better integrated the formation mechanism of complex fractures in reservoir fracturing into multi-parameter modelling to evaluate fracability. To address these limitations, machine learning approaches offer a promising solution by integrating multi-parameter datasets (e.g., mineralogy, rock mechanics, stress anisotropy, and thermal properties). Future research should focus on hybrid models combining physics-based simulations with machine learning to capture both mechanistic insights and data-driven patterns.

4. Summary and perspectives

The above viewpoints not only focus on the current hotspots and challenges in academic research, but also originate from the pressing issues in deep-resource exploitation. Conclusively, the multi-scale mechanical behavior of shales with different mineral compositions at high-temperature and high-pressure conditions was systematically investigated. The multi-scale rupture mechanism of deep shale controlled by temperature, confining pressure, and mineral composition was revealed, which will improve the multi-scale rupture theory system of deep shale. Numerical models that accurately simulate the effect of mineral fraction differences on the mechanical behavior of shales have been developed. The multifactorial synergistic mechanism affecting shale brittle damage was elucidated, which can provide a reference for promoting efficient resource development and preventing and controlling geological disasters. An intelligent prediction method for fracability of shale in deep reservoirs was developed, which provides a reference for the selection of candidates for fracturing in deep reservoirs as well as accurate fracturing design. Furthermore, a methodology for precise fracking design based on reservoirs with different mechanical behaviors was advocated. Based on the summary of this study, some future work is needed:

1) the cross-scale fracture characteristic of shale ranges from microscopic (mineral breakage, grain boundary slip) to macroscopic (fracture network extension).
2) numerical modelling considering spatial heterogeneity of minerals.
3) an intelligent prediction method for fracability considering multiple influences affecting complex fracture formation.

Acknowledgements

This work was supported by the Postdoctoral Fellowship Program and China Postdoctoral Science Foundation (No. BX20250034).

Conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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