Abstract

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Gas Breakthrough & Fracture Visualisation in Uncemented Geomaterial - Implications for Geological CO_2 Sequestration

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① Applicability to Geological Sequestration

This research programme was started with the following objectives. 1) To evaluate changes in mechanical properties and determine the physical indicators of susceptibility, underlying the **micromechanisms of failure** (e.g., fracturing) of clay caprocks. 2) To develop and calibrate an experimental set-up to perform controlled non-wetting fluid injection experiments using a high-pressure uniaxial Consolidation & Fracture Visualisation Cell (CFVC) to macroscopically visualise the impact of physical indicators on the mechanical properties during fracture formation and pattern in uncemented geomaterials.

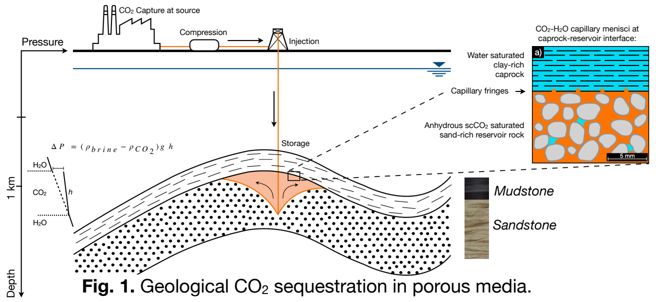


Fig. 1. Geological CO_2 sequestration in porous media.

RESEARCH QUESTIONS

1. Evaluate caprock CO_2 seal integrity;
2. Test shallow seated and buried (less indurated), relatively high compressibility clay-rich caprock materials;
3. Understanding the influence bulk fluid properties (e.g., pH, T, P, ionic concentration c_0, relative permittivity *k*') have on clay microstructure.
4. To determine the micromechanisms underlying failure (e.g., fracture formation) at the pore-scale.

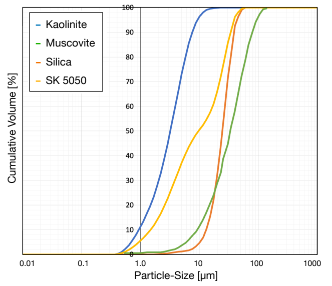
② Tested Materials & Sample Preparation

Representative caprock building materials were selected to test our hypothesis that the physical indicators; **particle-size distribution** (clay vs silt), **particle shape** (platy vs grain), **heterogeneity** (clay-silt mixtures), **clay microstructure** (1:1 vs 2:1) and differences in **mechanical behaviour** upon compression (i.e., compressibility) control breakthrough pressure and fracture formation. Samples are prepared by mixing dry powder of the raw material with fluid electrolyte concentrations 0.01 M or 0.5 M NaCl. The reconstruction of raw material from slurry allows for controlled and exact compositions, ensuring repeatability of experiment design and systematic hypothesis quantification. Samples have a circular cross-section: 75 mm in diameter and a height 10-25 mm dependent on pre-consolidation stress.

Material Properties

Mineralogy	Composition	Specific Gravity [g/cm³]	Particle D_{50} [µm]	Plastic Limit [w_P]	Liquid Limit [w_L]	Slurry Water Content [%]
Speswhite Kaolinite	$(Al_2O_3.2SiO_2.2H_2O)$	2.65	3.3	0.32	0.64	1.0
Muscovite Mica KLAB	$(KF)_2(AL_3O_3)_3(SiO_2)_6$	2.8	33.9	0.47	0.6	1.25
Silica (quartz)	SiO_2	2.605	22.9	0.23	0.34	0.45
Silica:Kaolin 50:50	-	2.6275	10	0.25	0.45	0.65

Particle-Size Distribution

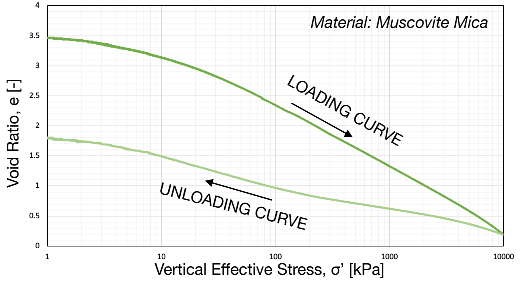


SAMPLE PRE-CONSOLIDATION

Methodology

1. 1D mechanical OR pneumatic consolidation to target density, representative of deep geological repositories.
2. Strain rate and initial moisture content determined from oedometer compression tests. Time for sample swelling to stabilise, ensures drained conditions to simulate on site long-term effects.
3. Controlled N_2 pressure increment and monitoring of sample volumetric deformation for stress-strain characterisation during N_2 injection.

1D Consolidation Curve



MECHANICAL 1D CONSOLIDATION

PNEUMATIC 1D CONSOLIDATION

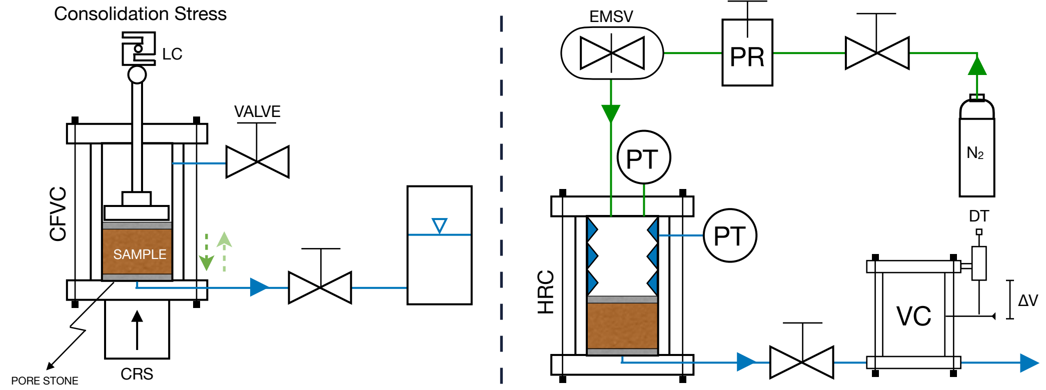


Fig. 2. Schematic diagrams of test equipment.

KEY			
CFVC - Consolidation & Fracture Visualisation Cell	PR - Pressure Regulator	HRC - Hydraulic Rowe Cell	▶ N_2
EMSV - Electromagnetic solenoid valve	PT - Pressure Transducer	VC - Volume Control (outflow)	▶ H_2O
CRS - Constant rate of strain consolidometer	DT - Displacement Transducer	LC - Load Cell	▶ $H_2O + N_2$

③ Experiment Methodology & Sample Evolution

INJECTION & FRACTURE VISUALISATION

1. Transparent cap attached to top flange to allow for fracture visualisation.
2. Pressurisation of reservoir chamber, using the incremental pressure increase method (50 kPa/15 min).
3. Sample compression as the resulting action of gas pressurisation.
4. Gas breakthrough (± fracture patterns or pothole structures) determined by large ΔV recorded at the outflow ± fracture visualisation.

INJECTION UNDER CONSTANT VERTICAL STRESS

1. Sample held under vertical effective stress reached during consolidation.
2. Pressurisation of reservoir chamber, using the incremental pressure increase method (50 kPa/15 min).
3. Consolidation as the resulting action of gas pressurisation.
4. Gas breakthrough at higher N_2 pressures then injection and visualisation method. Breakthrough determined by recording the change in ΔV at the outflow.

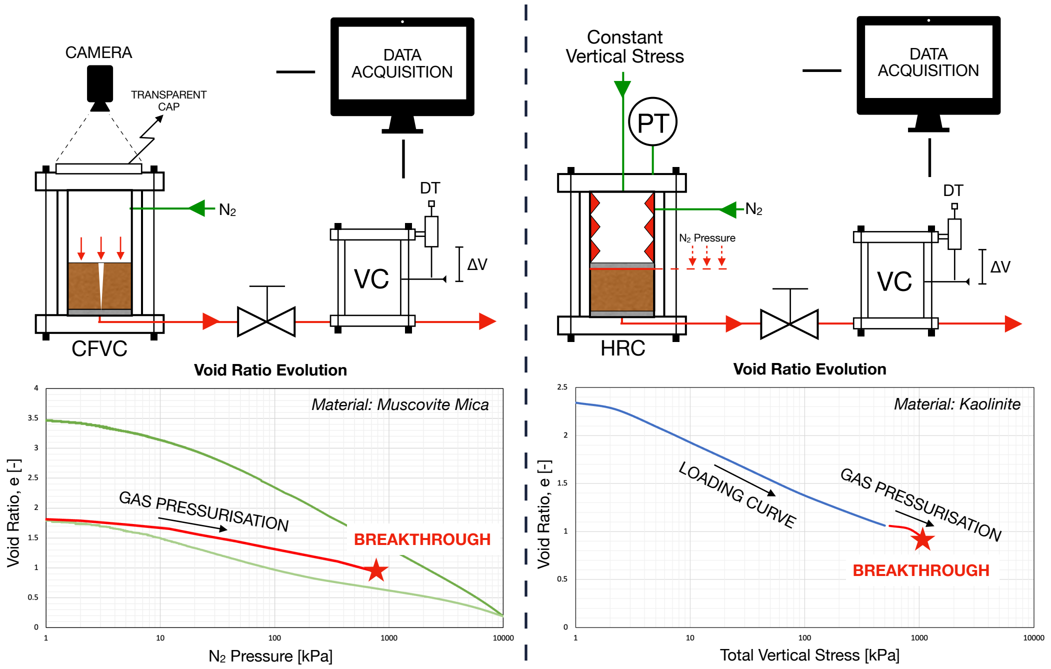


Fig. 3. Workflow of gas injection methodologies.

④ Pressurised Gas Injection Test

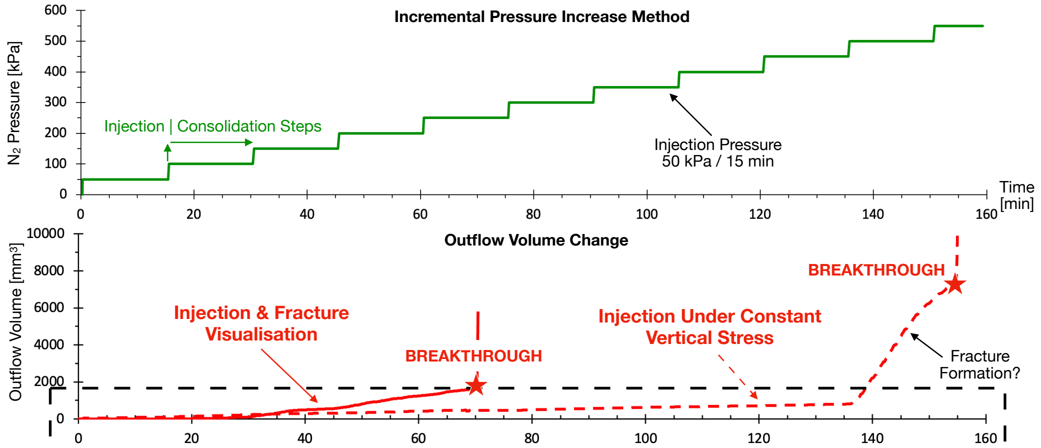


Fig. 4a. Pressurised gas injection example tests. Material: Kaolinite pre-consolidated to 500 kPa.

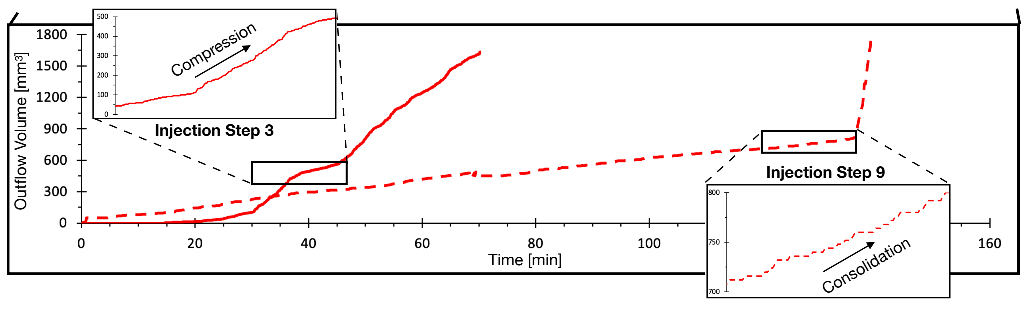


Fig. 4b. INSET: Volumetric deformation of samples upon gas pressurisation pre-breakthrough.

⑤ Physical Indicators Controlling Breakthrough

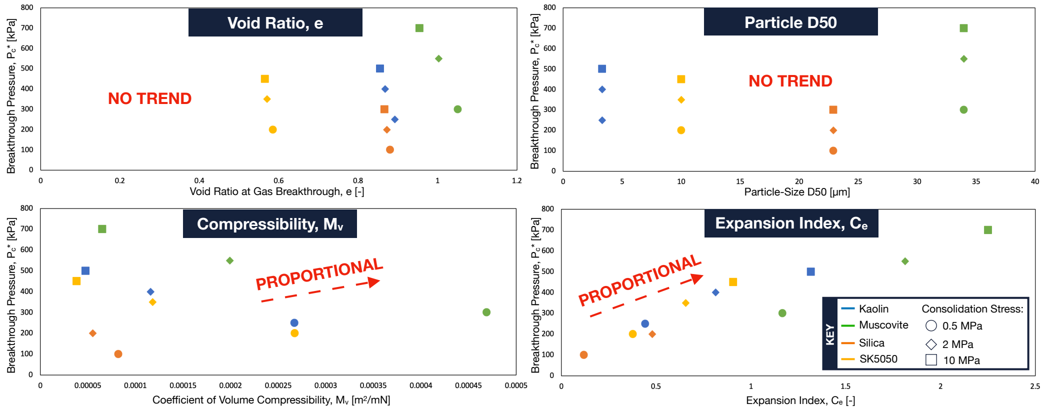


Fig. 5. Material density and particle size display no empirical correlation to P_c^*. In comparison, the more compressible and higher swelling potential the material the greater the P_c^*.

⑥ Internal Nature of Fracture Patterns

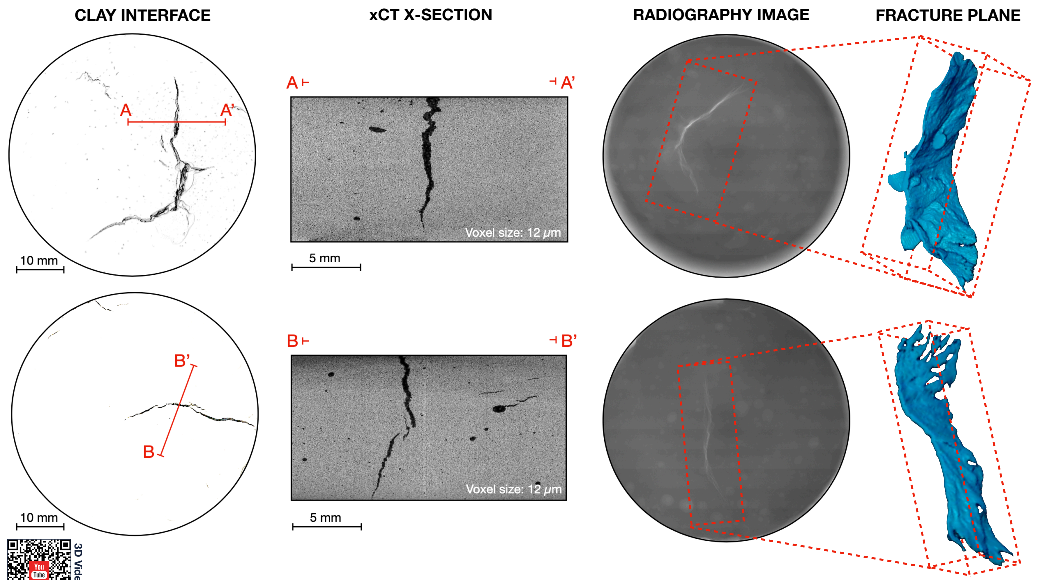


Fig. 6a. Pressurised gas induced fractures. Material: silica silt:kaolinite clay 50:50 mass fraction.

MUSCOVITE DESICCATION

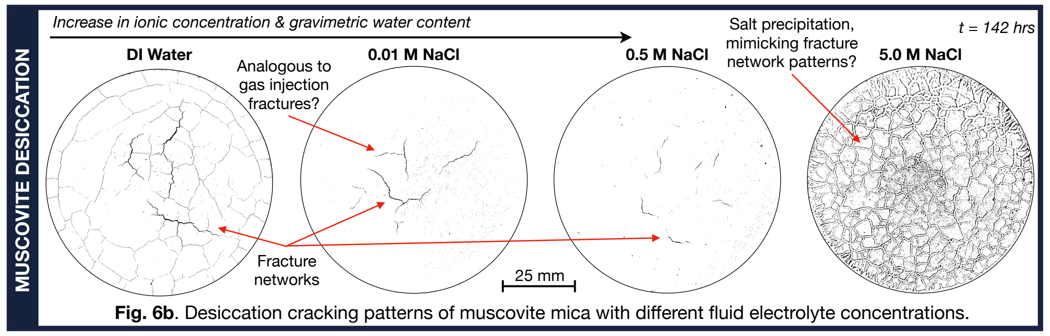


Fig. 6b. Desiccation cracking patterns of muscovite mica with different fluid electrolyte concentrations.

⑦ Research Summary

Findings / Implications:

- An innovative experimental set-up allowing for the onset of surface crack formation to be captured during gas injection into consolidated and intact clay-rich geomaterials **SECTION 3 & 4**.
- Material compressibility is an important parameters controlling particle distance evolution which ultimately governs breakthrough pressure **SECTION 5**.
- Gas invasion into the tested materials occurred at lower pressures than traditionally recorded air-entry-values **SECTION 5**.
- Injection of non-wetting gas (N_2) into consolidated clays results in the formation of large fracture patterns. Furthermore, heterogeneity is a controlling parameter in fracture pattern density **SECTION 6**.
- Increasing the fluid electrolyte concentration reduces desiccation cracking density **SECTION 6**.

Future / Ongoing Research:

- Understanding the effects of 1) fluid electrolyte concentration, 2) disjoining pressure, 3) time-dependancy, 4) particle crushing, and 5) exposure to reactive fluids, have on the micromechanisms of failure in uncemented geomaterials.

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ERE5.4 Coupled Thermo-Hydro-Mechanical-Chemical (THMC) Processes in Geo-Reservoirs with Emphasis on Clay Behaviour

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