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Advanced 4D Imaging of Shales at Micro- to Nano-scale: Investigating the time-lapse evolution Under Subsurface Thermal, Hydrological, Mechanical, and Chemical Conditions

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Mudstones and shales are the source of unconventional oil and gas reservoirs, as well as the primary control on the sealing efficiency for subsurface storage applications (e.g. energy, CO_2, H_2, waste). However, their fine-grained and heterogeneous nature makes their full characterisation highly challenging. Here we demonstrate the multi-scale and dynamic imaging approaches that can help meet these challenges and discuss limitations and future opportunities.

Microstructures can be characterised at scales from sub- nm (<1 nm) to over 1 m, using multi-scale and multi-model imaging approaches [1-3], including X-ray tomography, Focused Ion Beam Scanning Electron Microscope and Transmission electron microscopy tomography. The majority of pores in mudstones/shales range from 0.2 nm to 3μm, and we have documented 4 major types with 3 distinct size distributions [4]. Based on the REV analysis, pore sizes, types and distribution can be upscaled via three stages from sub-nm to cm-scale[5]. The permeability is pressure dependant, ranging from 1.0×10-17 to 1.0×10-22m2 [3, 5]. CO_2 adsorption is 3-7 times higher than CH_4 and over 10 times higher than H_2 [6]. Image based modelling has demonstrated that the non-Darcy effects (e.g., slip flow and Knudsen diffusion). Adsorption/desorption and surface diffusion takes major controls over time after injection [7].

Dynamic imaging of mudstones/shale has provided the opportunity to characterise the thermo-hydro-mechanical-chemical (THMC) properties and the coupling mechanism in mudstones/shales to investigate the sealing ability under realistic reservoir conditions. These include high temperature (from less than 10 ℃ up to 1000 ℃) [8], high pressure (e.g. confining pressure, indentation, torsion, deformation and fractures; up to 65 MPa) [9], fluids (e.g. diffusion, adsorption, flowing through, multi-phase flow) [10] and complex chemistry environment (brine and drilling fluids) [11]. Based on the dynamic behaviours observation and quantification, It can be concluded that mudstone/shales with horizontally thin-layered laminations, few fractures and less reactive minerals may act as the best caprocks.

Whilst the above has led to an improved understanding of shale/mudstone microstructure under static and dynamic conditions, significant challenges still remain regarding representivity and up-scaling, experimental analysis at subsurface-realistic temperatures, pressure and chemistry, accurate estimations of the long-term behaviours and the proper monitoring techniques.

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