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Editorial: Rock physics modeling and well-log practice for unconventional reservoirs

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Editorial on the Research Topic
Rock physics modeling and well-log practice for unconventional reservoirs

Unconventional resources with commercial interest in the world mainly include heavy oils, shales, coalbed methane and tight gas sands. The production and development of these resources have changed the supply pattern of global energy. Quantitative interpretation of geophysical data in the exploration, well logging and engineering development of the unconventional resources requires a comprehensive understanding of the physical properties of rocks and their relationships. The research of rock physics provides an interdisciplinary treatment of physical properties, whether it is highly related to geological, geophysical and geomechanical methodologies. The development of new rock physics methods is essential when integrating core, well-log, seismic data to improve the accuracy of formation evaluation and reservoir characterization. In this Research Topic, it includes 10 articles addressing a variety of rock physics studies on unconventional resources, highlighting fundamental theories, laboratory work and well-log interpretation.

The development of tight reservoirs is of significance to increase crude-oil production and optimize energy supply. These reservoirs have a low porosity/permeability with the high spatial heterogeneity, which requires new developments on the experimental and theoretical studies of acoustic properties. Ba et al. investigated the effects of pressure and fluid saturation on velocity and attenuation of tight sandstones. They conducted ultrasonic experiments on seven tight sandstones collected from the shale-oil strata as a function of the confining pressure. By analyzing the P-wave velocities and attenuations using the spectral-ratio method, they observed that the attenuation increases with both porosity and permeability and decreases with increasing pressure. Tight sandstones with oil saturation present higher attenuation than those of water and gas saturations. Furthermore, the dispersion and attenuation can be reasonably explained by a double-porosity theory, which takes into account mesoscopic heterogeneities of the rock frame and gas pockets. In tight gas reservoirs, the major flow channels are composed of micro/nanopores, in which the rarefaction effect is prominent and the traditional Darcy law is not appropriate for gas flow. A sound understanding of reservoir properties and gas flow mechanisms are required to effectively develop the natural gas in tight reservoirs. Zheng et al. conducted a 3D analysis of compressible gas slip flow by combining the Maxwell fist-order slip boundary condition and Navier-Stokes equations. By analyzing the flux rate and non-linear pressure variation for gas slip flow, they proposed a new gas flux formula which is in good agreement with published experimental data. By substituting the gas flux formula into Darcy's law for compressible gas, they also presented a new apparent permeability model which considers both slippage effect and Knudsen diffusion in a tight gas reservoir. Compared to the new model, other previous models may underestimate the apparent permeability of tight reservoirs. Their results show that the apparent permeability strongly depends on the reservoir pressure and pore-throat radius.

Calcite cement is widely distributed in sandstone reservoirs and may significantly affect its elastic and electrical properties. Wang et al. quantitatively analyzed the effects of calcite cement and porosity on the P- and S-wave velocities and electrical resistivity of artificial calcite-cemented sandstones manufactured by a new method. Interpretation and analyses of the experimental results demonstrate that the elastic and electrical rock properties are a comprehensive result of porosity, the content and distribution of the calcite cement, as well as the microstructure of the samples caused by the variation in the applied consolidation stress. Their results revealed the mechanisms of how porosity and calcite cement affect the elastic and electrical properties of calcite cemented sandstones and provided a theoretical basis for the accurate characterization of sandstone reservoirs through seismic and electromagnetic surveys. On the other hand, the presence of calcium in calcareous tight sandstone reservoirs will reduce the travel time of acoustic waves, increase the compensated density, and substantially increase the resistivity of the sandstone reservoir. The logging response characteristics are influenced by the change in calcium content, leading to possible large errors in lithology identification and reservoir parameters evaluation. Yu et al. proposed a method for resistivity correction and water saturation evaluation for calcareous tight sandstone reservoirs. They analyzed the controlling factors of oil-bearing property in the calcareous tight sandstone reservoir through systematic petrophysical experiments and established the petrophysical volume model. They used optimized cross-plot to extract lithology-sensitive logging curves to calculate the calcium content. On this basis, they applied the resistivity index associated with calcium content to correct the resistivity. Finally, they calculated the water saturation by variable rock-electro parameters to eliminate the influence of calcium content and improve the evaluation accuracy of the calcareous tight sandstone reservoir.

Lacustrine shale oil is widely distributed in lacustrine lake basins and has become an important field of petroleum resource exploration and development in the world. Quantitative analysis of fluid saturation in lacustrine shale is difficult due to the complexity of diagenetic minerals and pore types. Nuclear Magnetic Resonance (NMR) technique has emerged as a key technique for characterizing the fluid components of shale oil in downhole logging and laboratory measurements. Different fluids have different T1/T2 ratio and T2 relaxation time, and different T2 relaxation time reflect different size of the pores. Based on NMR experiments, Fan et al. evaluate the fluid occurrence state and saturation of lacustrine shale oil in Fengcheng Formation. Using the T1-T2 map, they developed a 2D T1-T2 NMR quantitative calculation method for quantifying the movable oil saturation. In addition to fluid saturation, understanding the elastic properties of shales are important to seismic imaging, wellbore stability analysis and hydraulic fracturing treatment of unconventional shale reservoirs. Jiang et al. studied the elastic properties of heterogeneous Eagle Ford Formation consisting of marl and interbedded limestone layers. They extracted the relationship between the compressional and shear velocities using well-log data. The empirical equation obtained in their work can be used to estimate the shear velocity of the Eagle Ford Formation when there is insufficient well-log data. They also obtained the correlations between the elastic properties and the Gamma Ray value. They found that the lower marl layers possess the lowest averaged values of velocities and Young's modulus while the upper limestone layers have the highest averaged values of these elastic parameters. Their analysis shows that the aspect ratio of confined fractures can be significantly influenced by the contract of Young's modulus in the shale layers.

Identification of gas hydrate-bearing sediments (GHBS) in engineering applications worldwide mainly relies on seismic exploration techniques. The existence of hydrates highly affects the elastic wave velocity and attenuation. Ba et al. explored the mechanism of wave propagation in hydrate-bearing sediments by developing a triple-porosity model. The model considers combined effects of various fluid flow mechanisms including the local fluid flows between the rock frame and clay/hydrate inclusions, and the classical Biot's global flow loss. The model relates P-wave velocity and attenuation with the sediment properties such as the hydrate volume ratio, clay content, porosity, and the hydrate inclusion radii. The model predictions are in good agreement with the well-log data from ODP sites in Japan. The new model associated with the hydrate morphology could be helpful to improve the accuracy in the estimation of hydrate content from seismic and well-log data. On the other hand, understanding the effect of cement slurry penetration is important for the application of appropriate drilling techniques and wellbore stability evaluation in GHBS. Wang et al. studied the effect of cement slurry penetration during cementing in GHBS. They used TOUGH + HYDRATE software packages to simulate the cement penetration process. They investigated the effects the cementing process parameters on the cement slurry penetration process including the hydration heat of cement slurry, cementing pressure difference, holding time of cementing pressure difference. Furthermore, they analyzed physical properties responses such as hydrate saturation, hydrate phase equilibrium temperature difference, permeability and porosity. Their results penetration process is complex and can be significantly affected by environmental and physical states.

Heavy oil is an important alternative oil resource to conventional oil and gas reservoirs because of its huge availability all over the world, which is twice the conventional oil reservoirs. Current methods for characterizing the elastic properties of Fengcheng heavy oil reservoirs, the third largest sub-oilfield in the Xinjiang oilfield system, mainly involve well logs inspection without rock physics analysis and modeling. Yuan et al. performed rock physics analysis of heavy oil sands in Fengcheng Oilfield, Xinjiang. With integration of well-log and laboratory data, they investigated the consolidation status of heavy oil sands using theoretical rock physics modeling. Their results suggest that the grain contacts are scarce, and the frame is loose and poorly consolidated, which are consistent with the SEM observations. The effective evaluation of consolidation status is useful for seismic reservoir characterization and drilling risk analysis.

Apart from the above rock physics studies, earthquake-induced building damage and secondary disasters such as landslide, collapse and mud-rock flow have attracted extensive attention because of their huge disaster causing force. The seismic response of the structure is closely related to the natural vibration frequency of the structure. It is important to determine the dynamic similarity relation in the shaking table model test. Guo et al. proposed a design method using frequency as input seismic wave similarity design control quantity. They studied the natural vibration frequencies of the prototype by means of the Gonza landslide field ground pulsation test. A new frequency compression ratio design scheme is given from the perspective of dynamic similarity.

The results of the rock physics theories and well-log practices presented in this Research Topic provide a glimpse of the challenges faced in the quantitative evaluation of physical properties in unconventional reservoirs by rock physicist, well-log analysts and geophysicists today. We hope you find this Research Topic to be a useful update on recent advances in rock physics of unconventional resources.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for submission.

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