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Influence of Poromechanical and Thermal Properties of the Caprock on the Safety of CO2 Storage

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SUMMARY

Geologic carbon sequestration is a promising option to reduce carbon dioxide emissions to the atmosphere and mitigate climate change. The injected CO2 will reach the storage formation at a colder temperature than that of the host rock. This cold CO2 will cool down the caprock by conduction, which will induce thermal stress reduction and pressure changes that will affect caprock stability. We analyzed thermoporomechanical response of Swiss shale and found that the effective stress changes induced by cooling do not have, in general, the potential to jeopardize the caprock sealing capacity.

Introduction

Geologic carbon sequestration is considered to have enough storage capacity to safely contribute in one fifth of the total reduction in carbon dioxide (CO_2) emissions that we should carry out in the following decades to mitigate climate change (IEA, 2010). The huge amounts of CO_2 that will be injected will induce overpressure and temperature decrease. Overpressure propagates fast over long distances, thus having the potential to affect faults that may be located several kilometers away from the injection well (Birkholzer and Zhou, 2009). Furthermore, CO_2 will generally reach the storage formation at a colder temperature than that corresponding to the geothermal gradient, because CO_2 does not have enough time to thermally equilibrate with the surrounding rock as it flows downwards along the injection well (Paterson et al., 2008).

The colder CO_2 will form a cooled region around the injection well (Figure 1) that advances much behind than the desaturation front (Gor et al., 2013; Vilarrasa et al., 2014). Though CO_2 will not penetrate into the caprock due to its high entry pressure, cooling will propagate into the lower portion of the caprock by conduction. This cooling of the caprock will induce thermal stresses and may also induce pressure changes. Thus, effective stresses will change, modifying caprock stability. Maintaining the caprock integrity is important to avoid CO_2 leakage and justifies the concern that cooling could cause fracture opening and shearing in the lower portion of the caprock (Goodarzi et al., 2012; Vilarrasa et al., 2015). Here, we focus on the effective stress changes in the lower portion of the caprock induced by cooling and analyze the subsequent caprock stability.

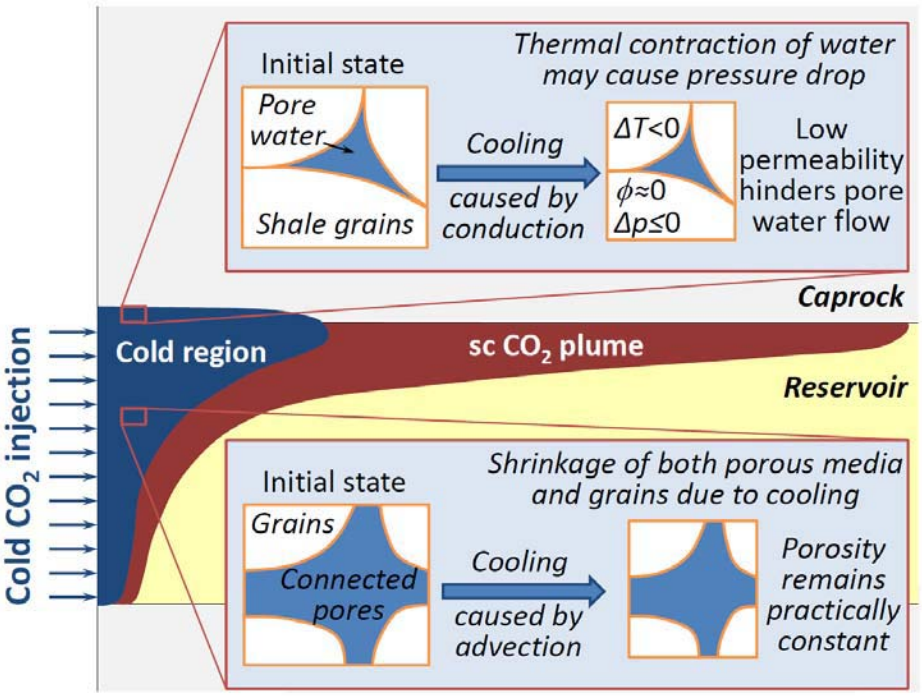

Figure 1 *Sketch of the considered geometry. Cold CO_2 region reaches the caprock, where contraction might cause fracturing due to effective stress changes.*

Theory

Caprock is assumed to be deforming under undrained conditions when the cold CO_2 front reaches its surface in the short-term, because the drainage processes for low-permeable formations are much longer than thermal conduction. Furthermore, pressure of CO_2 should be significantly higher (> 10 MPa) than the pore pressure in the caprock to start entering its pores. Thus, no CO_2 will be present into the caprock, so just the thermal effect on pore pressure p and vertical and horizontal stresses changes induced by the temperature difference ($d\sigma_v$ and $d\sigma_h$) acting on the caprock will be considered. Then, for an isotropic, linearly elastic material, which thermal and poroelastic parameters are assumed to be constant at the considered mean stress $P = (\sigma_v + 2\sigma_h)/3$ and temperature T ranges, the change in fluid pressure is given by

$$\frac{\beta}{BK}dp = (\alpha_f - \alpha_s)dT + \frac{\beta}{\phi K}dP \, , \tag{1}$$

where B is Skempton coefficient, K is the drained bulk modulus, and β is Biot coefficient, which are the parameters governing the poroelastic response of the caprock. The volumetric thermal expansion coefficients of the pore fluid and solid constituents of caprock are α_f and α_s, respectively (Coussy, 2004) and ϕ is the interconnected porosity. The approximate estimates for the variation of horizontal stress $d\sigma_h$ and vertical stress $d\sigma_v$ are based on the assumption that stresses vary isotropically with temperature changes and no horizontal strain is allowed at the outer boundary as a result of lateral confinement (Vilarrasa et al., 2013)

$$d\sigma_v = \alpha_d KdT \, , \tag{2}$$

$$d\sigma_h = \frac{1-2\nu}{1-\nu}dp + \alpha_d KdT \, , \tag{3}$$

where α_d is the volumetric thermal expansion coefficient of rock under drained conditions and ν is the Poisson's ratio. The decrease of temperature produces the contraction of the porous media and causes a decrease of vertical stress. The horizontal stress might increase or decrease depending on the change in pore pressure in the rock and its Poisson's ratio. Pore pressure variation though does not affect much the vertical stress, which remains largely lithostatic for the considered setup. Combining equations (2) and (3) with (1), one gets the following relationship for the undrained change in pore pressure p in the caprock as a function of the temperature change dT induced by cold CO_2 injection

$$\frac{\beta}{\phi K}\left[\frac{1}{B} - \frac{2(1-2\nu)}{3(1-\nu)}\right]dp = \left(\alpha_f - \alpha_s + \beta\frac{\alpha_d}{\phi}\right)dT \, . \tag{4}$$

Results

Swiss shale (Opalinus clay) was considered as the caprock representative for CO_2 storage. The material parameters used in this study (for P > 4 MPa) are reported in Table 1. Unjacketed bulk modulus K_s' was measured by the method proposed in Makhnenko and Labuz (2013) and drained bulk modulus was calculated by taking B = 0.8 as reported for effective mean stresses larger than 4 MPa by Wild et al. (2015). That allowed calculation of $\beta = 1 - K/K_s'$.

parameter	**symbol**	**value**	**source**
Unjacketed bulk modulus	K_s'	9 GPa	measured
Interconnected porosity	ϕ	0.12	measured
Skempton B coefficient	B	0.8	Wild et al. (2015)
Drained bulk modulus	K	2.7 GPa	calculated
Biot coefficient	β	0.7	calculated
Poisson's ratio (isotropic)	ν	0.29±0.09	Bock (2009)
Poisson's ratio (parallel to bedding planes)	ν_{II}	0.25±0.09	Bock (2009)
Volumetric thermal expansion of pore fluid	α_f	$6\text{x}10^{-4}$ °C	Monfared et al. (2011)
Volum. thermal expansion of solid constituents	α_s	$0.3\text{x}10^{-4}$ °C	Monfared et al. (2011)
Drained volumetric thermal expansion	α_d	$0.6\text{x}10^{-4}$ °C	Monfared et al. (2011)

***Table 1** Material parameters of Opalinus clay.*

Due to the very limited data on the material parameters, only isotropic response is considered. However, for the case of horizontal stress (applied parallel to the bedding), Poisson's ratio for this direction – ν_{II} can be taken into account. Since the pore pressure and vertical and horizontal stresses

are changing monotonically with the Poisson’s ratio, we investigate only two limiting cases for ν_{II} = (0.16, 0.34). The lower boundary of Opalinus clay that can be taken as a representative caprock lies at a depth of 950 meters and the approximate in-situ conditions are the following (Vietor et al., 2012)
σ_v = 25 MPa, σ_h = 20 MPa, p = 10 MPa, and T = 40 °C
So, σ_v can be considered as the major principal stress and σ_h is the minor principal stress.

Assuming cooling of the caprock down to 20 °C due to cold CO_2 injection, the following changes in pore pressure and horizontal and vertical stresses are predicted
1) ν_{II} = 0.16, dT = -20 °C leads to dp = -1.1 MPa, $d\sigma_v$ = -3.2 MPa, and $d\sigma_h$ = -4.3 MPa;
2) ν_{II} = 0.34, dT = -20 °C leads to dp = -0.87 MPa, $d\sigma_v$ = -3.2 MPa, and $d\sigma_h$ = -3.6 MPa.

Failure envelope for Opalinus clay at 60 °C (less conservative case in Gräsle and Plischke, 2010) and the Mohr circles for initial state and case 1 are shown in Figure 2, where $\tau = (\sigma_h - \sigma_v)/2$ and $\sigma' = -p + (\sigma_h + \sigma_v)/2$. As it can be seen, the caprock integrity is not questioned for the considered cases.

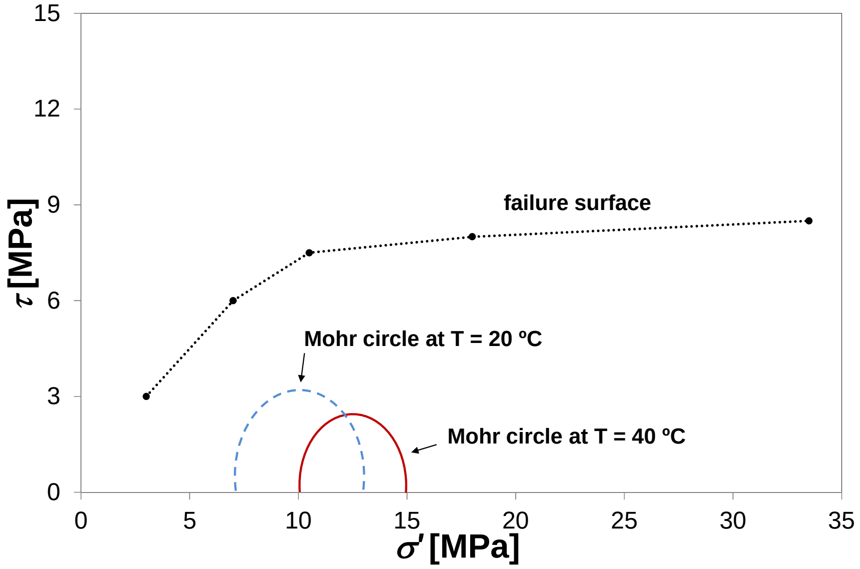

Figure 2 *Failure envelope for Opalinus clay (from Gräsle and Plischke, 2010) and Mohr circles for caprock at the initial state (40 °C, solid red circle) and after cooling to 20 °C (dashed blue circle).*

Also, for the undrained deformation, the change in caprock porosity can be calculated (Coussy, 2004)

$$d\phi = -\phi \frac{dp}{K_f} + \alpha_f \phi dT \,, \tag{5}$$

where K_f is the bulk modulus of pore fluid and it can be taken as the one of pure water: K_f = 2.2 GPa. Then, for the maximum porosity change for the two cases considered above will be $d\phi = 0.4\mathrm{x}10^{-3}$, which makes only 0.3% of the total ϕ. Clay-rich materials, like Opalinus clay might also experience poroelastoplastic deformation even for small thermally induced stresses. The contribution of plastic component will only reduce the pore pressure even more in the caprock, so the safety of the caprock is not compromised. Moreover, for undrained inelastic deformation the material might experience dilatant hardening (Makhnenko and Labuz, 2015), which will also move the Mohr circle further away from the failure surface.

Conclusions

We have analyzed the thermal effects on the caprock stability induced by cold CO_2 injection in deep saline aquifers. Cooling induces both thermal stress reduction in all directions and pressure changes induced by differences in the thermal expansion coefficient between the porous media and the pore fluid. Since the thermal expansion coefficient of the grains and that of the porous media are similar, porosity remains practically constant. Furthermore, pressure drops as a result of cooling, because the thermal expansion coefficient of the pore fluid is higher than that of the porous media. This pressure decrease improves the caprock stability, moving the stress state further away from the failure envelope. Overall, caprock stability is not compromised by cooling.

Acknowledgements

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References

Birkholzer, J. T. and Q. Zhou [2009] Basin-scale hydrogeologic impacts of CO_2 storage: Capacity and regulatory implications. *International Journal of Greenhouse Gas Control*, **3**, 745-756.

Bock, H. [2009] RA experiment - updated review of the rock mechanics properties of the Opalinus clay of the Mont Terri URL based on laboratory and field testing. *Mont Terri Tech. Report 2008-04*.

Coussy, O. [2004] *Poromechanics*. Wiley, New Jersey.

Goodarzi, S., A. Settari, and D. Keith [2012] Geomechanical modeling for CO_2 storage in Nisku aquifer in Wabamun lake area in Canada. *International Journal of Greenhouse Gas Control*, **10**, 113-122.

Gor, Y.G., T.R. Elliot, and J.H. Prévost [2013] Effects of thermal stresses on caprock integrity during CO_2 storage. *International Journal of Greenhouse Gas Control*, **12**, 300-309.

IEA [2010] *Energy technology perspectives. Scenarios & strategies to 2050. Executive summary.* International Energy Agency.

Gräsle, W. and I. Plischke [2010] LT Experiment: Mechanical Behavior of Opalinus Clay, Final report from Phases 6–14. *Mont Terri Tech. Report TR 2009-07.*

Makhnenko, R. and J. Labuz [2013] Unjacketed bulk compressibility of sandstone in laboratory experiments. *Poromechanics V - Proceedings of the 5th Biot Conference on Poromechanics*, 481-488.

Makhnenko, R.Y. and J.F. Labuz [2015] Dilatant hardening of fluid-saturated sandstone. *J. Geophys. Res. Solid Earth*, **120**, 909-922.

Monfared, M., J. Sulem, P. Delage, and M. Mohajerani [2011] A laboratory investigation on thermal properties of the Opalinus claystone. *Rock Mechanics Rock Engineering*, **44**(6), 735-747.

Paterson, L., Lu, M., Connell, L.D. and Ennis-King, J. [2008] Numerical modeling of pressure and temperature profiles including phase transitions in carbon dioxide wells. *SPE Annual Technical Conference and Exhibition*, Denver, USA, 21-24 September 2008.

Vietor, T., H. Müller, B. Frieg, and G. Klee [2012] Stress measurements in the geothermal well Schlattingen, Northern Switzerland. *Geomechanik-Kolloquium*, Freiberg, 16 November 2012.

Vilarrasa, V., O. Silva, J. Carrera, and S. Olivella [2013] Liquid CO_2 injection for geological storage in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **14**, 84-96.

Vilarrasa, V., Olivella, S., Carrera, J. and J. Rutqvist [2014] Long term impacts of cold CO_2 injection on the caprock integrity. *International Journal of Greenhouse Gas Control*, **24**, 1-13.

Vilarrasa, V., J. Rutqvist, and A.P. Rinaldi [2015] Thermal and capillary effects on the caprock mechanical stability at In Salah, Algeria. *Greenhouse Gases: Science and Technology*, doi: 10.1002/ghg.1486.

Wild, K.M., F. Amann, C.D. Martin, J. Wassermann, and C. David [2015] Dilatancy of clay shales and its impact on pore pressure evolution and effective stress for different triaxial stress paths. *49th US Rock Mechanics/ Geomechanics Symposium*, San Francisco, 28 June - 1 July 2015, ARMA 15-0496.