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Direct Measurement of Permeability and its Evolution with Stress

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Abstract

Permeability, a key reservoir quality indicator, is pivotal for modelling and forecasting the dynamic behavior of reservoirs. It is also a key input parameter for fracturing simulators. Permeability in shale reservoirs and its variation with stress is complex, as fluid flow occurs both via fractures and ultra-tight pores hosted either by organic matter or inorganic matrix. For tight and ultra-tight rocks, measurements are time intensive and due to a lack of standardized testing protocol, petrophysicists rely on estimating permeability by inverting data obtained from other sources. However, such inversion involves using empirical constants which may not work due to heterogeneity resulting from variation in rock fabric, constituents and pore structure. Reservoir engineers combine analogue production and other empirical data to establish a range of assumed matrix and fracture permeability values, often limiting its forecasting power due to a lack of integration with the geological model and understanding of property controls. The assumed possible model scenarios have a direct impact in the field economics, leading to uncertainty ranges that may prevent projects from meeting the economics screening criteria. The high value of information carried by a baseline matrix permeability measurement and the corresponding fracture uplift in unconventional reservoirs result in a strong business case for direct permeability measurements at representative reservoir conditions and stresses.

This paper reports the results of a multi-well testing campaign designed to measure permeability and its variation with stress for various lithofacies. Using petrophysical modeling and extensive thin section study, dominant lithofacies were first identified in the region of interest. Permeability measurements were undertaken for a large number of samples, selected to adequately represent each lithofacies. Measurements were performed on intact plugs using steady-state and unsteady-state technique. Supercritical nitrogen used as pore fluid offers the benefits of being inert and with viscosity significantly lower than brine and other organic solvents, while eliminating the need for Klinkenberg and Forchheimer corrections. CT scans and thin section images acquired on the tested samples permitted integrating the experimental observations with the observed rock fabric and pore structure.

For the six dominant lithofacies, measured permeability at insitu effective stress varied between 10 nano-Darcy to 32 micro-Darcy. To obtain the permeability of the rock matrix, low resolution plug CT scans were used to screen the samples for any observable fractures. Moreover, permeability hysteresis (permanent damage in permeability, after increasing the effective stress by few thousand psi to mimic drawdown, and then returning to the initial reservoir effective stress) ranged between 4% to 90% and increased with increasing clay content and with decreasing stiffer constituent content. Furthermore, analysis of unsteady-state pressure data for a sample exhibited distinctly different rates of pressure decay, suggesting existence of two separate flow paths which was verified by thin section imaging and micro-CT image analysis. Finally, unsteady-state measurement provided direct measurement of pore volume under stress.

The results of this study can be used to design drawdown/production strategy for field operation. Understanding of permeability hysteresis will help in candidate selection for EOR or re-stimulation operations once a well has been produced for few months and ultimately begun to decline.