Using Formation-Tester Measurements to Estimate Depth of Invasion and Water Saturation in Deeply Invaded Tight-Gas Sandstones

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Abstract:

Mud-filtrate invasion displaces in-situ formation fluids away from the wellbore in porous and permeable rocks. In the presence of water-base mud (WBM), invasion is accompanied by salt mixing between mud filtrate and formation brine. Formation resistivity will vary radially away from the borehole due to post-invasion distribution of water saturation (Sw) and electrolyte concentration. In tight sandstones, the depth of mud-filtrate invasion often exceeds the depth of investigation (DOI) of deep-sensing resistivity logs. Thus, deep and electrically conductive filtrate invasion coupled with shoulder-bed effects result in the overestimation of Sw, leading to underestimated hydrocarbon pore volume. Reliable methods are needed for the accurate assessment of radius of invasion (ROI) and Sw in deeply invaded formations.

Formation-testing operations are impacted by mud-filtrate invasion, where often long fluid pump-out is needed to acquire hydrocarbon samples with minimal mud-filtrate contamination. However, unlike other well logging tools, formation-testing probes do not have a fixed DOI that limits their ability to pump-out mud filtrate until acquiring original formation fluids (i.e., sensing the uninvaded zone). We use an in-house petrophysical and fluid flow simulator to perform numerical simulations of formation testing, mud-filtrate invasion, and well logs to estimate ROI and Sw. The simulations are initialized with the construction of a multi-layer petrophysical model. Initial guesses of volumetric concentration of shale, porosity, Sw, irreducible water saturation, and residual hydrocarbon saturation are obtained from conventional petrophysical interpretation. Fluid-dependent petrophysical properties (permeability, capillary pressure, and relative permeability), mud properties, rock mineral composition, and in-situ fluid properties are obtained from laboratory measurements. Using our multi-phase formation testing simulator, we simulate actual fluid sampling operations by implementing five drawdown cycles performed with a dual-packer formation tester over 9 hours. Additionally, apparent resistivity logs and nuclear logs (e.g., gamma ray, bulk density, and neutron porosity) logs are numerically simulated to match the available well logs.

The studied sandstone reservoir is characterized by low porosity (up to 14 pu), low-to-medium permeability (up to 40 mD), and high residual gas saturation (40 to 50%). Deep mud-filtrate invasion resulted from extended overbalanced exposure to saline WBM (17 days of invasion and 1,800 psi overbalance pressure) coupled with the low mud-filtrate storage capacity of tight sandstones. Therefore, the uninvaded formation is located far beyond the DOI of resistivity tools, whereby deep resistivity values are lower than those of uninvaded formation resistivity. Through the numerical simulation of formation testing, we estimated ROI and Sw. Likewise, we quantified the hydrocarbon breakthrough time which matched the measured hydrocarbon breakthrough time. Estimated ROI was approximately 2.5 meters and estimated Sw was approximately 13% lower than Sw derived from resistivity logs, therefore improving the appraisal of original gas in place.

Bio:

Tarek S. Mohamed is a PhD Candidate at the University of Texas at Austin, pursuing a PhD degree in Petroleum Engineering. He works as a graduate research assistant at the Joint Industry Research Consortium on Formation Evaluation at the University of Texas at Austin. He holds an MS degree in Petroleum Engineering and a Graduate Certificate in Data Science and Analytics from the University of Oklahoma. His master's research focused on coalbed methane characterization, modeling, and simulation. His research interests include reservoir modeling and simulation, petrophysics, formation evaluation, well-test analysis, and machine learning applications. He served as secretary and president of the Student Chapter of SPWLA at The University of Texas at Austin in 2022 and 2023, respectively.