Fluid Dynamics of multiphase displacement in reservoir rocks

Understanding the dynamics of multiphase fluid movement in the subsurface is important due to its presence in hydrocarbon recovery and the geological storage of carbon dioxide. Macroscopic flow in these reservoirs is typically modelled by extending Darcy's law to multiphase flow [1]. This implicitly assumes that fluids flow in connected pathways, and that the interface between phases is stable and unchanging once steady-state has been achieved [2-3].

However, a range of complex interface dynamics have been observed at steady-state, with fluid phase interfaces being able to disconnect and reconnect intermittently in a series of snap-off and reconnection events [4]. This flow regime, termed intermittent pathway flow, deviates from the traditional view of connected pathway flow, where the connectivity of the fluid phases is constant in time. The dynamic nature of fluid connectivity influences the key characteristics of subsurface multiphase flow – energy dissipation during flow and trapping – and so must be understood to model fluid movement in the Earth's crust.

The tool that we use to study flow is high-resolution X-ray imaging, where we can take three-dimensional images of the rock and the fluids within it at micron resolution. We aim to understand the controls on intermittent pathway flow and link its role in larger scale manifestations of flow such as relative permeability. This will lead to accurate, physics based, modelling of subsurface fluid flow. We explore the creation of intermittent pathways through the simultaneous injection of two fluid phases into a carbonate rock. The parameter space relevant to the subsurface is varied by changing the total flow rate, the flow rate ratio of both fluid phases and the viscosity of the fluids. We used 3 fluid pairings: nitrogen/brine, decane/brine and hexadecane/brine.

The X-ray images were acquired over a period of 40 minutes to collect enough X-ray counts so that the images could be reconstructed with minimal artefacts. This means that intermittent pathways are not observed directly, and have to be inferred for the time averaged imagery. Figure 1 shows the sample with both nitrogen and brine occupying the pore space, with brine being the bright phase and nitrogen being the dark phase. There is however, an intermediate greyscale caused by the occupation of both nitrogen and brine in the same pore during a scan – this is segmented out in the RHS of Figure 1 in blue; these regions are where intermittent pathway flow occurred during a scan.

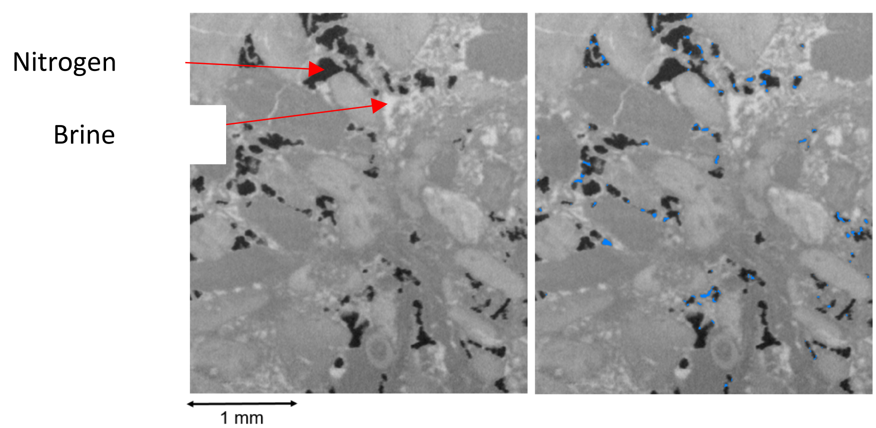

Figure 1: Greyscale image of the carbonate with both nitrogen and brine occupying the pore space. The intermediate greyscale, interpreted as intermittency, is shown in blue on the right.

We observed that the classification of intermittent flow pathways had a huge impact on the connectivity of the non-wetting phase, as demonstrated in Figure 2. Without the inclusion of intermittent areas, the non-wetting phase was not connected across the sample for the nitrogen/brine experiments and decane/brine experiments. No intermittent pathway flow was observed in the hexadecane/brine experiments. Capillary forces play an important role in the generation of intermittency, with the non-wetting phase always occupying the largest pores, brine always occupying the smallest pores and intermittency occurring in the intermediate sized pores. As the capillary number of the non-wetting phase increases (by increasing the flow rate), it can invade smaller pores and intermittency then also occurs in smaller pores.

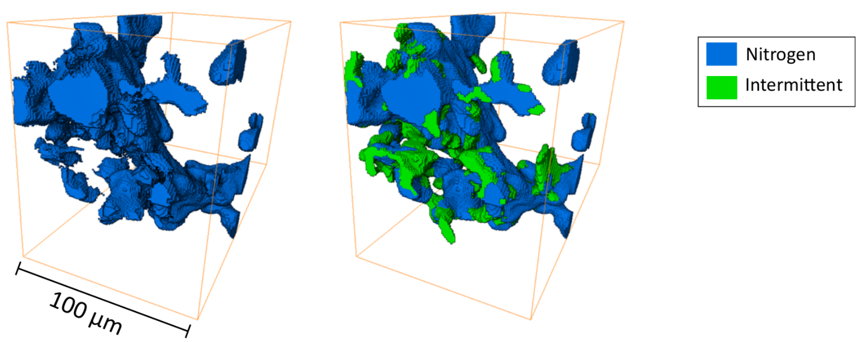

Figure 2: Segmented subvolume showing the importance of intermittent pathways in the connectivity of the NWP.

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[3] Blunt, M. J. (2017), Multiphase Flow in Permeable Media: A Pore-Scale Perspective, Cambridge University Press

[4] Reynolds, C. A., H. Menke, M. Andrew, M. J. Blunt, and S. Krevor (2017), Dynamic uid connectivity during steady-state multiphase ow in a sandstone, Proceedings of the National Academy of Sciences, 114(31), 81878192.