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Visualising the coupled mechanics of CO_2 breakthrough

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1 Introduction

Successful geological CO_2 storage relies on the availability of an impermeable caprock formation that overlies the injection reservoir and prevents CO2 migration to the surface through a combination of trapping mechanisms that are activated at different scales. Shales have been widely studied as potential caprock formations because of their favourable properties such as very low permeability and high capillarity. Shales are highly heterogeneous and anisotropic materials whose response is governed by strong Thermo-Hydro-Chemo-Mechanical (THMC) couplings that conventional constitutive models often fail to represent. In the context of CO_2 storage, characterisation of caprock integrity and sealing capacity is usually evaluated in terms capillary entry pressure [1, 2]. In addition to the hydromechanical response, CO2 introduces a chemical component (mineral dissolution and/or precipitation) the impact of which on shales remains a challenging topic due to the extreme mass transfer limitations. In this study, the impact of CO_2 injection in a Swiss shale, the Opalinus Clay, is for the first time assessed with live x-ray tomography. This approach aims to identify and decouple the different THMC mechanisms that take place, through quantitative 3D image analysis.

2 Hydromechanical testing during live x-ray tomography

Opalinus Clay samples (h = d = 5 mm) are tested during in-situ x-ray tomography using an original high pressure and temperature cell [3]. The presented work is divided in two parts: (i) CO_2 injection at increasing pressure steps (uCO_2) under isotropic confinement (p) and (ii) direct isotropic exposure to supercritical CO_2 (pCO_2). In both series of tests, the tested Opalinus Clay sample has been progressively resaturated under free swelling conditions before being mounted in the x-ray compatible cell. The kinematics of the tested samples are acquired and quantitatively processed with 3D x-ray image analysis during different time intervals.

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3 CO_2 breakthrough

CO2 breakthrough under confined conditions (isotropic compression, p = 10 MPa) is assessed with live x-ray tomography (7.8 μm/px) and the volumetric response of the sample is evaluated with image analysis on the different scans before and after each loading phase. CO_2 is injected in the sample from the bottom (h = 0) under increasing constant pressure steps of 2 MPa (uCO_2 = 2, 4, 6 and MPa). Upon confinement application the sample contracts while after the first CO_2 pressure level (scan 02) no significant volumetric activity is measured. Further CO_2 pressure increase (scans 03 to 05) results in swelling response, which is attributed to CO_2 breakthrough, i.e., breakthrough pressure 2-4 MPa (consistent with [4]). The calculated volumetric maps (Figure 1) reveal an increasing localized swelling activity evolving from the bottom (injection) side of the sample upwards – it is particularly visible in scan 05.

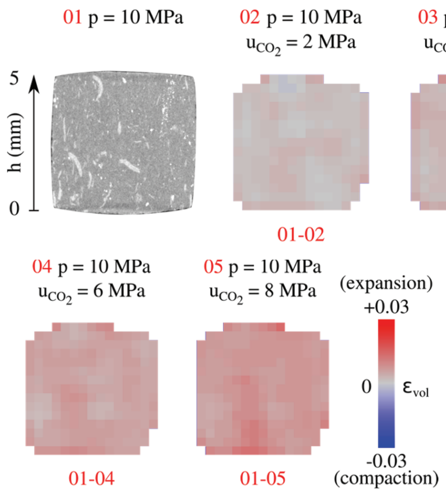

Fig. 1: Localised volumetric deformation at different levels of CO_2 injection pressure

The more localized swelling activity of the sample is further demonstrated in Figure 2, where the max. volumetric strain throughout the sample's height is plotted. When CO_2 breakthrough occurs (uCO_2 = 4 MPa) higher volumetric strain is measured close to the injection which further increases as injection increases. The varying pattern of max. vol. strain along the sample suggest the creation of additional breakthrough conduits. It is important to mention the pre-existence of micro-fissures in the sample initially under unconfined conditions. Even though these micro-cracks disappear after the application of confinement (at the given resolution) and are not any more visible even after breakthrough, the high swelling activity can be attributed to locations where high concentration of fissures is observed. These motivating results show that even at resolutions lower than the average pore size of the material, 3D image analysis can reveal important insight on the localised behaviour which in the context of CO_2 storage can be related to potential leakage paths.

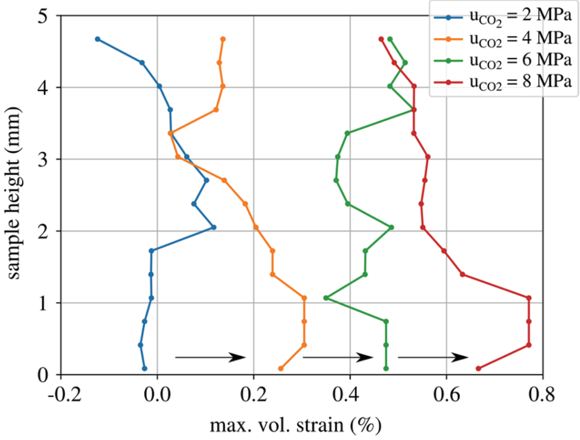

Fig. 2: Maximum volumetric strain along the height of the sample for different CO_2 injection pressures

4 Isotropic exposure to supercritical CO2

Isotropic exposure of an Opalinus Clay sample to supercritical CO_2 (pCO_2 = 10 MPa pressure and 34°C) is evaluated with 3D x-ray imaging (5.7 µm/px) over a time period of 56 days. Direct CO2 exposure results in initial swelling due to thermal loading, followed by slight compaction and local micro-fissuring due water evaporation in the anhydrous CO_2 (see Figure 3). This interaction can occur at the bottom of the caprock formation with the buoyant CO_2, leading to partial desaturation of the caprock which can threaten its mechanical integrity. Again a highly localised strain activity around the three pre-existing horizontal fissures is observed. Cracks are more prone than intact matrix to opening/closing upon THM loading which here is imposed both by thermal loading and CO_2 drying, they thus have a crucial role in the integrity of the entire storage system.

For the first time, local CO_2 concentration in the material has been measured based on the developed method explained in [5], where density variations attributed to constant mass volumetric deformation from Digital Volume Correlation can be directly compensated by applying an attenuation correction. Any remaining grey value difference is attributed to mass exchanges, here CO_2 invasion. Sample swelling enables CO_2 invasion in the material, in particular through the fissured zones, while upon volume stabilisation CO_2 concentration continues to increase even in zones within the clay matrix. Remaining increased density regions around the cracks after depressurisation could correspond to chemical activity (mineral precipitation) from CO_2 exposure. While this cannot be confirmed from the post-exposure mineralogical analysis, these results reveal the potential of in-situ imaging of small size shale samples on the detection and understanding of the different coupled THMC phenomena.

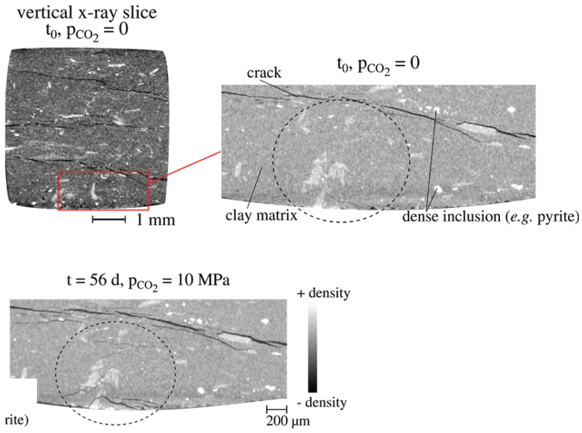

Fig. 3: Dessication fissures due to contact with supercritical CO_2

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