We CO2 11

CO2 Flow, Alteration And Geomechanical Response In Confining Units – An Experimental Approach

E. Skurtveit[1,2]*, A. Sundal[2], M. Soldal[1], G. Sauvin[1], T.I. Bjørnarå[1]
[1]NGI (Norwegian Geotechnical Institute), [2]UiO (University of Oslo)

Summary

Seal integrity during injection operations is a topic of great interest both within the CO2 storage community, for wastewater injection and traditional reservoir pressure support. The Little Grand Wash fault, central Utah, USA, provides an excellent location for studying seal bypass systems in a siliciclastic sedimentary sequence. Two mode I siltstone fractures with significantly different apertures and varying degree of sample bleaching due to alterations from reactive fluid flow are studied together with two intact rock reference samples from the same depth level in the core. The experimental work addresses fracture flow and stiffness relationships. Observed differences in fracture closure trends may be explained as a rapid decrease in stiffness and flow for altered samples due to the fluid rock interaction process altering the fracture surface contact area for this sample.

Introduction

Seal integrity during injection operations is a topic of great interest both within the CO_2 storage community, for wastewater injection and traditional reservoir pressure support. Large efforts are made to identify safe operation limits, and towards understanding critical areas for failure such as fault zones. Knowledge about seal bypass systems is essential for the planning of monitoring and remediation related to injection wells.

The Jurassic Entrada Sandstone (Peterson, 1988), at Little Grand Wash in central Utah, USA, is an exhumed paleo-reservoir showing evidence of CO_2 accumulations in geological history. It provides an excellent field location for studying seal bypass systems in a siliciclastic sedimentary sequence. Migration of CO_2 (and methane) saturated groundwater causes bleaching of sealing siltstone layers that originally are stained red by Fe-oxides. The resulting patterns are easily observed in the field and allow for identification of relict fluid pathways. Fracture corridors related to faults and folding (Ogata *et al.* 2014) are identified as the main pathway for seal bypass, whereas chemical diffusion fronts are identified on reservoir–seal boundaries and along fractures. Key questions are related to the system transport properties and if bleaching may altering the mechanical properties. Effects of chemical alteration on the geomechancial properties in low permeable material is challenging to document and quantify in experimental work due to the low reaction potential for relatively short timescales. This natural CO_2 storage analogue provides an opportunity for experimental measurements of flow properties and mechanical changes in naturally fractured and altered sealing units and for comparison with non-altered samples from the same system. A research-well drilled into the footwall damage zone of the Little Grand Wash fault in 2012 retrieved a complete core from a multi-storied succession of reservoirs and cap-rocks (Kampman *et al.*, 2014). Core samples from this well has been used for experimental investigation of fracture flow and stiffness properties addressing the questions above.

Fracture properties like aperture and contact areas are directly controlling fracture flow and stiffness. Alteration due to fluid-rock interaction within fractures, or in the host rock along the fracture surface, will change the fracture stiffness and flow (Lang *et al.* 2016). Pyrak-Nolte and Nolte (2016) have proposed a universal scaling relationship between fracture flow and stiffness. The work is based on extensive experimental results and models mainly related to hard rock, whereas the application of such models for siliciclastyic rocks need to be further documented.

The current experimental work addresses fracture flow and stiffness relationships from the low permeable silty part of the "earthy member" (informal) in the upper Entrada Sandstone. Two mode I fractures with significantly different apertures and varying degree of sample bleaching due to alterations from reactive fluid flow are studied together with two intact rock reference samples from the same core depth. The work provides new insight into the stress dependent variation in flow properties and corresponding stiffness for low permeable siliciclastic rocks. The experimental work includes measurements of volumetric flow rate, deformation and acoustic velocity, providing well-documented behaviour during the experiments. Computer tomography (CT) images before and after the test provides data on the fracture aperture and contact distribution. Mineralogical and micro-textural analysis based on thin sections and scanning electron microscope (SEM) studies of fractures and host rock provides knowledge of the alteration within the samples. The comprehensive dataset presented provides the basis for in-depth discussion of alteration effects in siliciclastic fractures within a CO_2 saturated system. A more detailed analysis of the stress dependency of the permeability for one of the core couplets is presented in Bjørnarå *et al.*, 2018.

Experimental method

Fracture flow and stiffness tests were performed in a triaxial cell using isotropic pressure conditions. All-around confining pressure was applied to the specimen through oil pressure in the main pressure chamber. Two horizontal strain sensors measured the horizontal strain of the specimen. Each sensor consists of a submersible linear variable differential transformer (LVDT) fixed in a very light metal ring, which encloses the specimen. One horizontal strain-sensor was used for measuring the change in the diameter at the lower part (at one third of sample height) of the specimen, and one was used to

measure the change in the diameter at the upper part (at two thirds of the sample height). The two sensors were oriented 90° relative to each other and placed such that the upper sensor (Rad5) was measuring across the fracture, whereas the lower sensor (Rad4) was measuring along the fracture for the two fractured samples. Acoustic velocity sensors were placed similarly, P-wave velocity was measured along fracture and S-wave velocity across fracture. Axial deformation was recorded using LVDT sensors and both P- and S-wave velocity in the axial direction were measured. Sensor placement was similar for the intact reference samples. A Nikon Metrology industrial high resolution computer tomography (CT) was used for the sample imaging before and after testing, whereas microstructure and mineral composition of fracture surfaces were characterized using a HITACHI SU 5000 scanning electron microscope (SEM).

The experimental test procedure is divided into a main phase consisting of a hydrostatic loading phase up to 9 MPa effective confining stress (isotropic stress) followed by hydrostatic unloading back down to 1 MPa. Loading is paused every 2 MPa and a flow check performed. All the tests were performed under drained conditions, using a back-pressure of 10 MPa with brine as the pore fluid. The flow check is performed by establishing a steady state flow across the sample and measuring the volumetric flow rate.

Experimental results
In total, four samples were studied, two with fractures and two intact reference samples. All samples are from the CO2W55 well in Little Grand Wash fault, Utah (Kampman *et al*. 2014). One fracture and host rock couplet from 24 m depth is from a red unaltered siltstone, whereas the second couplet from depth 45 m, is from a bleached, altered siltstone. An overview of the samples tested is shown in Table 1 and photos from each plug is presented in Figure 1 together with CT images showing fracture aperture and morphology.

*Table 1 Overview of samples tested and short sample description.*

Well name	Depth	Sample ID	Plug description	Plug height	Plug diameter	Matrix porosity
	(m)			(mm)	(mm)	(%)
CO2W55	24.77	LGW1 (T2243)	Thin vertical mode I fracture in red siltstone	52.17	25.52	
CO2W55	24.71	LGW2 (T2265)	Red reference siltstone	52.12	25.54	5.8 - 6.0
CO2W55	45.75	LGW7 (T2233)	Thick vertical mode I fracture in bleached siltstone	52.19	25.56	
CO2W55	45.81	LGW8 (T2250)	Bleached reference siltstone	52.13	25.51	7.6 - 7.8

The experimental program provides useful insight into effects of alteration of both host rock and fractures. From the 9 MPa loading cycle, systematic changes in stress dependent flow properties are observed (Figure 2a). From 2 to 5 orders of magnitude higher flow rates are found for the fractured samples compared to the host rock. The largest difference is observed for the altered samples (LGW7 and LGW8). The wide, altered fracture in sample LGW7 shows 1 to 3 orders of magnitude higher flow rates compared to the thin, unaltered fracture in sample LGW8. A strong reduction in fracture flow is observed for the loading up to 9 MPa, whereas the unloading is associated with less variation. This hysteresis effect is more pronounced for the altered samples than for the unaltered samples. This seems to be the case for both the fractured sample and the host rock. In the plot of flow against volumetric strain (Figure 2b), flow and strain correlate for both the loading and unloading phase except for the unaltered fracture test (LGW1), where an abrupt reduction in flow is associated with the last loading step (from 7 to 9 MPa). The two altered samples (host rock and fracture) stand out with a very high reduction in flow associated with the first 2 to 4 mS of deformation before approaching the same trend as for the unaltered samples LGW1 and LGW2 (Figure 2b). Two different trends are observed for the stress dependency of the fracture stiffness (Figure 3a) and S-wave velocity (Figure

3b) for the altered fractured sample (LGW7), whereas for the unaltered fractured sample (LGW1) the measurements follow a linear trend.
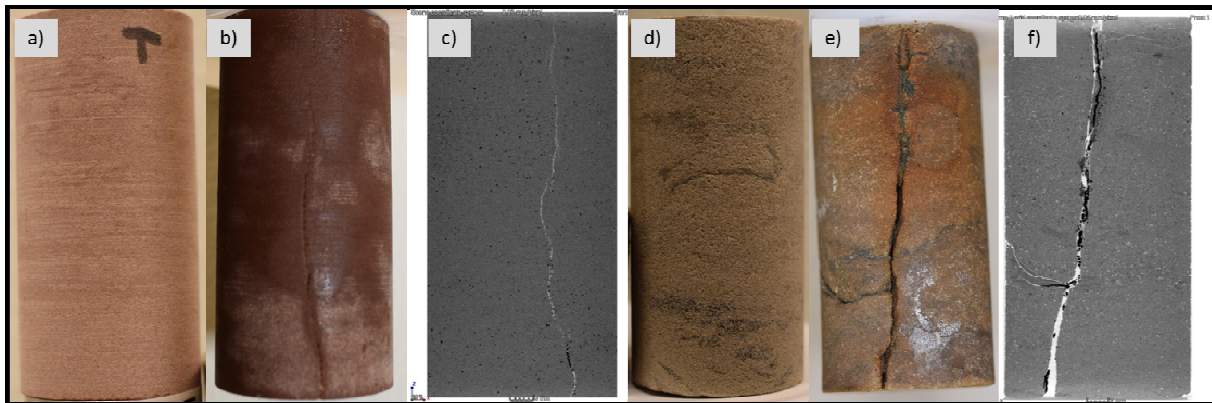
Figure 1 *Samples with 25 mm diameter used in the experimental work on an unaltered reddish siltstone and a bleached, altered siltstone. Intact unaltered host rock sample LGW2 (a), fractured unaltered sample, LGW1 (b), CT image of unaltered fractured sample LGW1 (c), intact bleached sample LGW8 (d), fractured altered host rock (LGW7) (e) and CT image of altered fractured sample LGW7 (f). In the CT images white is air and dark is dense material. A dark fracture-fill identified as oxides is observed mainly for the altered fracture in LGW7(e and f).*
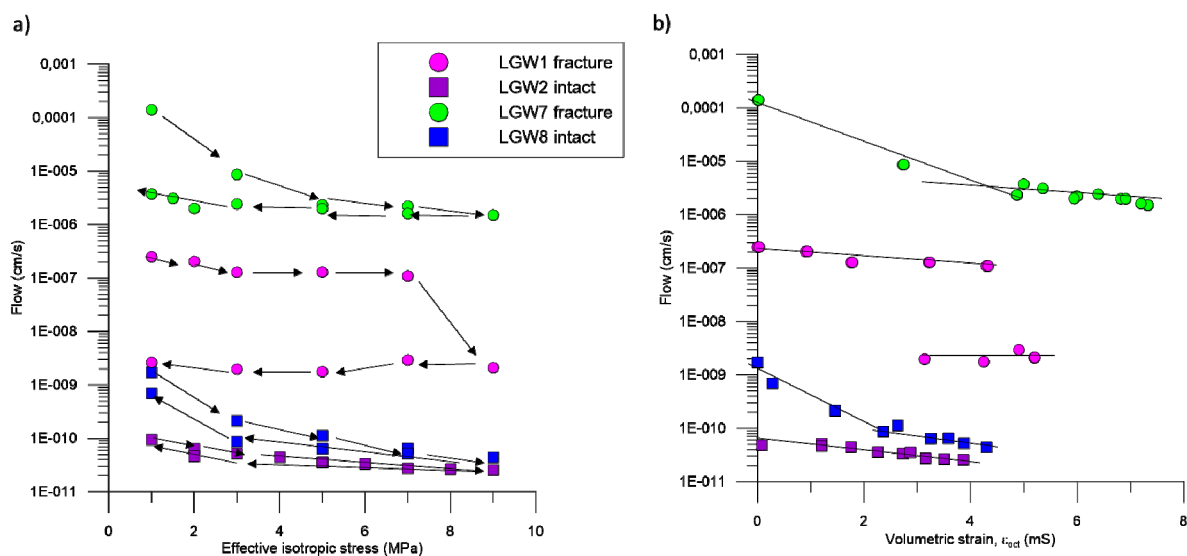

Figure 2 *Measured stress-dependent flow as a function of effective isotropic stress (a) and volumetric strain (b) for fractured and intact sample. Arrows show loading direction in (a). In (b) trend lines are added to highlight the initial fast decrease in flow rate with strain for the fractured and intact bleached siltstone (LGW7 and LGW8) compared to the red siltstone where the decrease in flow rate with strain is slower.*

Discussion

Pyrak-Nolte and Morris (2000) shows that relationships between fracture specific stiffness and flow may be divided into two different categories; (1) rapid and (2) slow decrease in flow for increasing fracture stiffness. The two categories are related to the fracture aperture correlation, contact area and asperity distribution. Contact area distribution may be varying with lithology (host rock) and sample size. However, for the current experimental work both lithology and sample sizes are similar, and the difference in fracture stiffness and flow relationship might be related to the fracture alteration in a similar way as shown by Lang *et al*. (2016): The observed variation in stiffness and flow trends may be explained as a rapid decrease in stiffness and flow for altered samples due to the fluid-rock interaction process for this sample. Although the grain size distribution of the cores appears to be

slightly coarser for the bleached siltstone compared to the red siltstone, both samples couplets display similar lithologies: sub-arkosic framework with abundant fine grained matrix, illitic clay-coats and pore-filling clay-mix as well as patchy, poikilotopic carbonate cement. Alteration processes related to the bleaching are removal and/or reduction of Fe-oxides, whereas pyrite and gypsum precipitates on the same fractured surface indicates alternating red-ox conditions in multiple fluid circulation episodes. For the altered fracture (LGW7), a highly uncorrelated aperture distribution is suggested, which indicate that the contact area is much smaller for the altered fracture in LGW7 than for the unaltered fracture in LGW1. A difference in contact area and aperture distribution for the two fractures is visible from the CT images (Figure 1), and may support the difference in stiffness observed for the two samples. Similar effects may be seen for the intact host rock, where the chemical processes may have changed the grain contact areas and hence the mechanical response of the material, suggesting a mechanical influence of geochemical alteration also for the bleached/altered host rock.
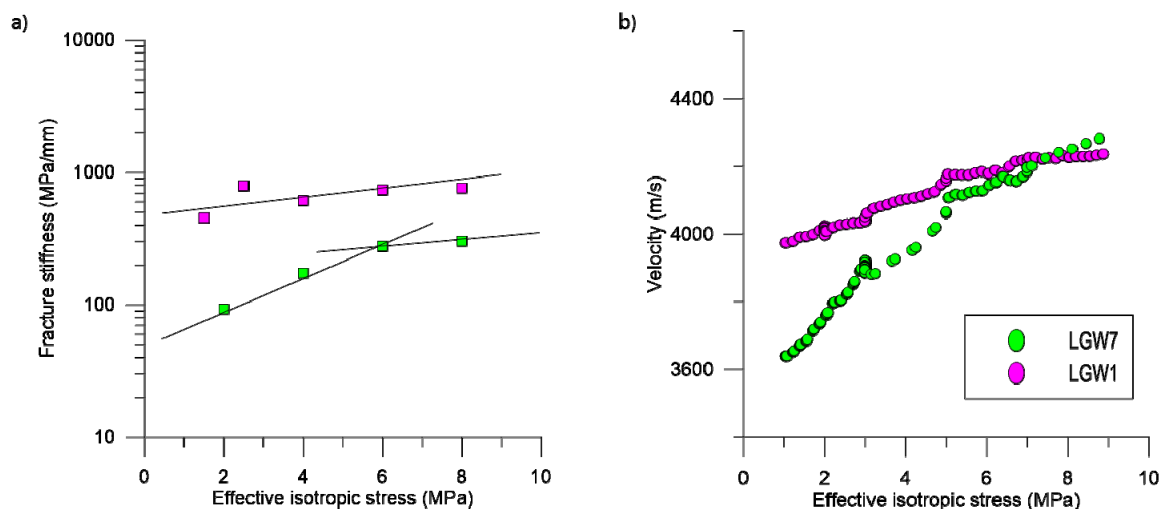
Figure 3 *Fracture stiffness, K_n, defined as $d\sigma/d\varepsilon_f$ (a) and radial S-velocity (b) for the fractured red siltstone (LGW1) and the bleached siltstone (LGW7) showing a marked change in trend during loading (closure) of the bleached siltstone fracture compared to the red siltstone.*

Acknowledgement

References

Bjørnarå, T. I., Skurtveit, E., and Sauvin, G. (2018). Stress-dependent fracture permeability in core samples: an experimental and numerical study. In Second International Discrete Fracture Network Engineering (DFNE) Conference, 20-22 June 2018, Seattle, Washington, USA

Kampman, N., M. Bickle, A. Maskell, H. Chapman, J. Evans, G. Purser, Z. Zhou, M. Schaller, J.C. Gattacceca, P. Bertier, [2014] Drilling and sampling a natural CO_2 reservoir: Implications for fluid flow and CO_2-fluid–rock reactions during CO_2 migration through the overburden, *Chemical Geology*, 369 51-82.

Lang, P. S., A. Paluszny, and R. W. Zimmerman [2016], Evolution of fracture normal stiffness due to pressure dissolution and precipitation, *International Journal of Rock Mechanics and Mining Sciences*, 88, 12-22.

Ogata, K., K. Senger, A. Braathen, J. Tveranger, [2014] Fracture corridors as seal-bypass systems in siliciclastic reservoir-cap rock successions: Field-based insights from the Jurassic Entrada Formation (SE Utah, USA), *Journal of Structural Geology*, 66 162-187.

Peterson, F. [1988], "Stratigraphy and nomenclature of Middle and Upper Jurassic rocks, western Colorado Plateau, Utah and Arizona, In: Revisions to stratigraphic nomenclature of Jurassic and Cretaceous rocks of the Colorado Plateau", *U.S. Geological Survey Bulletin*, 1633-B, p. B13-56

Pyrak-Nolte, L., and J. Morris [2000], Single fractures under normal stress: The relation between fracture specific stiffness and fluid flow, *International Journal of Rock Mechanics and Mining Sciences*, 37(1), 245-262.

Pyrak-Nolte, L. J., and D. D. Nolte [2016], Approaching a universal scaling relationship between fracture stiffness and fluid flow, *Nature communications,* 7, 10663.