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Potential fracture propagation into the caprock induced by cold CO_2 injection in normal faulting stress regimes

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ABSTRACT

Thermal effects are an important component in the analysis of geologic carbon storage because the injected CO_2 reaches the storage formation at a lower temperature than that of the reservoir rock. The main fear is related to the possibility that the shear slip that may occur within the reservoir due to cooling could propagate into the caprock, which could result in CO_2 leakage. We model a baserock–reservoir–caprock system in a normal faulting stress regime using an axisymmetric model in which we inject cold CO_2 and use an elasto-plastic constitutive model to simulate inelastic deformation. CO_2 forms a cold region around the injection well of a significantly smaller extension than the CO_2 plume. Within this cold region, inelastic strain is yielded due to the thermal stress reduction caused by the thermal contraction of the rock. This inelastic strain occurs only within the reservoir and does not propagate into the caprock. Actually, the stability of the lower portion of the caprock improves in the cooled region as a result of a stress redistribution that occurs to satisfy stress equilibrium and displacement compatibility caused by the thermal stress reduction of the reservoir. This stress redistribution tightens the caprock and prevents CO_2 leakage. Thus, thermally induced stresses are not likely to generate fracture propagation into the caprock in normal faulting stress regimes.

1. Introduction

Thermal effects will be important in geologic carbon storage because the injected CO_2 will reach the storage formation at a lower temperature than that corresponding to the geothermal gradient, especially at high flow rates.[1] Despite the few existing CO_2 storage sites, there are already some examples of large temperature difference between the injected CO_2 and the host rock. The most studied case is In Salah, Algeria, where CO_2 entered the reservoir 45 °C colder than the rock.[2,3] But the largest temperature difference has been reached at Cranfield, Mississippi, where it was of 55 °C.[4] As for other storage sites, such as Sleipner, Norway,[5] Ketzin, Germany,[6] Otway, Australia,[7] Weyburn, Canada[8,9] and Nisku, Canada,[10] they also present a temperature difference between the injected CO_2 and the storage formation, but of smaller magnitude than the first two mentioned cases. Furthermore, Vilarrasa et al.[11] showed that injecting CO_2 in liquid conditions is energetically efficient and therefore, it is likely to become a common practice. Since liquid CO_2 is relatively cold (temperature below 31.1 °C), thermal effects may become large, especially as the depth of the storage formation increases.

A temperature difference causes a contraction of the rock due to cooling that induces a thermal stress reduction (the sign convention of soil mechanics is considered here).[12] Thus, the effective stresses decrease, which brings the stress state closer to failure conditions. The thermal stress reduction may become large in stiff formations and/or for large temperature contrasts. Thus, in such cases, failure conditions, i.e., tensile or shear failure, could be reached. In the case of shear failure, it would cause shear

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Table 1
Material properties used in the thermo-hydro-mechanical analysis of cold CO_2 injection.

Property	Reservoir	Caprock and baserock
Permeability, k (m^2)	10^{-13}	10^{-18}
Relative water permeability, k_{rw} (–)	S_w^3	S_w^6
Relative CO_2 permeability, k_{rc} (–)	S_c^3	S_c^6
Gas entry pressure, p_0 (MPa)	0.02	0.6
van Genuchten m (–)	0.8	0.5
Porosity, φ (–)	0.15	0.01
Young's modulus, E (GPa)	10.5	5.0
Poisson ratio, ν (–)	0.3	0.3
Cohesion, c (MPa)	0.01	0.01
Friction angle, ϕ' (–)	30	27.7
Thermal conductivity, λ (W/m/K)	2.4	1.5
Solid specific heat capacity, c_p (J/kg/K)	874	874
Linear thermal expansion coefficient, α_T (°C^{-1})	10^{-5}	10^{-5}

slip of fractures and subsequently, induce microseismicity. Shear slip opens up fractures, especially in the direction perpendicular to shear,[13] which significantly increases fracture permeability.[14] Hence, provided that microseismicity is kept under control, shear slip is beneficial while it occurs within the storage formation, because injectivity increases. However, if shear slip propagates into the caprock, it may open up migration paths through which CO_2 could leak. To assess whether CO_2 leakage has occurred or not, microseismicity monitoring can be very useful.

Microseismicity monitoring at In Salah has revealed that no CO_2 leakage has occurred.[15] It has also been observed that the microseismicity rate is proportional to the injection rate,[16] which is indicative that the hydraulic effect dominates in this case. However, part of the microseismicity may have been induced by thermal effects.[17] These thermal effects mainly concentrate around the injection well because the cooling front advances much behind than the desaturation and the overpressure fronts.[18–20] Nevertheless, thermal effects can also have an effect on the stability of faults in the far field.[21] But the worries about thermal effects focus on the induced thermal stresses that occur around the injection well.

The main fear is whether the fracture instability that may occur within the reservoir due to cooling has the potential to propagate into the caprock, which could result in CO_2 leakage. It has been argued that the thermal stress reduction that occurs in the lower portion of the caprock could yield tensile stresses and thus, create hydrofractures that may penetrate several tens of meters into the caprock.[22,10,23] However, other studies show that the thermal stress reduction that occurs in the reservoir causes a stress redistribution that increases the horizontal stresses at the lower portion of the caprock, tightening it and hindering fracture instability.[11,20] Thus, the question of whether cold CO_2 may induce fracture instability and propagation into the caprock remains open.

The objective of this paper is precisely to investigate whether cold CO_2 injection in a deep saline formation could generate fracture instability and/or fracture propagation into the caprock. To this end, we model a baserock–reservoir–caprock system in which we inject cold CO_2 and use an elasto-plastic constitutive model to simulate inelastic deformation. This approach is novel to address this problem, which has been previously studied only considering elasticity.

2. Methods

2.1. Model setup

We consider a baserock–reservoir–caprock system in a normal faulting stress regime. The thermo-hydro-mechanical properties of the reservoir, baserock and caprock are detailed in Table 1. They correspond to those of a permeable sandstone reservoir with homogeneous grain size[24] and a low-permeability, high capillary entry pressure shale caprock and baserock.[25] We assume that the system is in hydrostatic conditions and that the geothermal gradient is 33 °C/km and the surface temperature is of 5 °C. We consider a normal faulting stress regime with the horizontal effective stresses corresponding to a lateral earth pressure coefficient of 0.46, i.e., $\sigma'_{h_0} = 0.46\sigma'_{v_0}$ (where σ'_{h_0} [M L^{-1} T^{-2}] is the initial horizontal effective stress and σ'_{v_0} [M L^{-1} T^{-2}] is the initial vertical effective stress), which is equivalent to a mobilized friction coefficient of 0.4 typical of intraplate sedimentary formations.[26]

We inject 0.2 Mt/yr of CO_2 at 20 °C through a vertical well, which we represent with an axisymmetric model, in a 20 m-thick reservoir whose top is placed at a depth of 1500 m (Fig. 1). The other hydraulic boundary conditions are constant pressure at the outer boundary and no flow at the top and bottom boundaries. The outer boundary has a relatively small effect on overpressure evolution for this particular simulation because the induced overpressure for the considered injection rate remains low. Temperature is fixed at the top and bottom boundaries of the domain. Displacements are restricted normal to the bottom, outer and injection well boundaries. The effect of the type of mechanical condition at the bottom and outer boundaries, i.e., fixed or no displacement perpendicular to the boundary, is negligible. A vertical lithostatic stress is applied at the top of the caprock.

2.2. Flow of heat and fluids

Mass conservation of each fluid phase can be expressed as,[27]

$$\frac{\partial\left(\varphi S_\alpha \rho_\alpha\right)}{\partial t} + \nabla \cdot \left(\rho_\alpha \mathbf{q}_\alpha\right) = r_\alpha, \quad \alpha = c, w, \tag{1}$$