

Experimentally Produced Increase in the Permeability of Caprock by Flow of Carbon Dioxide Saturated Water*

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Abstract

CO₂ injection into oil fields and depleted hydrocarbon reservoirs is important for enhance oil recovery and carbon storage, respectively. The injection not only alters the in-situ stress and geochemical conditions, but also the thermal properties of the storage domain. The temperature of the injected CO₂ is usually considerably lower than the formation temperature. This will cause the rocks surrounding the injection well bore to be cooled rapidly, with the rate of cooling reducing with distance away from the well.

Previous work has identified heterogeneous horizontal permeabilities varying from the nanoDarcy to milliDarcy range, and that change to the pore structure of lower permeability rocks has a greater effect on permeabilities than for the higher permeability rocks. Any change in the pore structure caused by thermal fracturing could have significant effects on the permeability of the reservoir and sealing units. Results from direct experiments of thermal fracturing of intact caprock and storage domain samples have not been published previously, although it is clearly of vital importance in enhanced oil recovery and assessing the viability of CO₂ geological storage systems.

We performed experiments involving oven heating of samples of caprocks and reservoir rocks from In Salah Gas Field, Algeria, to various temperatures (50-500°C) under reservoir stress conditions. The samples were then quenched in room temperature fluid, at ambient pressure conditions. A pore pressure of 20 MPa and confining pressures 30 MPa to 80 MPa were used to simulate the change in effective reservoir stress conditions. The permeability and elastic wave properties (P- and S-waves) of the samples were measured pre- and post-heat treatment. Thermal fracturing caused an increase in permeability up to 3 orders of magnitude and significant decrease in P- and S-waves velocity.

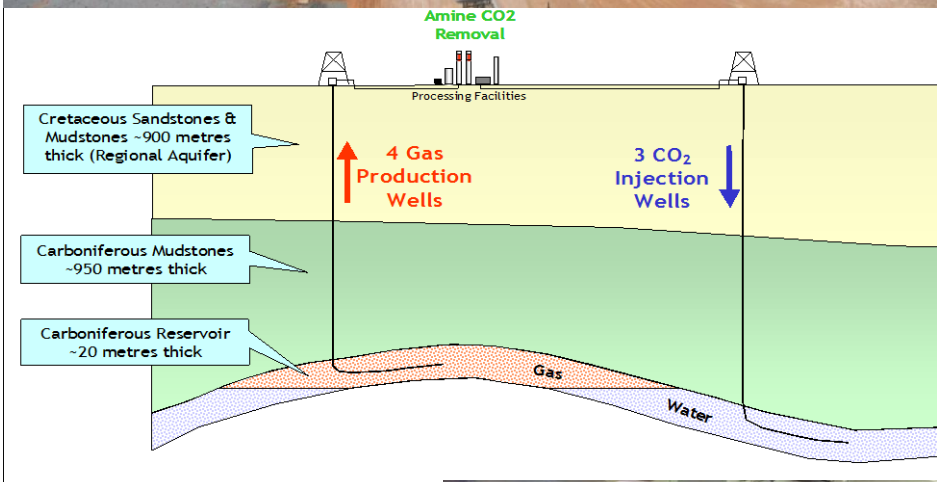
Experimentally Produced Increase in the Permeability of Caprock by Flow of Carbon Dioxide Saturated Water

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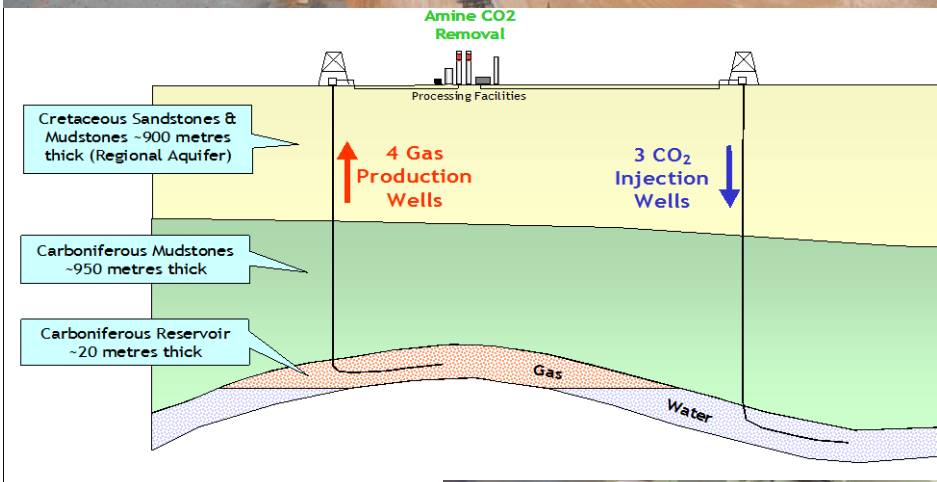
Context



- Working on the In Salah Gas JIP (PhD to Post doc, 2004 – present)
- Krechba gas field produces ~ 9 billion cubic meters of natural gas per year.
- 10% of the gas is CO₂ which is separated and then stored into saline reservoir



Context



- Injection of CO₂ will change the pressure and geochemical conditions in the reservoir/caprock – how will this affect the physical properties of the rock?
- Experimental and analytical approach to understand the changes due to reactive fluid flow



Outline

- Experimental and analytical procedure
- Results
- Conclusion

Experimental approach

1. **Characterise samples**
Petrophysically and petrologically for effective pressure and non-reactive pore fluid conditions
2. **Experimentally recreate chemical change** caused by CO₂ injection and see how this affects the petrophysical and petrological characteristics of the rocks



Experimental apparatus

Upstream and downstream pore fluid pump system

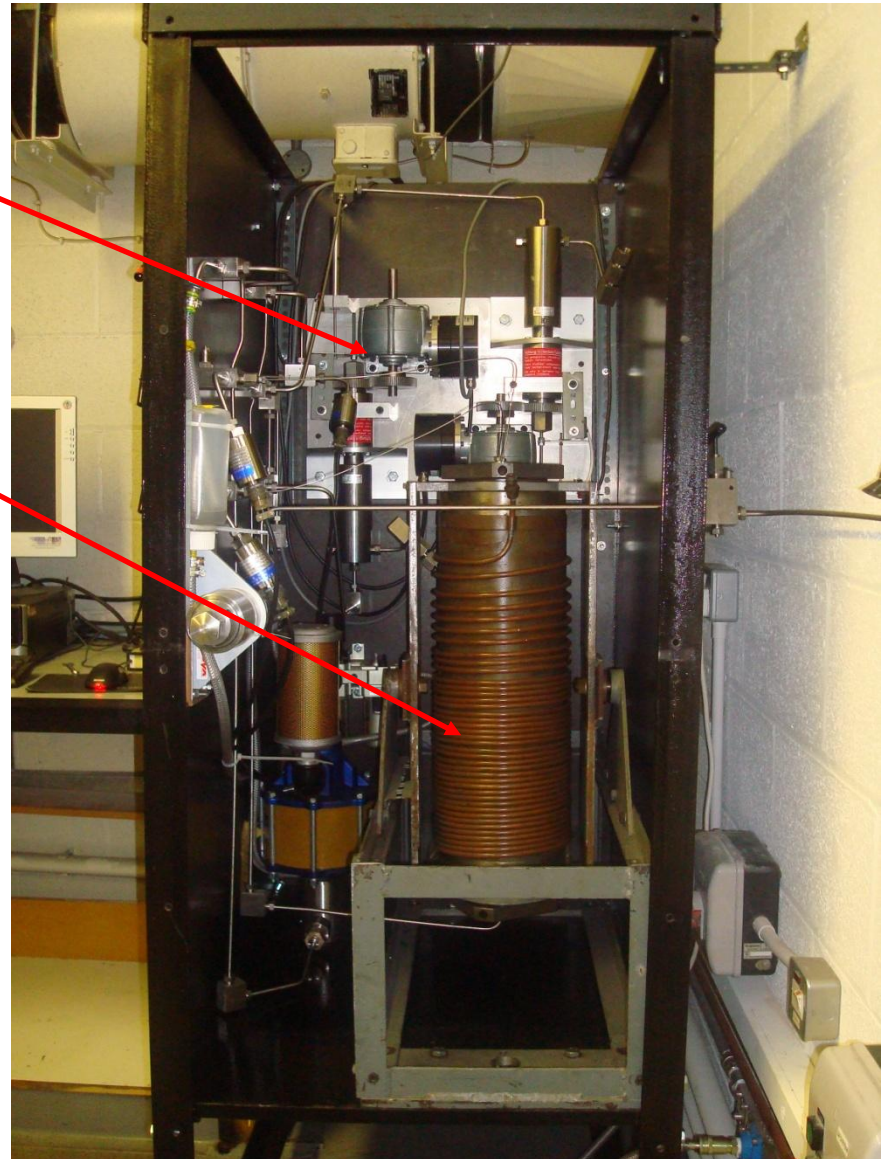
250 MPa, Argon, CO₂, Water, Acid, reactive fluid

Confining pressure pump system

250 MPa ~ 10km depth

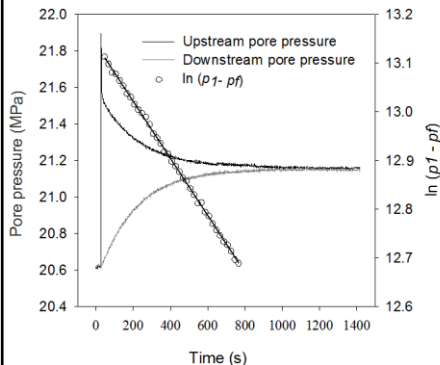
Measure Permeability (to sub nanoDarcy) by:

- 1 Flow (constant flow or constant head) method
- 2 Transient pulse decay (TPD) method
- 3 Pore oscillation technique



Techniques for measuring low permeability

- Transient pulse decay
- *Steady state*



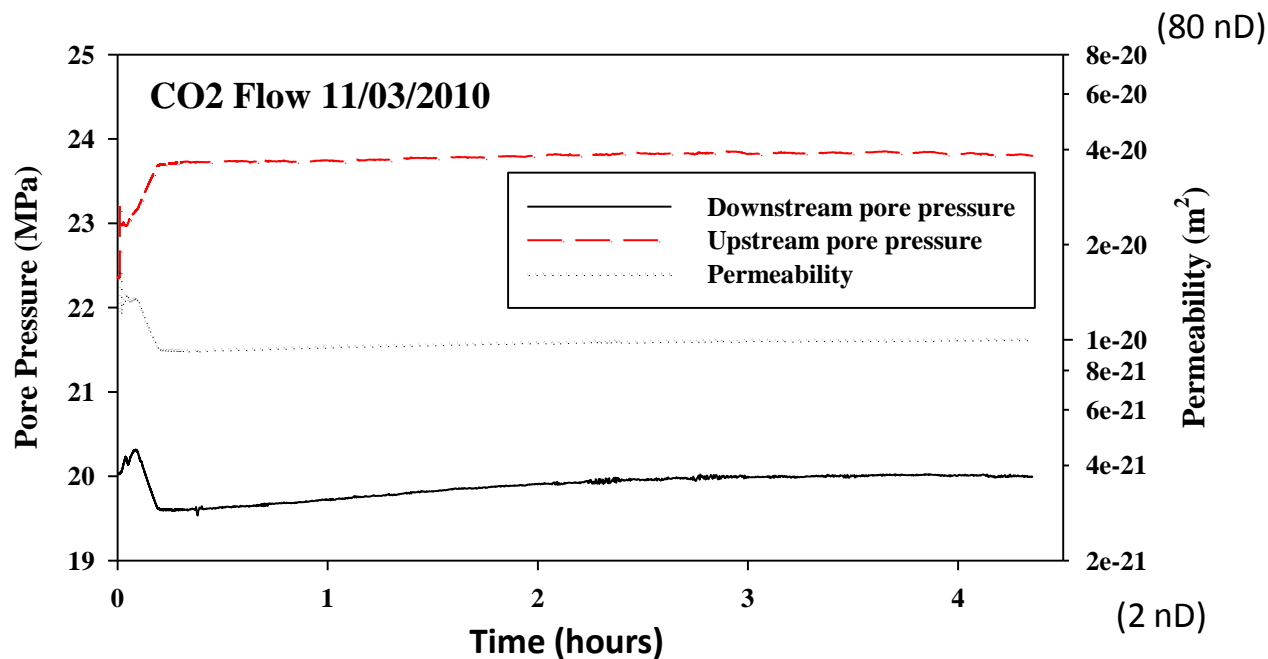
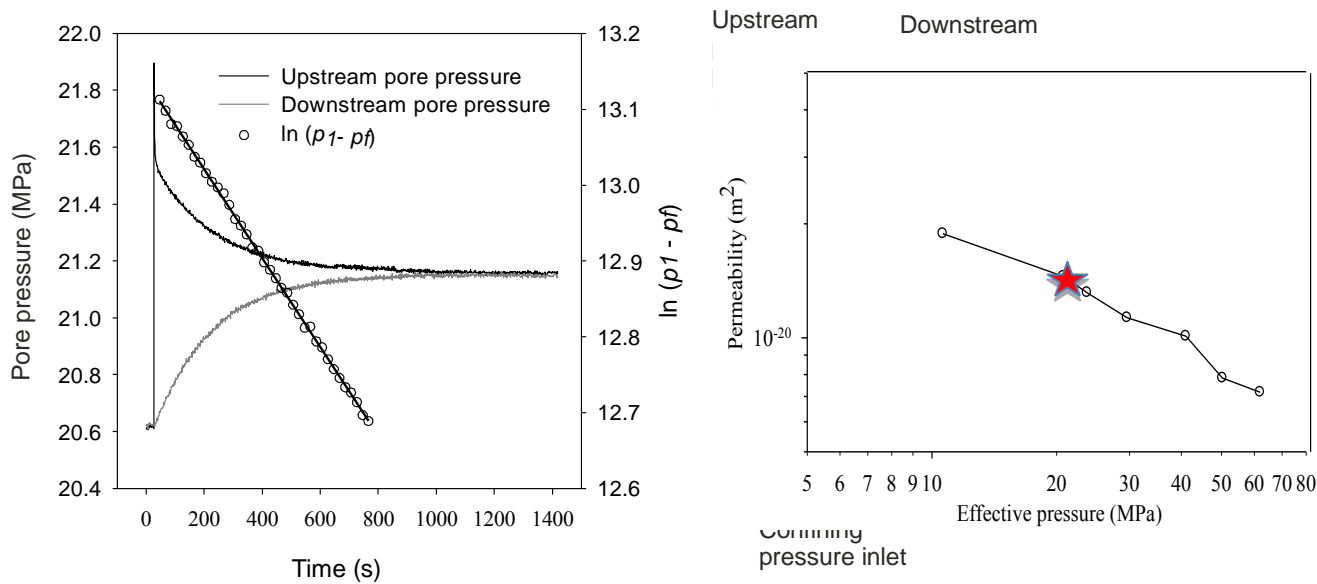
TPD method

- Relatively quick test of permeability at set pressure conditions.
- Calculated from decay of an induced pressure difference.
- Relatively little fluid movement
- Can alter conditions and re-measure to build up a graph showing permeability pressure relationships

Presenter's notes: We then measured the permeability of the samples.

We can measure permeability in 3 ways, pressure oscillation, steady state, and TPD. We didn't use the pressure oscillation technique. We can use the steady state method, but it's slow for low permeability rocks. We use steady state later on as it gives us bulk fluid movement for fluid rock interaction. For the characterisation of the samples we use the TPD method because.

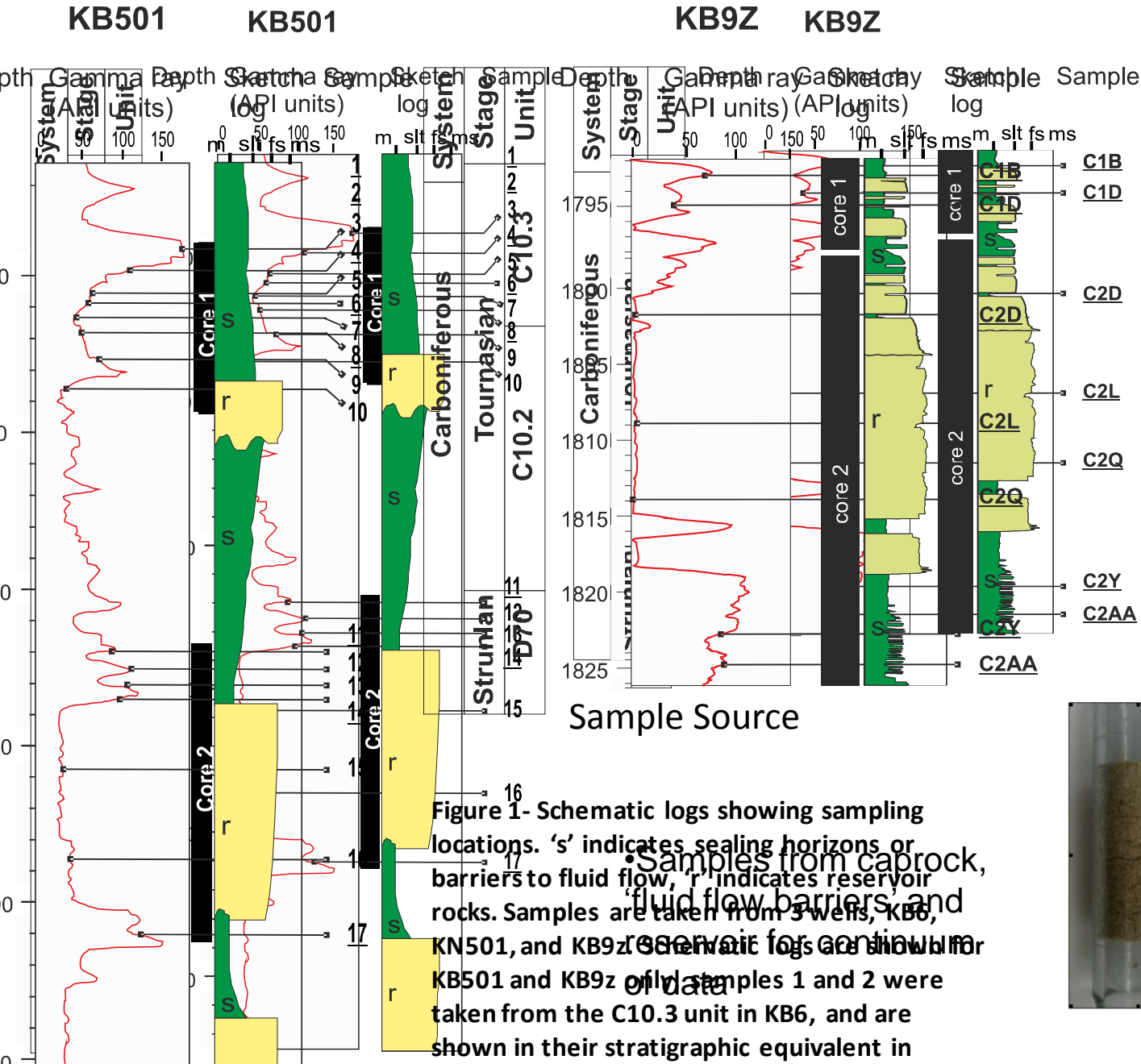
Measurement of permeability, TPD and Flow methods



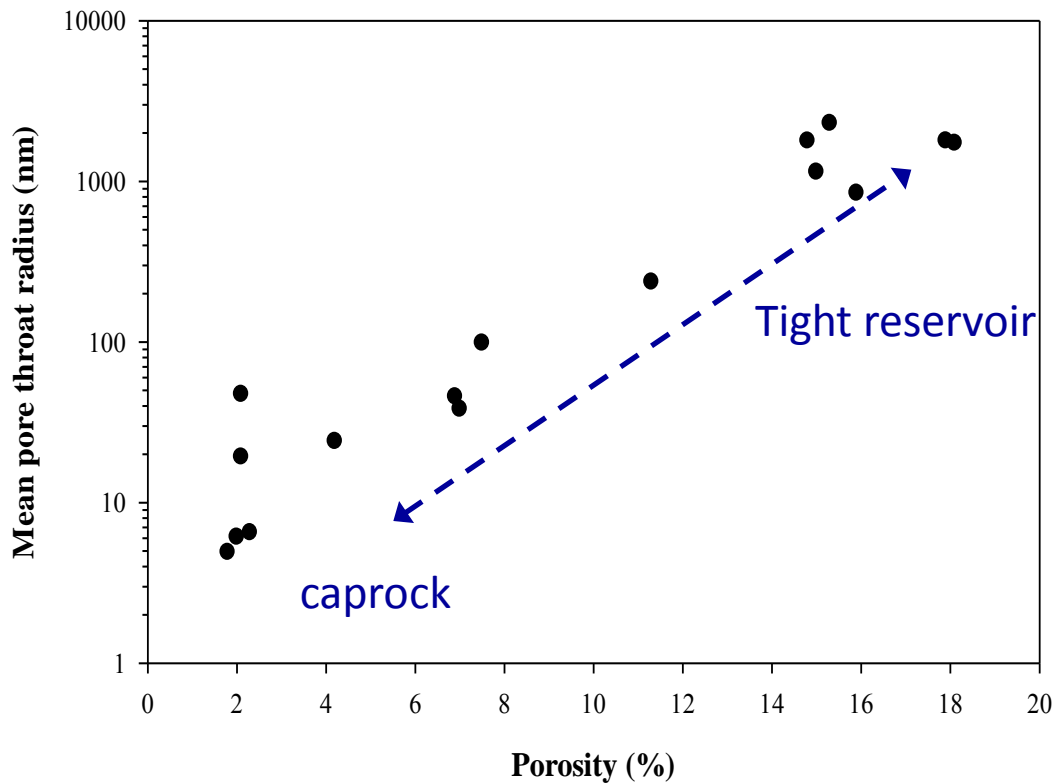
Flow method

- Longer test, based on Darcy's law.
- Allows more volume of reactive fluid to flow
- Too long to reasonably build up a graph showing permeability pressure relationships –
- But can overlay on the the graph made from TPD measurements

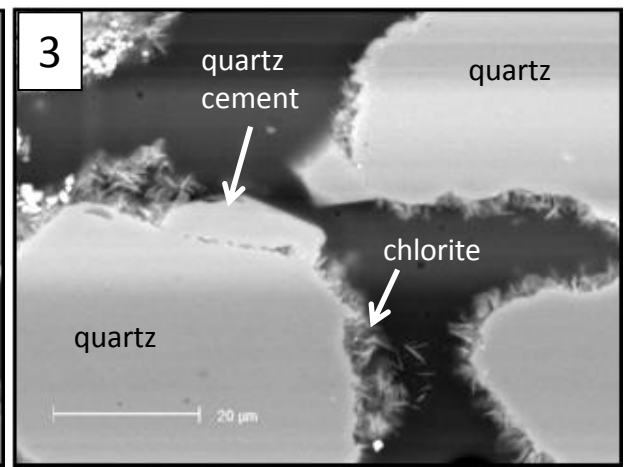
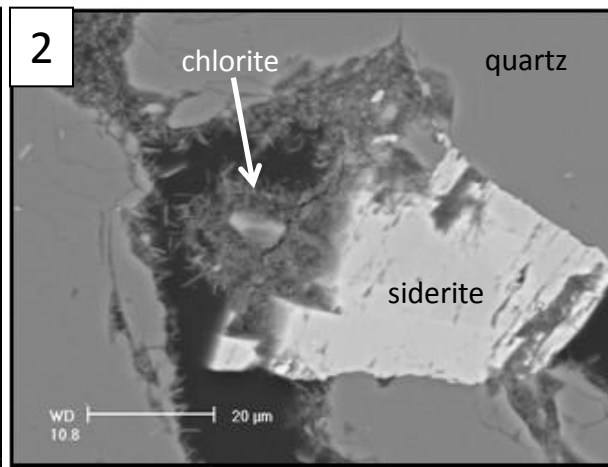
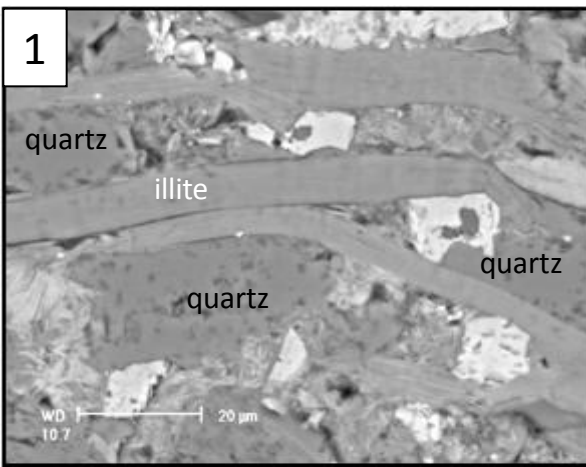
Samples



Sample characterisation - Controls on porosity/ pore throat radius



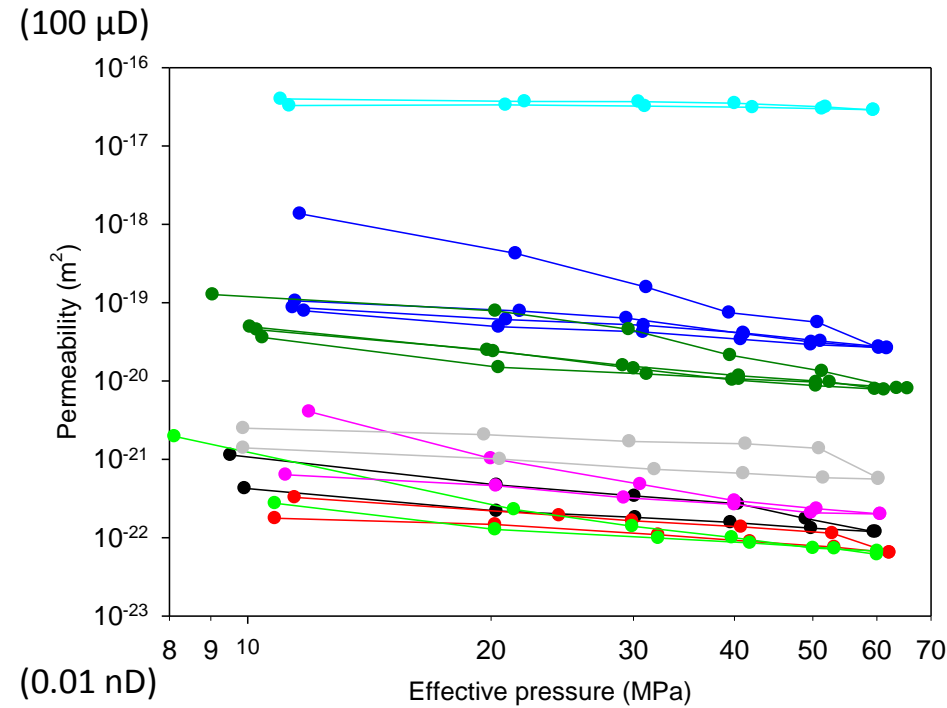
- Use MICP and found a range of porosity and pore throat radius
- SEM images show the controls on porosity and permeability



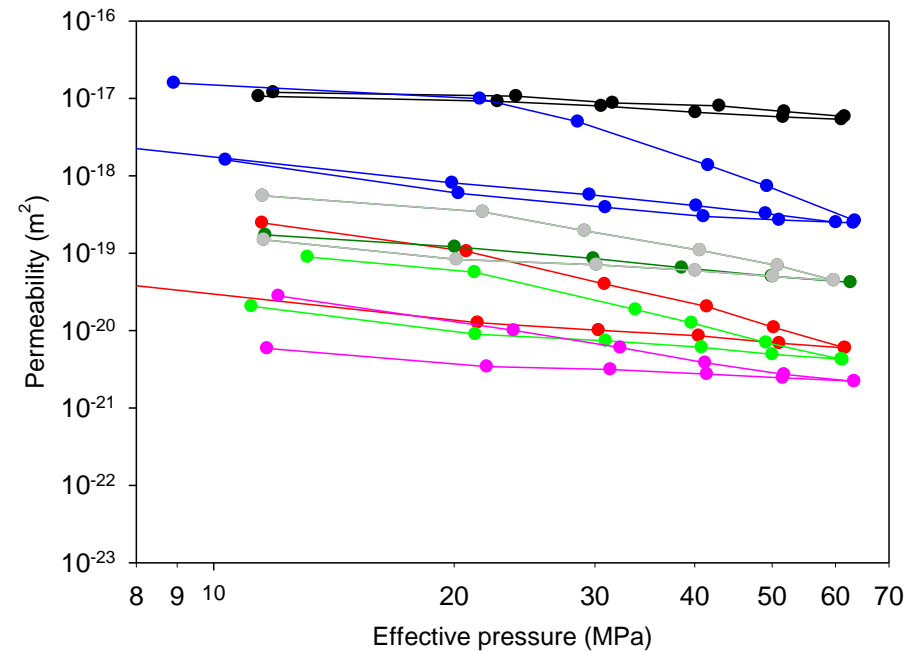
Outline

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Sample characterisation - Permeability measurements for all samples



Vertically measured



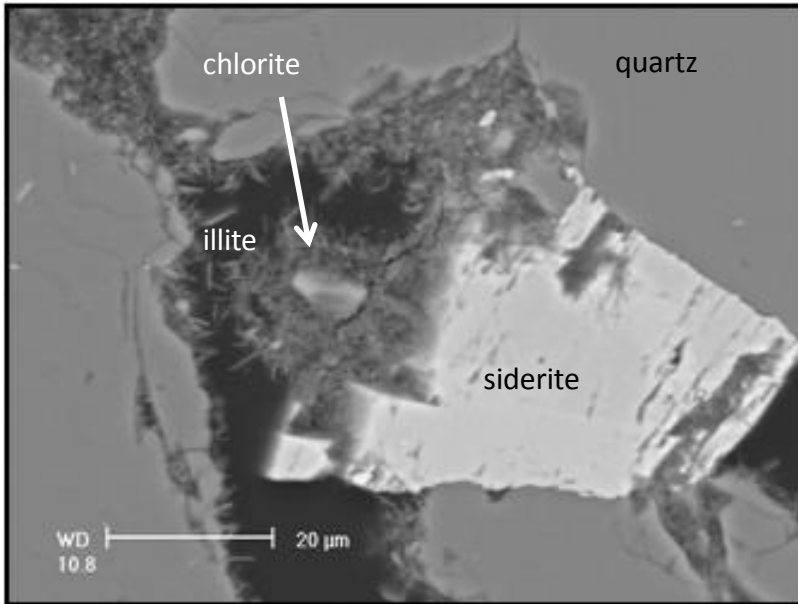
Horizontally measured

- Vertical k range from 30.1 μD to 0.089nD
- Horizontal k range from 6.3 μD to 1.00nD
- K measured vertically is less than those measured horizontally

Samples characterised for reservoir/ caprock quality

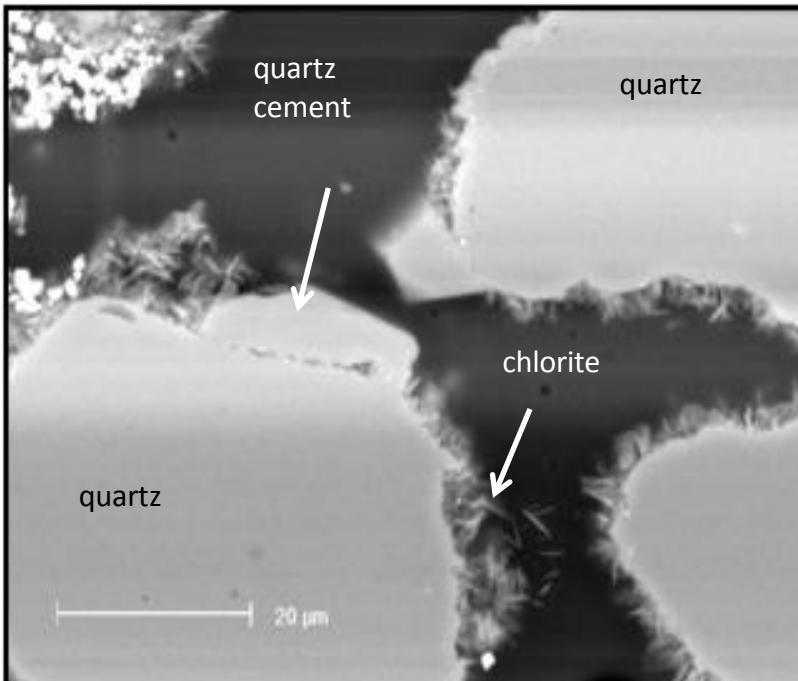
How will geochemical changes associated with CO_2 sequestration affect rock quality?

Potential effects of reactive fluid flow



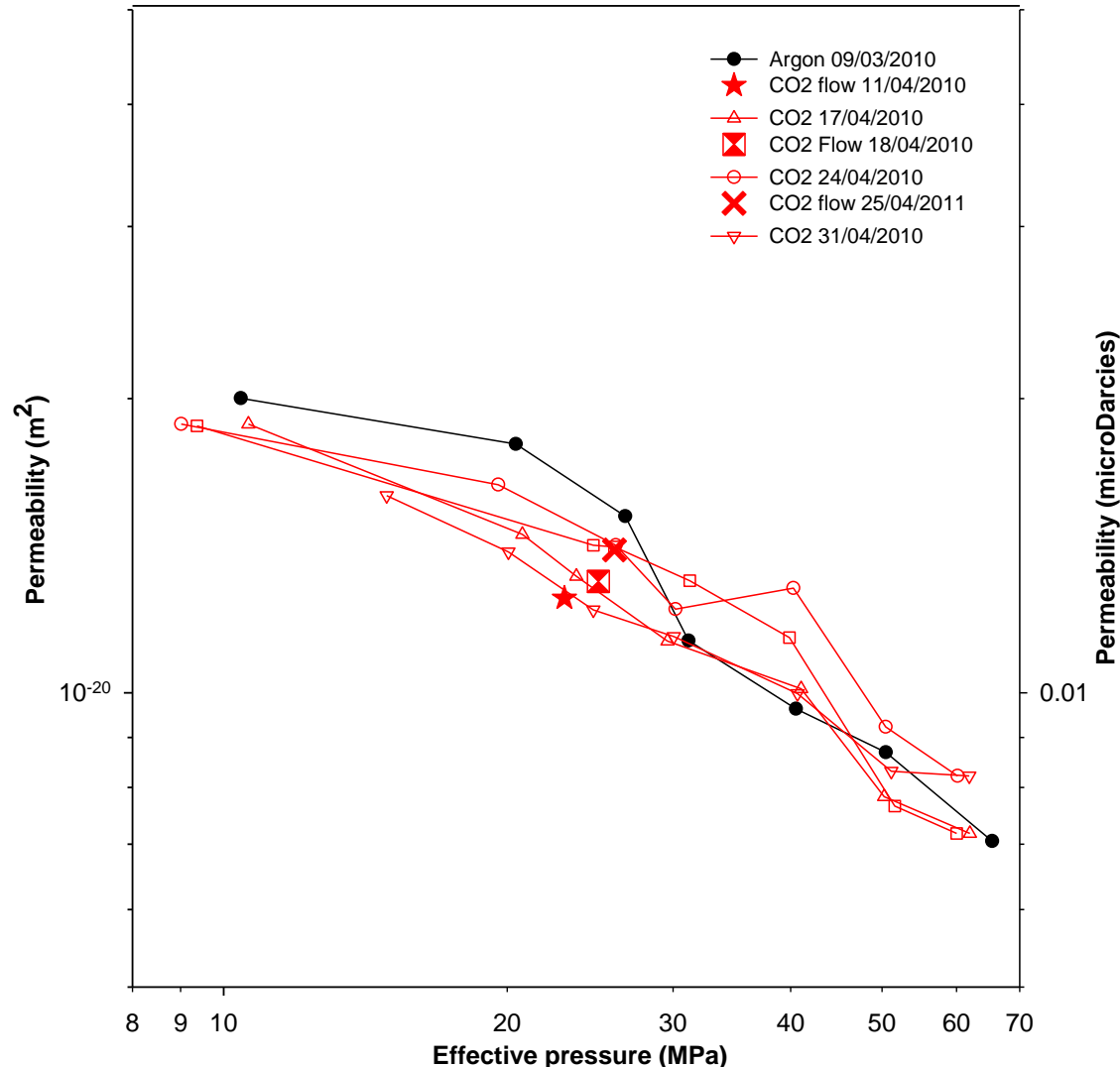
- Chlorite and siderite control porosity, pore throat radius and thus permeability
- Small dissolution losses could lead to changes in permeability and storage properties

To understand the geochemical effect of CO₂ - for the same sample



1. Characterise permeability for
 - a) inert fluids
 - b) confirm effect of dry CO₂ or distilled water
2. Flow CO₂ saturated water through the sample and measure changes in permeability, porosity, surface area, petrology, etc

Permeability with reactive fluid flow – Characterisation with inert fluid and dry CO₂

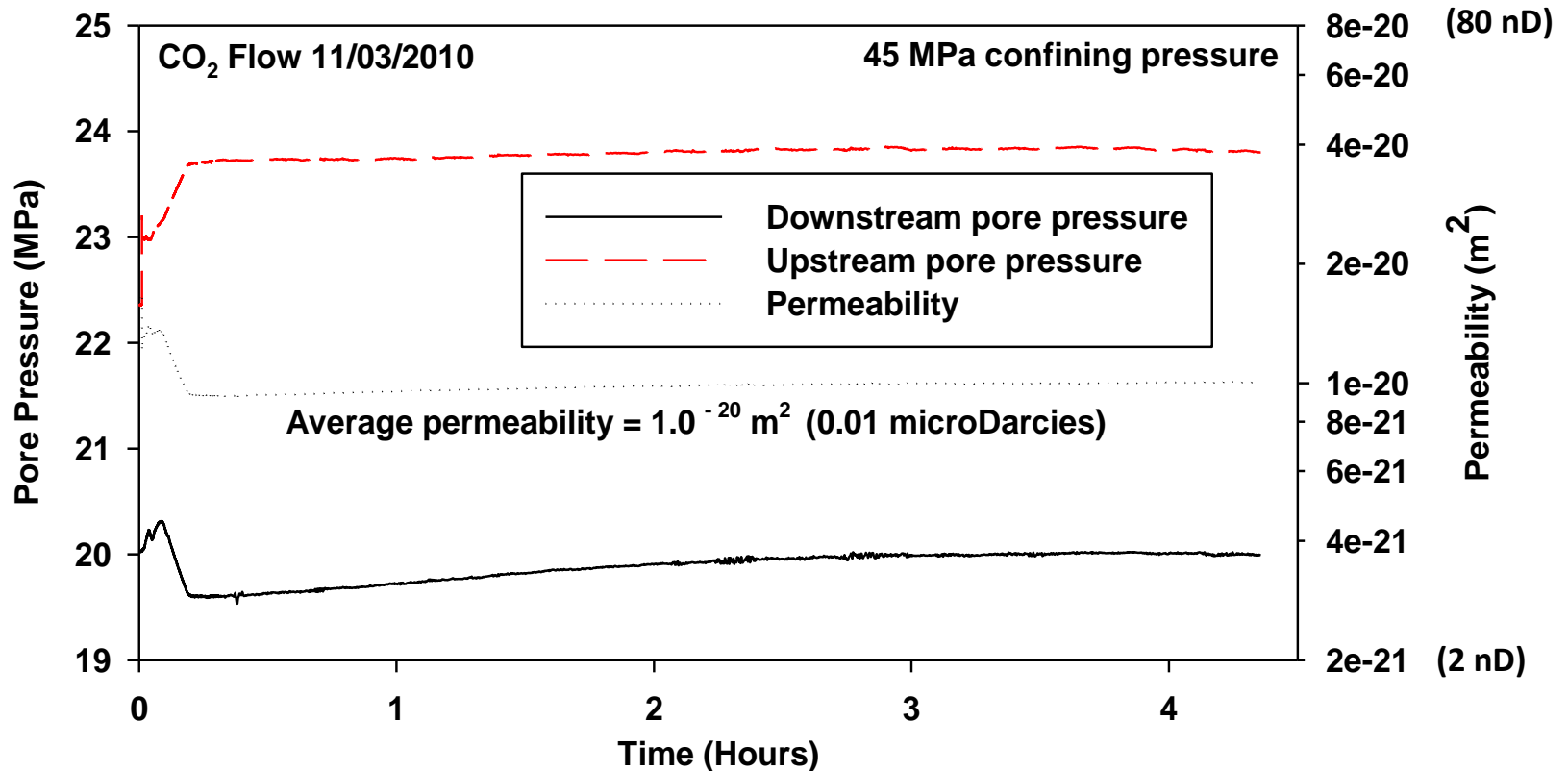


DRY CO₂

1. Permeability measured across a range of pressures using the TPD method with inert argon as pore fluid
2. Repeated TPD tests with CO₂ pore fluid
3. Permeability measured by flowing CO₂ through samples at approximate reservoir conditions
4. Repeated steps 2 and 3

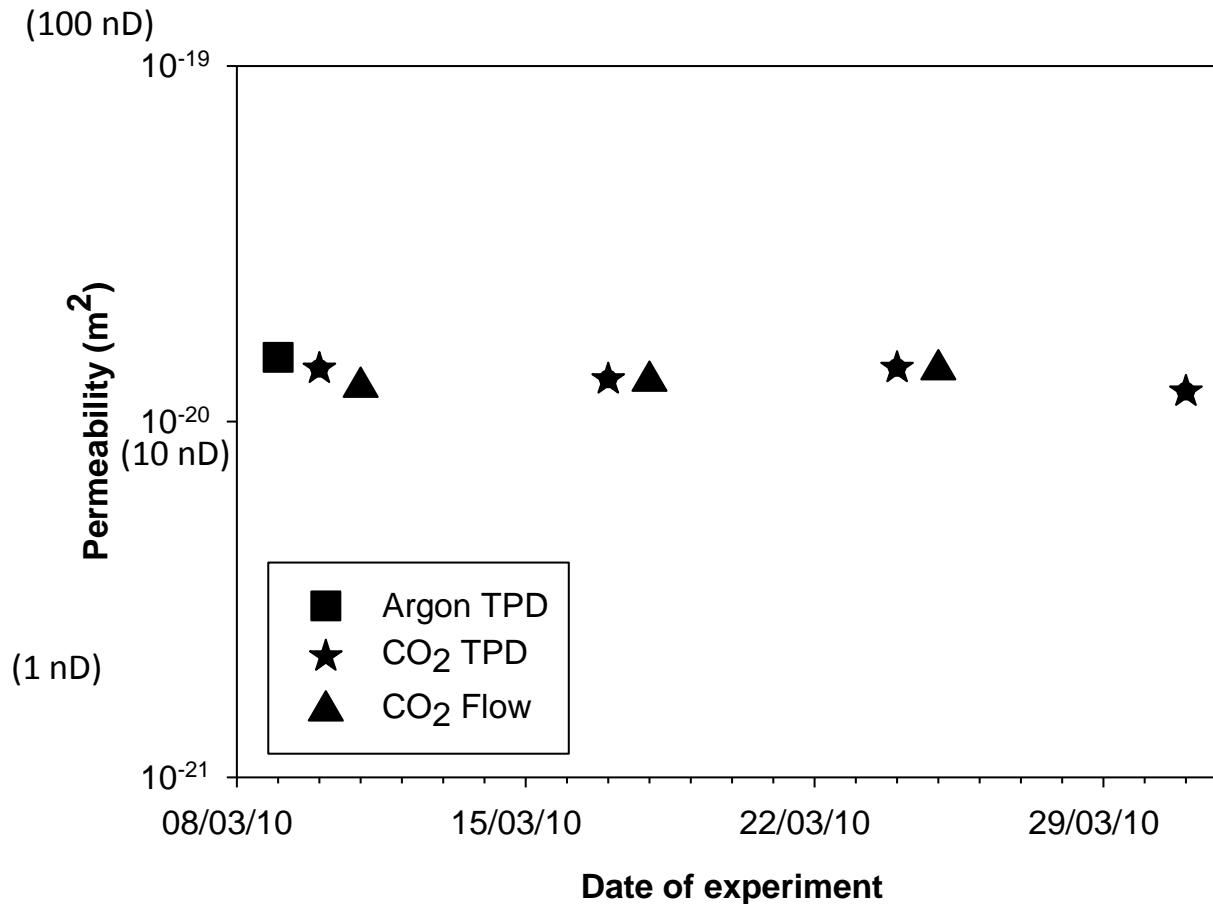
- Results all overly
- Repeated flow and TPD tests using CO₂ **do not change** the sample permeability (within the constraints of this experiment)

Constant permeability during dry CO₂ flow



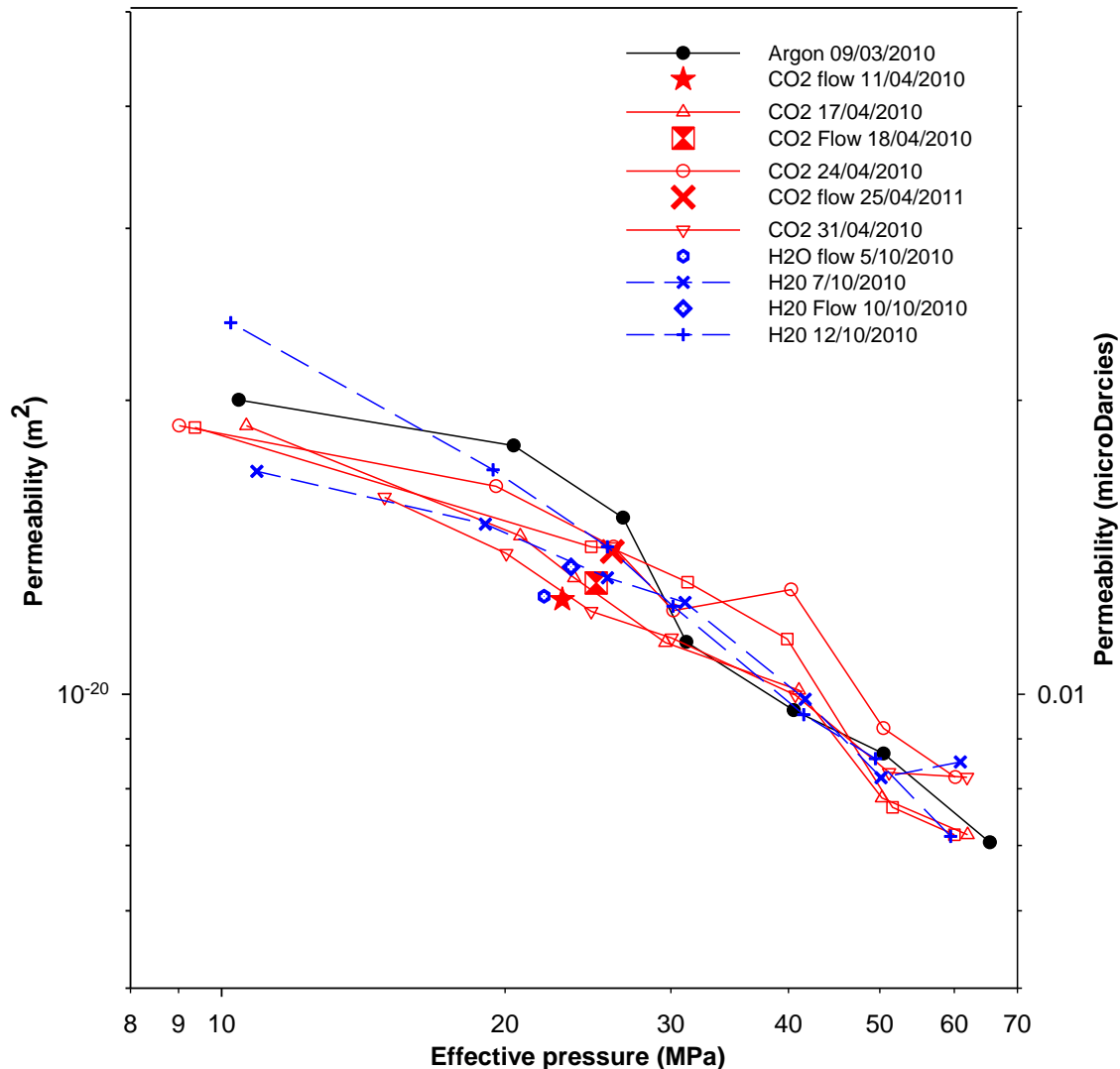
- Constant permeability during dry CO₂ flow

Permeability with reactive fluid flow – Characterisation with inert fluid and dry CO₂



- Same results as previous slide, presented as permeability against time at approximate reservoir conditions
- Repeated flow and TPD tests using CO₂ do not change the sample permeability (within the constraints of this experiment)
- What about distilled water?

Permeability with reactive fluid flow – Characterisation with inert fluid, dry CO₂, and distilled water

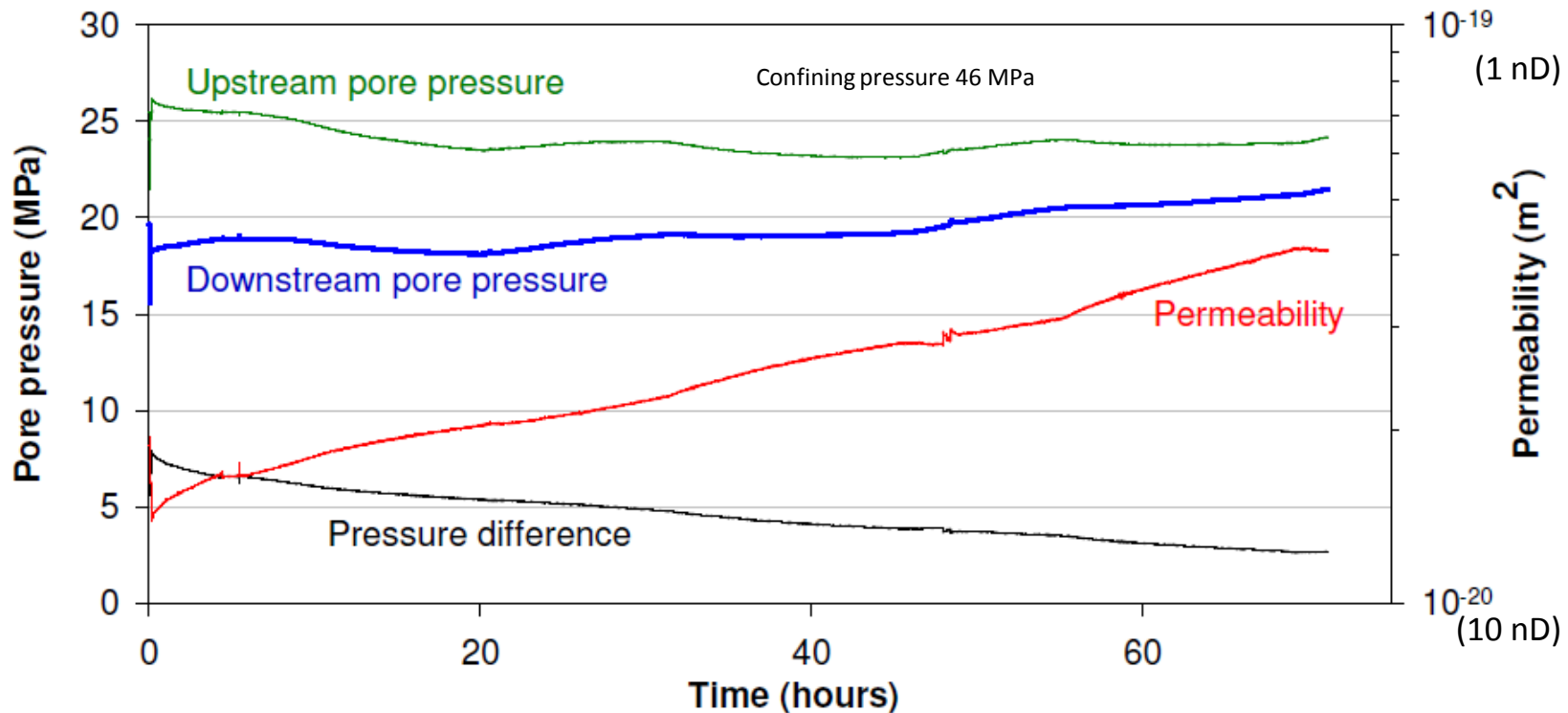


- Previous results using Argon and CO₂
- Repeated TPD and flow experiments on the same sample using water as pore fluid

Distilled water

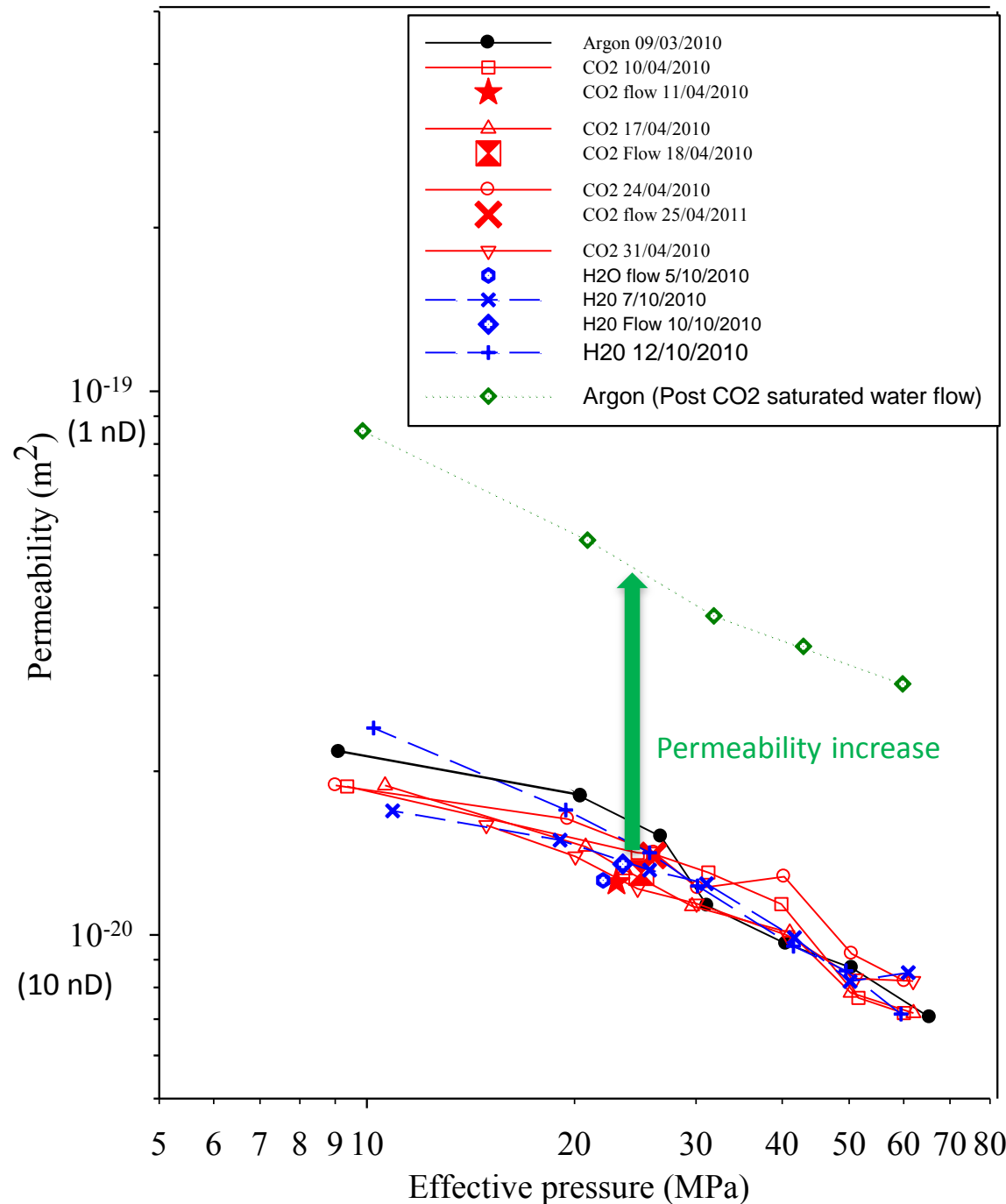
- Repeated flow and TPD tests using water **do not change** the sample permeability (within the constraints of this experiment)
- What about CO₂ saturated water?

CO₂ saturated water pore fluid flow results



- Pressure difference across the sample falls with time under constant flow rate
- Permeability increases with time
- After the experiment, the sample was dried and permeability tested using TPD method for a range of effective pressures with inert argon pore fluid

Post CO₂ saturated water flow



- Permeability increase
- Why?
- Microstructural and petrophysical observations pre and post test

on 09/03/2010
 2 10/04/2010
 2 flow 11/04/2010
 2 17/04/2010
 2 Flow 18/04/2010
 2 24/04/2010
 2 flow 25/04/2011
 2 31/04/2010
 2 flow 5/10/2010
 2 7/10/2010
 2 Flow 10/10/2010
 2 12/10/2010

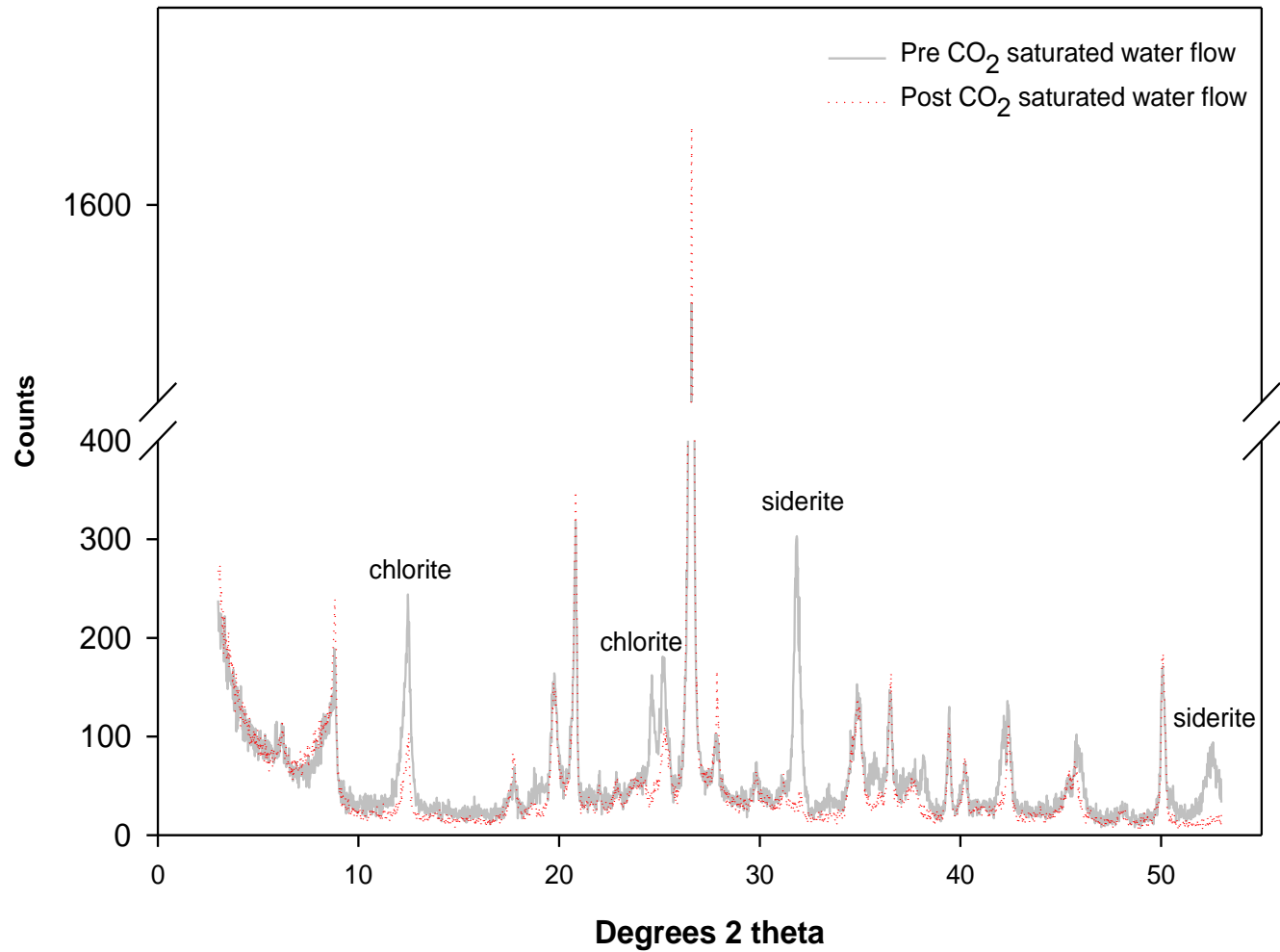
CO₂ saturated water pore fluid flow results

	CO2 saturated water flow	
	Before	After
Porosity (%)	7	10
Weight (g)	6.83	6.3904
Surface area m2/g	0.901	0.423

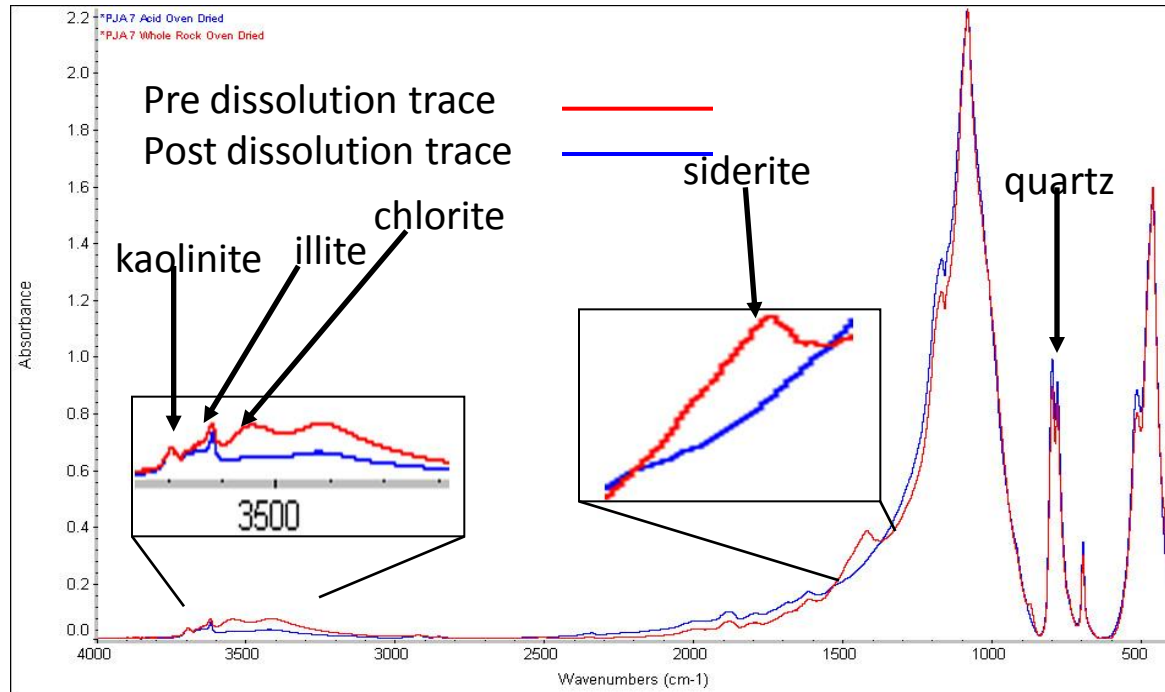
- Increase in porosity
- Weight loss of sample
- Decrease in surface area
- Dissolution?
- What minerals?
- Evidence from XRD, FTIR spectroscopy, SEM

Geochemical reaction - XRD

Loss of siderite and chlorite indicated in
XRD and FTIR plots



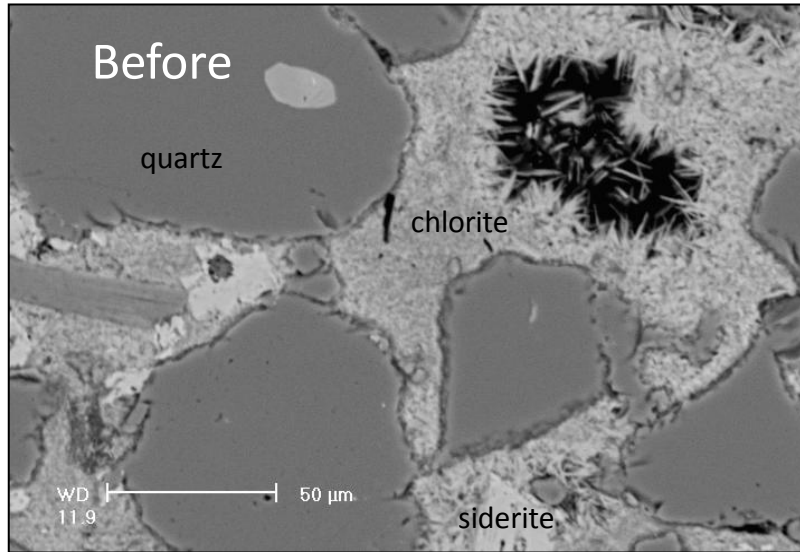
Geochemical reaction– FTIR



- Comparison of pre and post dissolution samples

- Loss of siderite and chlorite (leaching of iron) indicated in FTIR plot

SEM images before and after CO₂ saturated water flow



Before

Chlorite and siderite filling pore throats and blocking pore space

After

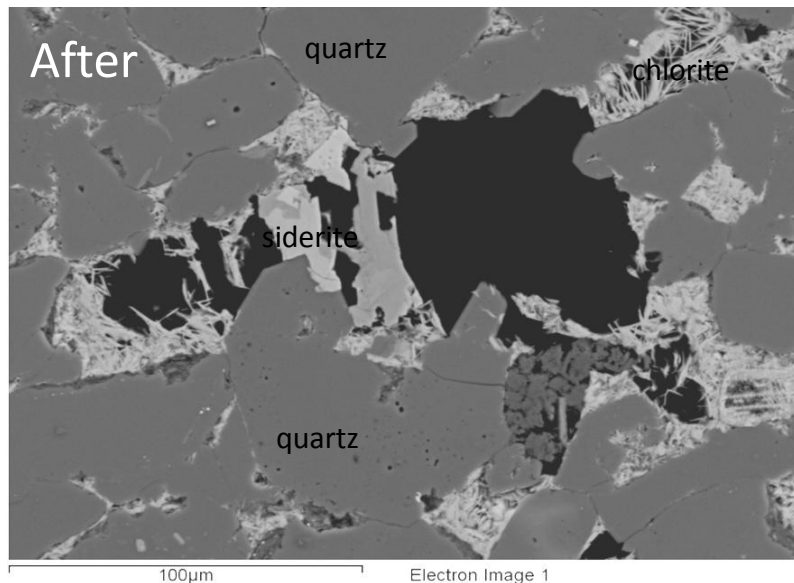
Dissolution of chlorite and siderite starting in open pores

But

This does not tell us about re-precipitation of dissolved material elsewhere in the system – could this lead to localised permeability decreases?

Rates of dissolution

Experiments on powdered samples to tell us about rates of dissolution



Conclusions

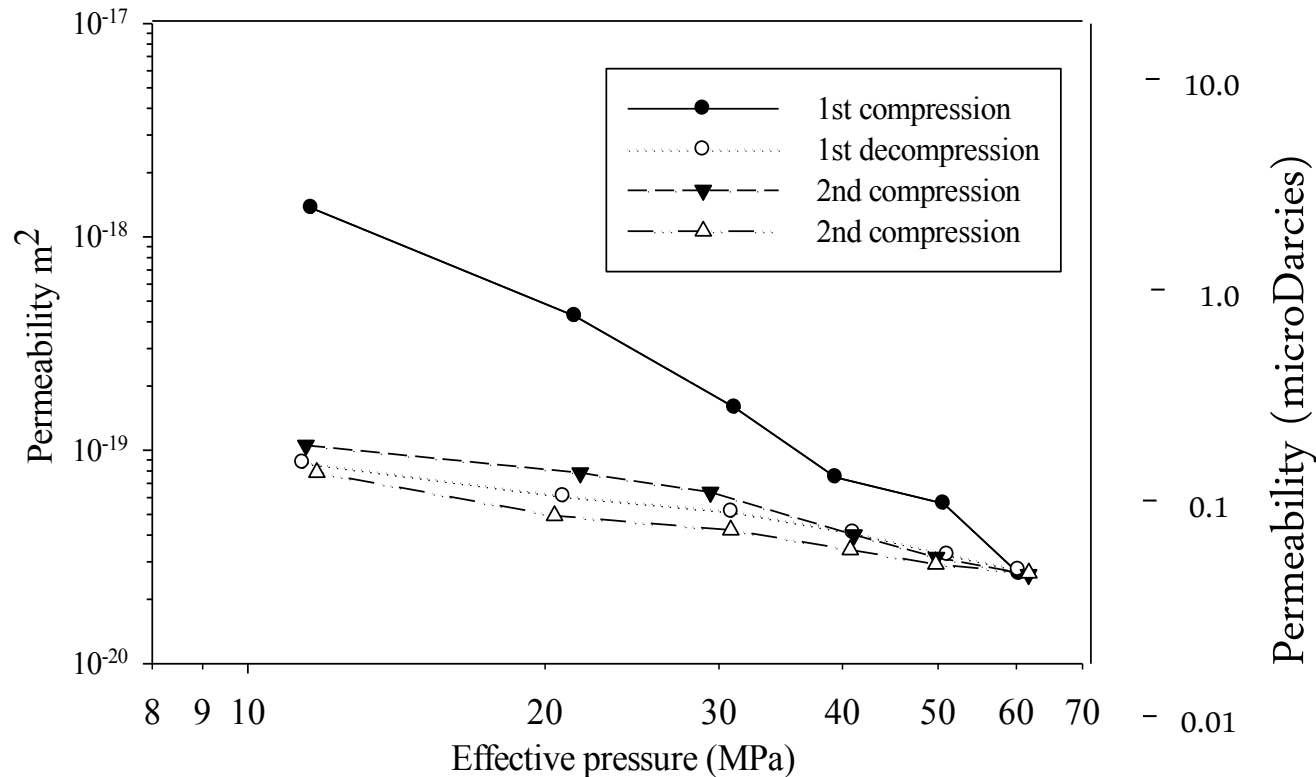
Early results indicate

- Storage domain rocks sensitive to geochemical change caused by injection
- These effects may locally affect storage capability and flow properties positively or negatively

Future experiments

- Effects on other rock properties? Strength? Seismic properties? Elastic properties?
- Combined dissolution/ precipitation experiments

Typical range of permeability measurements for 1 sample



- Pressure cycling closed microfractures caused by core exhumation (stress relief) damage
- One compressive phase was sufficient to produce behaviour that was independent of further cycles