Advances in Geo-Energy Research

Vol. 6, No. 4, p. 271-275, 2022

Editorial

Advances in multiscale rock physics for unconventional reservoirs

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Keywords:
Unconventional reservoirs
rock physics
multiscale
physical model

Cited as:
Cai, J., Zhao, L., Zhang, F., Wei, W. Advances in multiscale rock physics for unconventional reservoirs. Advances in Geo-Energy Research, 2022, 6(4): 271-275.
https://doi.org/10.46690/ager.2022.04.01

Abstract:
The multiscale rock physics of unconventional reservoirs have drawn increasing attention in recent years, which involves several essential issues, including measuring method, transport property, physics model, characteristic scale, and their application. These issues vastly affect science and engineering regarding the exploration and development of unconventional reservoirs. To encourage communication on the advances of research on the rock physics of unconventional reservoirs, a conference on Multiscale Rock Physics for Unconventional Reservoirs was jointly organized by the journals *Energies* and *Advances in Geo-Energy Research*. Due to the limitations of movement caused by COVID-19, 21 experts introduced their work online, and the conference featured the latest multiscale theories, experimental methods and numerical simulations on unconventional reservoirs.

1. Introduction

Unconventional reservoirs, such as shale oil and gas, tight sand oil and gas, coalbed methane, and gas hydrate, will continue to change the world's energy development patterns. Increasing the development efficiency of unconventional resources (particularly natural gas) can not only ensure energy security, but is also critical for carbon emission reduction and environmental protection (Wang et al., 2020; Afagwu et al., 2021). Technological breakthroughs in the exploration and development of unconventional reservoirs require the improved understanding of subsurface formation, which usually exhibits multi-type and multiscale structure (Hart et al., 2013; Zhao et al., 2016; Cai et al., 2022b).

Rock physics provide a basic understanding tool to address the relationship between geophysical observations and the intrinsic properties of rocks, and are widely used to characterize oil and gas reservoirs (Fu et al., 2021; Cai et al., 2022a). These properties include but are not limited to elastic, mechanical, transport, lithology, rock frame, pore fabric, fluid, and stress characteristics of subsurface rocks (Mukerji et al., 1995; Zhao et al., 2021). The scale of structural characterization ranges from *nm* scale for organic nanopores through *μm* scale for micropores and grains, *mm* to *cm* scale for lamina, *dm* to *m* scale for layering and fracture, to the macroscopic (*km*) scale (Nordahl and Ringrose, 2008; Bailly et al., 2019; Lund Snee and Zoback, 2020). It is necessary to integrate different types of geophysical methods (laboratory measurement, logging, seismic, electrical and other analyses) for a better characterization of subsurface rocks, as their complex multiphysics and multiscale structure are coupled.

Given this background, a conference on Multiscale Rock Physics for Unconventional Reservoir was held by the journals *Energies* and *Advances in Geo-Energy Research*, in which 21

Yandy Scientific Press

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Received May 13, 2022; revised May 23, 2022; accepted May 26, 2022; available online May 27, 2022.

reports were assigned to three sections: theories and models in multiscale rock physics, the key characteristics and evolution of seismic and digital rock physics, and rock physics modeling and characterization of unconventional reservoirs. The research topics covered in this workshop are briefly summarized below.

2. Theories and models in multiscale rock physics

Sorting out the relationships between elastic wave responses at different scales has been a challenge for existing basic rock physics theories and relevant applied techniques. Jing Ba, from Hohai University, delivered a presentation entitled "Multiscale Rock Physics Model and Parameter Prediction for Tight Reservoirs". He analyzed the elastic parameters and attenuation (inverse quality factor) of tight rocks at different frequencies based on ultrasonic observations, sonic logging and seismic data for tight/shale reservoirs in the Yanchang Formation. In addition, Prof. Ba proposed theoretical equations of elastic wave propagation in a complex porous media according to the fabric structure and mineral component characteristics. He further verified and calibrated a multiscale rock physics model for tight reservoirs based on experiments, sonic logging and seismic data.

In a lecture entitled "Frequency Dependence of Elastic Parameters for Oil-Saturated Unconventional Reservoirs", Zhifang Yang, from RIPED PetroChina, revealed the rock physical experimental characteristics of Chang 7 shale oil reservoirs in the Ordos Basin at the multi-frequency domain. She revealed that the longitudinal wave shows obvious velocity dispersion, the velocity dispersion is the strongest when the oil saturation is about 70%, and the frequency and fluid have a weak influence on the shear wave velocity. It was also shown that the temperature can cause a 7% velocity change, which should not be ignored for unconventional reservoirs.

Pinbo Ding, from the China University of Petroleum (Beijing), gave a presentation on "Rock Physics and Seismic Physical Modeling of Multiscale Faults, Vugs and Fractures in Carbonate Reservoir". He performed rock physics experiments using synthetic rocks with controlled fractures and discussed two important mechanisms of seismic wave propagation: Scattering and wave-induced flow. He also reported multiscale fracture prediction and hydrocarbon detection based on wave-induced flow mechanisms.

Chen Guo, from Chang'an University, presented a talk on the "Multiphysics Upscaling and the Uncertainty Quantification of the Physical Property Prediction for Fractured Formation". She focused on the joint evaluation of upscaled electrical, mechanical and flow properties, with multiphysics analyzing methods applied to the fractured shale formation. Combined with the advanced self-supervised learning and probabilistic machine learning framework, she efficiently obtained a reasonable prediction with uncertainty quantification for the upscaled physical properties of the fractured model. The expected outcome provides a remarkable scientific perspective to understand the nature of the shale fracture network, and also supports the favorable evaluation of logging and fracturing in shale formations.

In the lecture titled "Study on Mechanical Properties and Main Controlling Factors of Marine-Continental Transition Shale", delivered by Jian Xiong from Southwestern Petroleum University, mineral composition was highlighted as an important factor controlling the mechanical properties of transitional facies rocks. In addition, sedimentary structures were found to have a significant impact on rock mechanics. These features make it difficult to predict the rock mechanical properties of transition facies by using conventional statistics methods. To overcome this problem, he proposed a combination of multiple intelligent algorithms to predict the rock mechanical parameters, which is beneficial to the development of marine-continental transition facies reservoirs.

Wei Wei, from the China University of Geosciences (Wuhan), delivered a presentation on "The Construction of Tortuosity Model and the Analysis of its Influence Factor for Reservoir Rock". Therein, a novel method was proposed to construct a streamtube of fixed length, in which the tube has self-similarity behavior during the generating process in two-dimensional (2D) and three-dimensional (3D) spaces. In this model, the single capillary can be dominated by three parameters: pore fraction, tortuosity and fractal dimension. The author also highlighted the need for further research on the tortuosity issues, namely the improvement and optimization of the analysis method between electrical conductivity and permeability in reservoir rocks.

Shengbiao Liu, from the China University of Petroleum (East China), presented a talk entitled "Hydrate Distribution in Fractured Reservoirs: Insights from Anisotropic Acoustic Measurements". He investigated anisotropic acoustic velocities in an artificial sandstone with aligned fractures during hydrate formation and dissociation. Furthermore, he studied the differences regarding the measured anisotropic elastic parameters with respect to hydrate saturation between hydrate formation and dissociation, and found that the hydrate binding to the grains in fractures can evolve to bridge the fracture surfaces during hydrate formation, and this bridging hydrate gradually transforms to floating hydrate in the pore system during dissociation. The results provide a substantial contribution to improve the accuracy of hydrate assessment in fractured reservoirs.

3. Key characteristics and evolution of seismic and digital rock physics

Rock physics investigations are essential for the seismic prediction of shale-gas sweet spots. Shale reservoir formations exhibit strongly intrinsic anisotropy and thus are difficult to be explored and predicted using conventional seismic exploration theories and methods. Feng Zhang, from the China University of Petroleum (Beijing), delivered a presentation on "Rock Physics Based Seismic Prediction of Shale-gas Sweet Spots". Based on rock physics experiments and theoretical modeling, he reported how the rock properties of marine shale in Southern China affect its seismic anisotropy. He also introduced a seismic inversion method suitable to strongly vertically transverse the isotropy of shale formations. Finally, he presented a quantitative seismic interpretation for organic matter content prediction, brittleness evaluation, and fracture characterization based on anisotropic seismic inversion and statistic rock physics.

Hui Li, from Xi'an Jiaotong University, delivered a talk on the "Experimental Investigation of Oil Sands and its Seismic Application". With modified low-impedance transducers and an optimized measurement workflow, the elastic responses of oil sand samples with varying saturation levels and fluid types were successfully investigated under varying temperature and pressure conditions. He characterized both ultrasonic P- and S-wave velocities of bitumen-saturated sand rocks and of bitumen itself at a wider temperature range. He further bridged a frequency-dependent impedance-temperature relation to the ultrasonic P-impedance and temperature through 4D time-lapse seismic technology, which could estimate the temperature distribution of the steam chamber in the bitumen sand reservoir.

Yaping Huang, from the China University of Mining and Technology, delivered a presentation on "Seismic Rock Physics Modeling Method and Parameter Prediction of Coalbed Methane Reservoir". Based on the analysis of coalbed methane reservoir characteristics, he constructed a rock physics model featuring dual pore structure and dual gas phase storage. He analyzed the influence of adsorbed gas content and pore structure on P-wave and S-wave velocity and studied the relationship between gas content and seismic response characteristics. He also discussed the feasibility of gas content prediction using back propagation neural network and support vector machine.

In a presentation on "The Critical Issues and Consideration on the Study of Multiscale Rock Physics", Jianchao Cai, from the China University of Petroleum (Beijing), discussed the important problem of multiscale physics properties due to different measurement scales, in order to characterize the reservoir rock. He analyzed the problem from five aspects: measuring method, transport properties, physics model, representative elementary volume, and basic application, and illuminated the multiscale influence using different examples. He also presented his opinion on how to deal with the multiscale problem based on advanced technology in the future, including upscaling technique, coupling different measurement data, and the modeling of multiscale transport phenomena.

Xin Nie, from Yangtze University, presented the "Numerical Simulation Shale Conductivity Based on Digital Rock Technology and its Application", wherein he established 3D multi-component models of shale based on an improved Markov Chain Monte Carlo method and 2D QEMSCAN image. He studied the conductivity of shales based on these models and discussed the influence of different parameters, including porosity and contents of clay, organic matters and pyrite. He also presented a new approach to building 3D shale multiscale multi-component digital rock models based on deep learning and layer representative elementary volume.

Jun Lu, from the China University of Geosciences (Beijing), presented a report entitled "Inversion of Anisotropy Parameters of Tight Sandstone Gas Reservoir". Orthorhombic tight sandstone is decomposed into a thin interbed with vertically transverse isotropy and fracture-induced horizontally transverse isotropy. On this basis, he proposed a method of separating the split PS-waves in shot records, and realized the inversion of fracture azimuths and densities based on the common receiver gathers. Furthermore, he derived a novel strategy to invert the vertically transverse isotropy parameters of background interbed structure based on the migration velocity analyses of PP and split PS waves. This work effectively supported the discovery of favorable reservoirs in the second member of Xujiahe Formation in the Xinchang area.

In the talk entitled "Anisotropic Dynamic and Static Modulus Correlation for Organic-Rich Shales and its Application in a Lacustrine Shale Reservoir", given by Yang Wang from SINOPEC Geophysical Research Institute, multi-stage triaxial tests were performed on 13 pairs of shale samples from a lacustrine shale reservoir, with the axial load applied perpendicular and parallel to bedding planes. He investigated the correlation between dynamic and static modulus in both bedding-normal and bedding-parallel directions by considering the *in-situ* stress condition, and found that the predicted minimum horizontal stress considering anisotropy can be verified by the Kaiser effect.

4. Rock physics modeling and characterization of unconventional reservoirs

The seismic rock physics properties and modeling of unconventional reservoirs are essential for the interpretation of sonic and seismic data for reservoir parameters estimation, geological model building and sweet spot identification. Organic self-sourced shale exhibits the unique features of multiphysics (elastic, inelastic and adsorption), multi-phases (organic-inorganic phase), multi-pores (nano-organic pores, inorganic pores, and cracks), and multi-fluids (brine, oil, gas, and condensate).

In a lecture on "Seismic Rock Physics Characteristics and Modeling of Unconventional Shale Reservoirs", Luanxiao Zhao, from Tongji University, mainly discussed and explored three issues regarding the seismic rock physics of unconventional shale oil and gas reservoirs: (1) how to characterize the elasticity of the in-organic frame of organic shale; (2) how to quantify the influences of thermal maturation on the elastic modeling of organic shale; and (3) how to incorporate the surface stress into rock physics modeling to explore the effects of nanopores and adsorption on the elastic properties of organic shale.

Yang Zhao, from the China University of Petroleum (Beijing), presented a talk on "Three-dimensional Anisotropic Seismic *In-situ* Stress Estimation", including the innovation of a 3D *in-situ* stress estimation method using anisotropic pre-stack seismic data. He divulged that the 3D *in-situ* stress field can be directly calculated from seismic data instead of using an interpolation process that is limited by issues of horizontal discontinuity. He introduced different scales of seismic attributes to approximate the horizontal strains and extended them to the classical uniform horizontal strains. The horizontal strains were derived based on the theory of plate and were reported to depend on the different scales of attributes that reflect the geological structure influence.

On the topic of "Adaptive Calculation of Elastic Modulus of Tight Sandstone Components and Prediction of Key Parameters of Double Sweet Spots", Suzhen Shi, from the China University of Mining and Technology (Beijng), acquired the accurate value of equivalent elastic parameters of rock components by the random walk algorithm. She carried out shear wave velocity prediction, intersection analysis and used rock physics templates to analyze the sensitive parameters, in order to predict the sweet spots of tight sandstone reservoir. The results showed that the optimized component modulus presented high accuracy after the verification of rock physics experimental data, and the relative error between the predicted S-wave curve and the actual S-wave curve was small.

Jianyong Xie, from Chengdu University of Technology, delivered a presentation on "Theoretical and Experimental Study on the Evaluation of Brittleness". He investigated the controlling factors of shale brittleness at different loading stages, and determined the relative contribution of the main controlling factors at each stage based on the energy evolution law. By evaluating the shale cores with different buried depths, he proposed a new brittleness index that has stronger sensitivity in assessing the effect of overburden pressure. He also proved the existence of a causal relationship between the influencing factors and the newly proposed brittleness model. The results have great importance in guiding the identification of shale oil-gas sweet spots and fracturing development.

Linqi Zhu, from Institute of Deep-Sea Science and Engineering, the Chinese Academy of Sciences, gave a talk entitled "Key Factors of Marine Shale Conductivity in Southern China". Therein, comprehensive analyses on large core samples and resistivity logs were presented for the Longmaxi-Wufeng formation from different areas. His findings revealed that mineral composition directly impacts resistivity in low-porosity systems. When organic matter is not carbonized, similar to biosilica, it further increases shale resistivity. This series of analyses paves the way for expanding the research on shale gas electrical conduction mechanisms and saturation models.

Liang Xiao, from the China University of Geosciences (Beijing), presented a lecture on the "Effect of Saturated Oil to Nuclear Magnetic Resonance (NMR) Responses and Correction Method in Tight Sandstone Reservoirs". He recovered several representative core samples drilled from different types of reservoirs for NMR experiments under three saturation conditions. The results illustrated the effect of saturated oil on the T_2 spectra, and showed the contorted phenomenon in the T_2 distributions of core samples with relatively low porosity and permeability. He proposed a method to correct the deviation of the T_2 spectrum between oil saturated conditions and fully brine saturated conditions in tight reservoirs. By using the corrected T_2 spectrum, he accurately characterized the pore structure of several low-permeability and tight sandstone reservoirs in Northwest China.

Xinmin Ge, from the China University of Petroleum (East China), held a presentation on the "Numerical Simulation of NMR Relaxation Mechanism and Response Characteristics of Continental Shale Oil". He established a petrophysical model and conducted a complete set of numerical simulation schemes for shale oil reservoirs under complex wettability conditions. He demonstrated that wettability has a great influence on the T_1 and T_2 spectra of shale oil, and lipophilic reservoirs and hydrophilic reservoirs display different relaxation responses. Furthermore, the calculation model of oil/water saturation could be established by using the geometric average value of T_1/T_2, which has great potential application in shale reservoirs.

5. Conclusion

At the conference discussed herein, 21 experts introduced their latest achievements in multiscale rock physics for the characterization of unconventional reservoirs in three aspects. These advances involve the research hotspots of multiscale measuring methods, the modeling of transport properties, construction of seismic rock physics models, and *in-situ* application of rock physics. The findings presented contribute immensely to the development of rock physics in the fields of basic theories, physics experiments and numerical simulation, promoting the potential joint application of various new methods/approaches to rock physics.

Acknowledgement

The authors would like to thank the participants of the online conference for their inspiring work and the MDPI group for their diligent proposals, which led to the high level of the conference with more than 150,000 attendees. The conference chairman J. Cai would like to acknowledge the contribution of the Fundamental Research Funds for the Central Universities (No. 2462021YXZZ005) toward his research on petrophysics of unconventional reservoirs.

Conflict of interest

The authors declare no competing interest.

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