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Effect of confining pressure (stress) on carbonate rock porosity and permeability: Integrated analysis using RCAL, NMR, and microtomography

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Carbonate reservoirs exhibit complex and heterogeneous pore systems, resulting from various depositional environments and diagenetic processes that control the spatial distribution of porosity and permeability. This heterogeneity presents significant challenges for predicting fluid flow behavior and accurately characterizing reservoir quality, especially in enhanced oil recovery (EOR) scenarios. Carbonate rocks are also susceptible to stress variations, which can alter pore geometry and connectivity, impacting their petrophysical properties. Understanding how porosity and permeability change under different pressures is essential for improving the reliability of multiphase flow experiments and refining oil reservoir simulation models, including compressibility, among others. In this context, the integration of techniques provides a comprehensive approach to monitoring changes in the porous medium and expanding insights into the distribution, size, and connectivity of pores across different scales, enabling a more robust evaluation of stress-induced effects in heterogeneous carbonate rocks. Therefore, this work aims to study the petrophysical properties of carbonate rocks with distinct geologic contexts and monitor changes in the porous medium through routine core analysis (RCAL), nuclear magnetic resonance (NMR), and time-resolved X-ray microtomography (μCT) tests as a function of confining pressure. This approach can provide insights into the importance of selecting an appropriate confining pressure safety zone in multiphase flow tests and aid in evaluating the compressibility model. Two groups of carbonate rock samples were used in this study: the Indiana Limestone (IL) from the Mississippian formation, acquired from Kokurec Industries Inc. (Caldwell, USA), and the Coquinas, which are analogous to Brazil's pre-salt reservoir facies from Morro do Chave's formation (MC), Sergipe-Alagoas Basin, Brazil. The samples were characterized by XRD to confirm their mineralogy. Plug samples (1.5″ × 2.0″) from the IL and MC lithologies were cleaned using toluene and methanol in a Soxhlet system. Petrophysical characteristics were then obtained in the following order: (i) acquisition of 3D images using μCT; (ii) NMR; (iii) cleaning; (iv) RCAL to obtain porosity and permeability as a function of varying confining pressure (500–5000 psi); (v) acquisition of 3D images using μCT; (vi) NMR. This methodology was applied to two lithology plugs to calculate the sample set's standard deviation. The experimental results revealed that confining pressure can significantly influence the petrophysical properties of carbonate rocks, with varying degrees of sensitivity depending on the internal pore structure and connectivity. In general, porosity showed a decreasing trend with increasing stress. At the same time, permeability exhibited more complex behavior, ranging from gradual reductions to abrupt changes, depending on the dominant flow pathways within the samples. NMR measurements indicated shifts in T_2 relaxation times, suggesting modifications in the pore size distribution and potential closure of larger pores under stress. Microtomography imaging before and after the experiments provided direct evidence of microstructural rearrangements, including pore collapse, redistribution, and, in some cases, the formation of microfractures. The integration of RCAL, NMR, and μCT proved essential for capturing complementary aspects of the porous medium at different scales. This multimethod approach enabled a more robust assessment of how stress affects the pore network beyond what isolated techniques could reveal. These insights underscore the importance of carefully selecting a confining pressure safety zone in multiphase flow experiments and contribute to refining compressibility models used in reservoir simulations. Overall, the findings highlight the critical role of combining experimental techniques to understand better and quantify the stress-dependent behavior of heterogeneous carbonate rocks.

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