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Impacts of thermally induced stresses on fracture stability during geological storage of CO_2

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Abstract

Geomechanical stability issues may arise due to induced thermal stresses because CO_2 will generally reach the storage formation at a temperature lower than that of the reservoir. Cold injection will form a cold region around the injection well, which will induce thermal stress reduction. We simulate cold CO_2 injection in deep saline formations in a normal faulting stress regime and investigate under what conditions thermal stresses may jeopardize the caprock sealing capacity by studying the effect of the heterogeneity of the thermal expansion coefficient between the reservoir and caprock. Furthermore, we use an elastoplastic constitutive model to account for inelastic deformation related to fracture instability. We find that the temperature difference should be limited in the presence of very stiff reservoirs, because the thermal stress reduction is proportional to the product of the rock stiffness, the temperature difference and the thermal expansion coefficient. Simulation results show that inelastic strain occurs in the cooled region within the reservoir, but fracture instability does not propagate into the caprock in the considered normal faulting stress regime. However, the cooled region of the lower portion of the caprock may experience yielding if the thermal expansion coefficient of the caprock is larger than that of the reservoir, because the thermal stress reduction in the caprock becomes larger than in the reservoir, which increases the deviatoric stress. Nevertheless, irreversible strain caused by cooling within the caprock are limited to a small region of the lower portion of the caprock and thus, the overall sealing capacity of the caprock is not compromised, so CO_2 leakage is unlikely to occur because of cooling.

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Keywords: cold CO_2; thermo-hydro-mechanical couplings; induced seismicity; fracture propagation; CO_2 leakage; caprock integrity

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1. Introduction

Geomechanical stability issues may arise due to induced thermal stresses because CO_2 will generally reach the storage formation at a temperature lower than that of the reservoir [1]. The most significant examples of this temperature difference are In Salah, Algeria, and Cranfield, Mississippi. At In Salah, CO_2 reached the storage formation 45 °C colder than the storage formation, even injecting CO_2 at the wellhead 5 °C warmer than the mean ambient temperature [2]. At Cranfield, CO_2 entered the storage formation 55 °C colder than the reservoir temperature [3]. Furthermore, liquid (cold) CO_2 injection is likely to become a common practice because it is energetically efficient and thus, it permits reducing the compression costs significantly [4].

Cold injection will form a cold region around the injection well [5], which will induce thermal stress reduction [6]. This may lead to fracture instabilities within the reservoir, leading to shear slip, and consequently, induced microseismicity [7]. This shear slip may be beneficial while it occurs within the reservoir because it opens up fractures due to dilatancy, enhancing injectivity [8, 9]. However, there is a certain fear about the possibility that this fracture instability within the reservoir caused by cooling propagates into the caprock.

The likelihood of fracture instability in the lower portion of the caprock depends on the stress regime. A strike slip stress regime is more prone to inducing fracture instability in the caprock than normal faulting or reverse faulting stress regimes. Using the geological setting of In Salah, which is characterized by a strike slip stress regime, Gor et al. [10] predicted that tensile stress would appear in the lower portion of the caprock after 12 years of injection. According to them, this tensile stress would create fractures that could penetrate some tens of meters into the caprock. However, the simulation results of Vilarrasa et al. [11], who modeled the In Salah storage site using the same stress state as Gor et al. [10], did not lead to tensile stresses for a 30 year injection with a similar temperature difference. Nevertheless, simulation results of both studies predicted mobilized friction angles around 50° in the lower portion of the caprock, so shear slip is likely to occur in the cooled region of the caprock. This shear slip induced by cooling could explain part of the microseismicity observed at In Salah [12, 13].

On the other hand, this mechanical instability is not observed in normal faulting and reverse faulting stress regimes. Vilarrasa et al. [14] showed that the thermal stress reduction that occurs in the reservoir induces stress redistribution, which happens to satisfy stress equilibrium and displacement compatibility. This stress redistribution causes the horizontal total stresses to increase in the lower portion of the caprock, tightening it. This increase in stability in the lower portion of the caprock leads to a reduction of the risk of CO_2 leakage around the injection well. However, Vilarrasa et al. [14] considered that the rocks behave elastically and that the thermal expansion coefficient of the reservoir and caprock were the same.

Here, we simulate cold CO_2 injection in deep saline formations in a normal faulting stress regime and investigate the effect of the heterogeneity of the thermal expansion coefficient between the reservoir and caprock. Furthermore, we use an elastoplastic constitutive model to account for inelastic deformation related to fracture instability. In this way, we assess the potential that thermally-induced fracture instability that may occur within the reservoir propagates into the caprock.

2. Methods

We consider injection of cold CO_2 in a baserock-reservoir-caprock system in a normal faulting stress regime. The top of the 20 m-thick reservoir is placed at a depth of 1500 m. The caprock and the baserock have a thickness of 50 m. Table 1 shows the rock properties, which correspond to those of a permeable sandstone, i.e., reservoir, with homogeneous grain size [15] and a low-permeability, high capillary entry pressure shale, i.e., caprock and baserock [16]. To investigate the effect of the thermal expansion coefficient of each layer, we consider three cases: *i*) one in which the thermal expansion coefficient of the reservoir and the caprock are equal; *ii*) another one in which the thermal expansion coefficient of the reservoir is greater than that of the caprock; and *iii*) a third one in which the thermal expansion coefficient of the caprock is greater than that of the reservoir.

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
Thermal expansion coefficient, α_T (ºC^{-1})	$1.0 \cdot 10^{-5}$	$0.5 \cdot 10^{-5}$-$3.0 \cdot 10^{-5}$

The system is initially in hydrostatic conditions and the temperature distribution follows a geothermal gradient of 33 °C/km with a surface temperature of 5 °C. The normal faulting stress regime considered in this study presents a horizontal effective stresses corresponding to a lateral earth pressure coefficient of 0.46, which is equivalent to a mobilized friction coefficient of 0.4, typical of intraplate sedimentary basins [17]. For details on the elastoplastic constitutive model used in this study, we refer the interested reader to Vilarrasa and Laloui [18].

An injection of 0.2 Mt/yr of CO_2 at 20 °C (liquid conditions) through a vertical well is imposed. Since the reservoir is at a temperature around 55 °C, the temperature difference is of 35 °C. The outer boundary has a prescribed pressure and temperature and the top and bottom boundaries are no flow boundaries. Displacements normal to the bottom, outer and injection well boundaries are impeded. At the top of the caprock, a vertical lithostatic stress is applied.

To solve this thermo-hydro-mechanical coupled problem, mass conservation of each phase, energy balance and momentum balance have to be solved simultaneously. These fully coupled thermo-hydro-mechanical simulations are performed using the finite element numerical code CODE_BRIGHT [19, 20], extended for CO_2 injection [4]. The mesh is composed of structured quadrilateral elements of 1 m in size in both horizontal and vertical directions within the reservoir, the lower 10 m of the caprock and the upper 10 m of the baserock. This fine mesh is maintained around the injection well for a radius of 50 m. Further away, the mesh becomes coarser, reaching a size of 50 m in the horizontal direction next to the outer boundary. Prior to simulating CO_2 injection, a steady-state calculation is carried out to ensure consistent initial conditions.

3. Results

3.1. Thermal expansion coefficient of the reservoir equal to that of the caprock

The injection of cold CO_2 forms a cold region around the injection well that has the same temperature as the injected CO_2. This cold region advances much behind than the CO_2 plume front because it has to cool down the rock [4, 5, 10, 11, 14]. Thus, the thermal stress reduction induced by cooling only affects a small portion of the reservoir in comparison with the much large extension affected by overpressure [21]. Advection is the heat transport mechanism that dominates in the reservoir because of its high permeability. But in the caprock, due to its low permeability, cooling propagates through conduction. However, the thermo-mechanical effect caused by this cooling is significant because the only region of the reservoir that yields is that affected by cooling (Fig. 1).

Fig. 1 shows the volumetric and the deviatoric plastic strain for the case in which the thermal expansion coefficient of the reservoir and the caprock are equal ($\alpha_T = 1.0 \cdot 10^{-5}$ °C^{-1}). Interestingly, the fracture instability that occurs within the reservoir does not propagate into the caprock. This is because the thermal stress reduction that occurs in the reservoir affects not only the horizontal stresses, but also the vertical stress. This reduction in the vertical stress in the reservoir is somehow similar to an excavation, which affects the stresses in its surroundings. To satisfy the overall stress equilibrium, the horizontal total stresses increase in the lower portion of the caprock, increasing its stability and preventing fracture propagation to penetrate into the lower portion of the caprock. Nevertheless, a small deviatoric plastic strain occurs in the caprock next to the reservoir-caprock interface, but without propagating upwards.

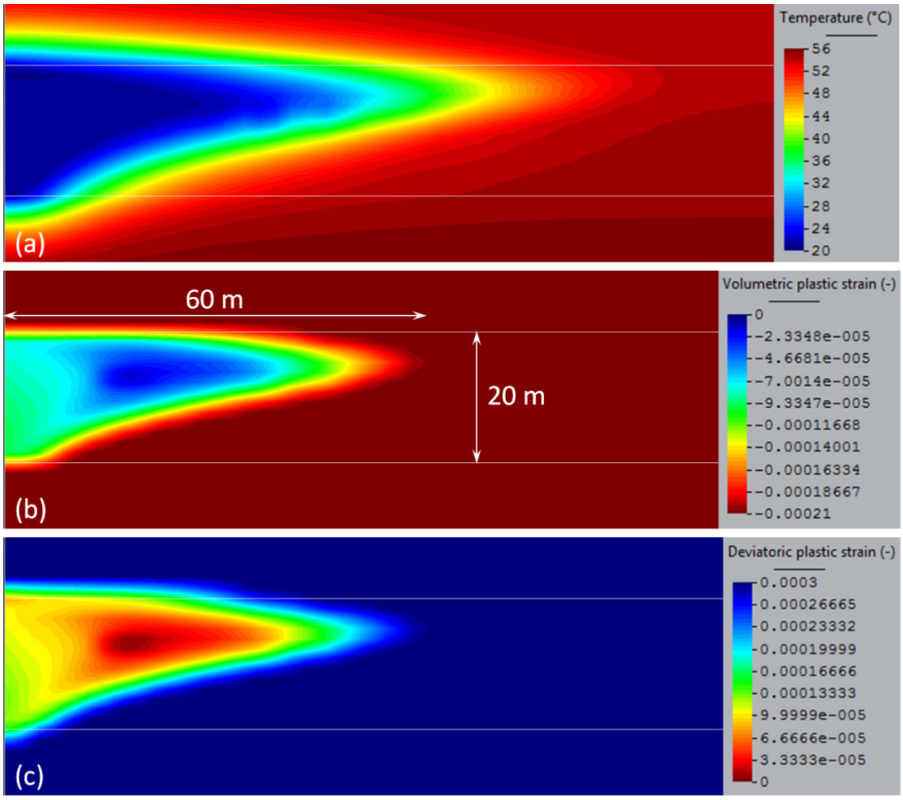

Fig. 1. (a) Temperature, (b) volumetric plastic strain and (c) deviatoric plastic strain after 1 year of cold CO_2 injection for the case in which the thermal expansion coefficient of the reservoir and the caprock are equal. A negative volumetric plastic strain indicates expansion.

3.2. Thermal expansion coefficient of the reservoir greater than that of the caprock

If the thermal expansion coefficient of the reservoir ($\alpha_T = 1.0 \cdot 10^{-5}$ °C^{-1}) is greater than that of the caprock ($\alpha_T = 0.5 \cdot 10^{-5}$ °C^{-1}), the situation is even safer. Fig. 2 displays the volumetric and the plastic strains after 1 year of cold CO_2 injection for this case. Neither the volumetric nor the deviatoric plastic strains propagate into the caprock, which ensures its integrity and minimizes the risk of CO_2 leakage.

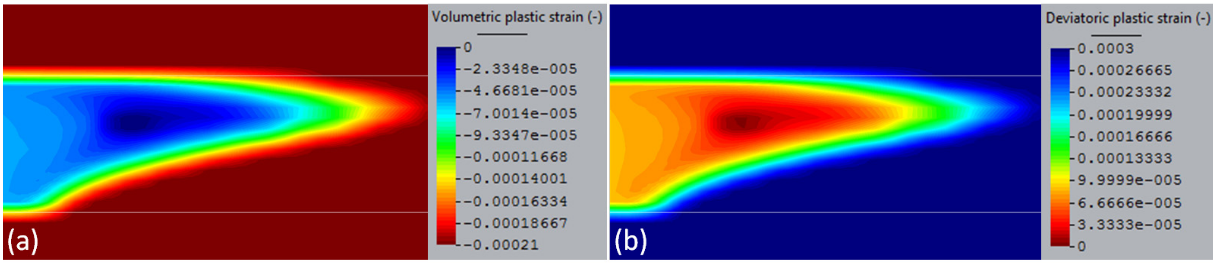

Fig. 2. (a) Volumetric plastic strain and (b) deviatoric plastic strain after 1 year of cold CO_2 injection for the case in which the thermal expansion coefficient of the reservoir is greater than that of the caprock.

3.3. Thermal expansion coefficient of the caprock greater than that of the reservoir

In the case in which the thermal expansion coefficient of the caprock ($\alpha_T = 3.0 \cdot 10^{-5}$ °C^{-1}) is greater than that of the reservoir ($\alpha_T = 1.0 \cdot 10^{-5}$ °C^{-1}), deviatoric plastic strain occurs in the lower portion of the caprock. Fig. 3 shows the volumetric and the plastic strains after 1 year of cold CO_2 injection for this case. Though the volumetric plastic strain remains confined within the reservoir, deviatoric plastic strain one order of magnitude larger than in the previous cases occurs in the lower portion of the caprock. However, the thickness of the caprock affected by irreversible deformation is very thin (less than 5 m). Therefore, even though some CO_2 may penetrate into the lower portion of the caprock due to opening of fractures, which may enhance permeability and reduce the entry pressure, CO_2 is unlikely to leak through the caprock because the sealing capacity of the vast majority of the caprock remains unaffected.

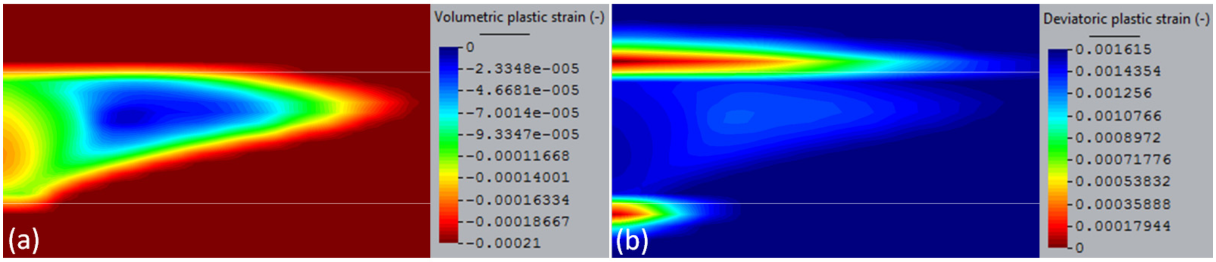

Fig. 3. (a) Volumetric plastic strain and (b) deviatoric plastic strain after 1 year of cold CO_2 injection for the case in which the thermal expansion coefficient of the caprock is greater than that of the reservoir. Note that the scale of the deviatoric plastic strain is different than for the other two cases.

3.4. Effect of the caprock thermal expansion coefficient

The distribution and magnitude of inelastic strain depends on the contrast between the thermal expansion coefficient of the reservoir and the caprock. The safer situation occurs for caprocks with a thermal expansion coefficient lower than that of the reservoir, in which case no damage of the caprock occurs (Fig. 2). On the other hand, caprocks with a thermal expansion coefficient greater than that of the reservoir undergo some damage in the lower portion of the caprock that is affected by cooling (Fig. 3). This is caused by the magnitude of the induced thermal stresses, which, assuming no lateral deformation in the far-field, are proportional to the thermal expansion coefficient as

$$\Delta\sigma_T = 3K\alpha_T\Delta T \,, \tag{1}$$

where K is the bulk modulus and ΔT is the temperature difference. Thus, the larger the thermal expansion coefficient, the larger the thermal stress reduction due to cooling (Fig. 4). The difference in thermal induced stresses between the caprock and the reservoir generates a shear stress at the reservoir-caprock interface that may cause yielding.

Fig. 4 displays the evolution of the minimum effective stress in the caprock close to its contact with the reservoir as a function of the caprock thermal expansion coefficient. The stresses decrease as the caprock is cooled down, but the reduction is larger for higher values of the thermal expansion coefficient (recall Equation (1)). This higher reduction for high values of the caprock thermal expansion coefficient leads to a lower mean effective stress that brings the stress state closer to failure. Furthermore, the deviatoric stress also becomes larger as the thermal stresses increase, which leads to yielding of the cooled portion of the caprock (Fig. 5).

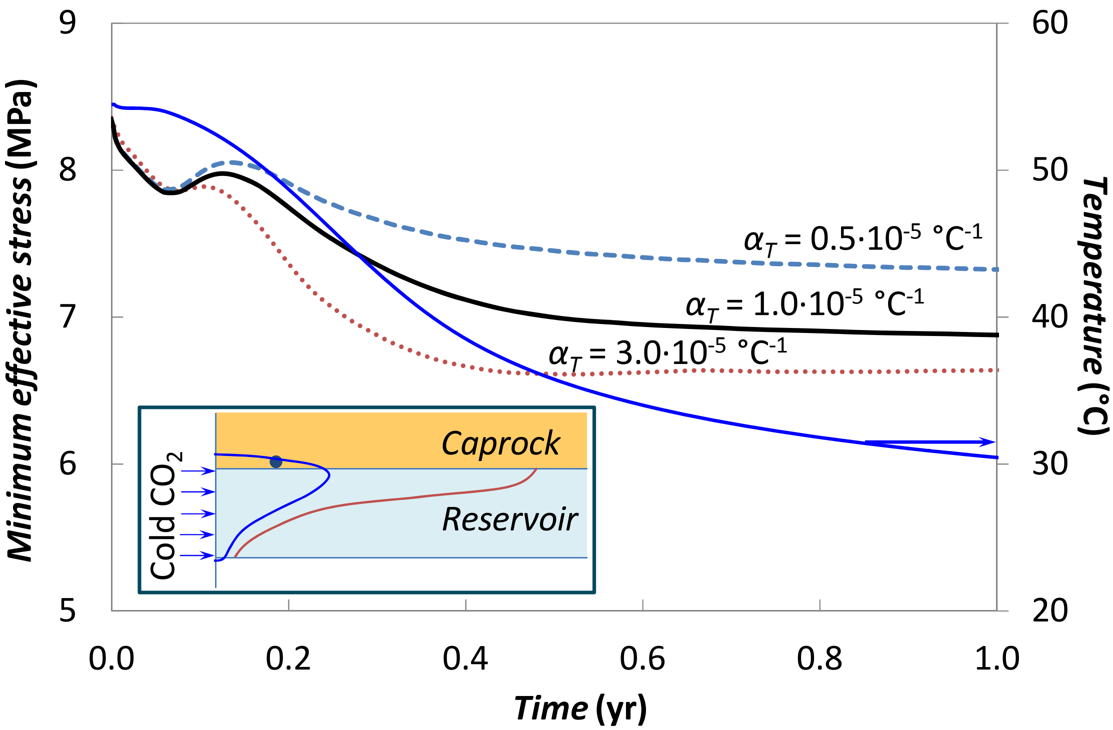

Fig. 4. Evolution of the minimum effective stress and temperature for three values of the thermal expansion coefficient of the caprock at a point of the caprock that is located 20 m away from the injection well and 1 m above the reservoir-caprock interface. The inset shows a schematic representation of the location of the observation point and the position of the CO_2 plume (red line) and cold region (blue line).

Fig. 5 shows the $q - p'$ (deviatoric stress – mean effective stress) trajectories in the caprock close to its contact with the reservoir as a function of the caprock thermal expansion coefficient. For a low value of the thermal expansion coefficient, the thermal stress reduction is lower than for a large value and therefore, the mean effective stress undergoes a lower reduction. This lower reduction in the mean effective stress, combined with a smaller increase in the deviatoric stress, permits the stress state to remain within the elastic region throughout the whole injection when the thermal expansion coefficient of the caprock is lower than that of the reservoir. When the thermal expansion coefficient of both the reservoir and the caprock are equal, the stress state reaches the failure envelope, inducing irreversible strain. This irreversible strain becomes even larger when the thermal expansion coefficient of the caprock is greater than that of the reservoir because of the larger thermal stress reduction (recall Figs. 1 and 3).

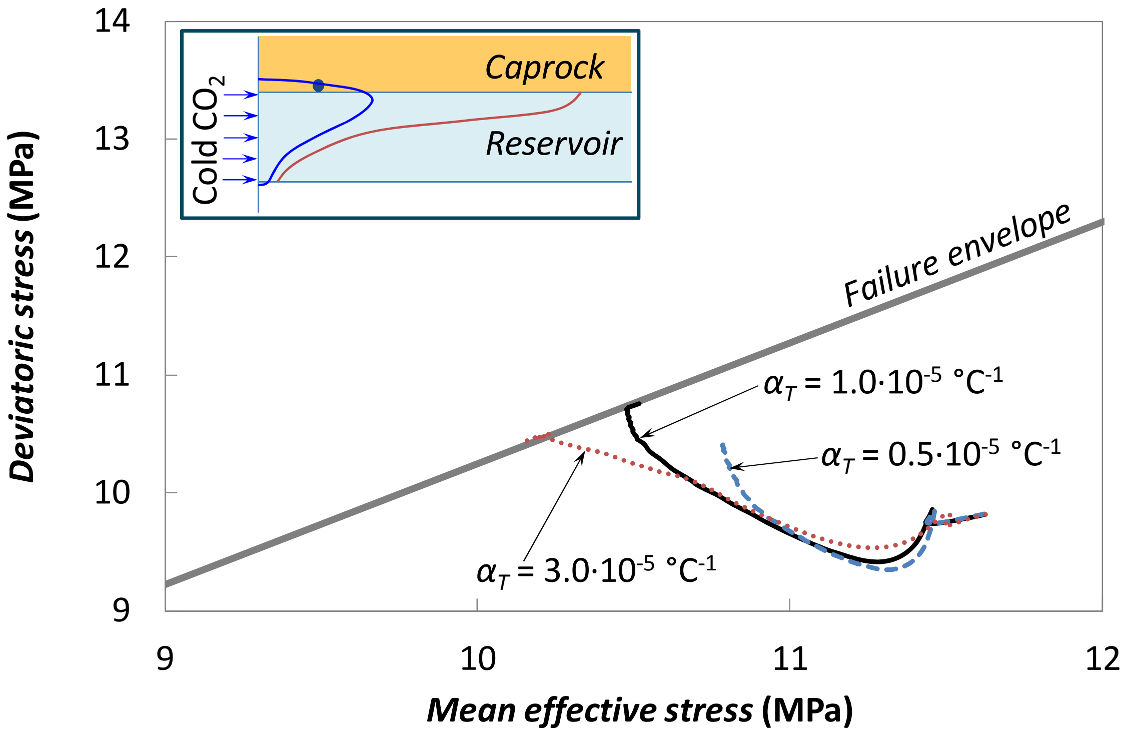

Fig. 5. $q - p'$ (deviatoric stress – mean effective stress) trajectories of a point of the caprock located 20 m away from the injection well and 1 m above the reservoir-caprock interface for three values of the thermal expansion coefficient of the caprock.

4. Discussion

Cooling has the potential to induce inelastic strain (Fig. 1). However, inelastic strains are very small, which indicates that only small shear slips of fractures are associated with this irreversible strain. These shear slips will induce microseismicity as the rock yields, but are unlikely to jeopardize the caprock sealing capacity. Indeed, inelastic strain does not propagate into the caprock even the strength of the caprock is lower than that of the reservoir (Table 1), at least for the normal faulting stress regime considered in this study.

The worst situation occurs when the thermal expansion coefficient of the caprock is greater than that of the reservoir. In this case, the cooled region of the lower portion of the caprock undergoes inelastic strain. However, the overall caprock sealing capacity is not compromised because inelastic strain does not extend more than 5 m into the caprock. Furthermore, the minimum effective stress is far from becoming negative, i.e., tensile stress does not take place, which means that hydrofractures are unlikely to be formed. Thus, cold CO_2 injection should not be feared because of the induced thermal stresses.

In general, the range of values of the thermal expansion coefficient of geomaterials is small [22-27]. For sandstone, it is usually around $10 \cdot 10^{-6}$ ºC^{-1} [28]. Limestone and shale present a wider variability, 2.5-$20 \cdot 10^{-6}$ ºC^{-1} for limestone [28] and 9-$23 \cdot 10^{-6}$ ºC^{-1} for shale [29]. Hence, in most of the situations, the heterogeneity of the thermal expansion coefficient between the reservoir and the caprock will be small, leading to similar values of the thermal expansion coefficient in both the reservoir and the caprock. Thus, a situation similar to the case in which both thermal expansion coefficients are equal will usually occur (Fig. 1). This fact is very beneficial because if the thermal expansion coefficient of the caprock is similar to that of the reservoir, the sealing caprock capacity will not be compromised due to cooling, which will prevent CO_2 leakage.

The thermo-plastic behaviour of shale may be complex [30]. Though an overconsolidated shale will expand if it is heated up, a normally consolidated shale will contract, i.e., thermal consolidation, because the yield surface shrinks as temperature increases and since the stress state would be close to the yield surface, the normally consolidated shale will yield. Yielding leads to rearrangement of the grain particles, which causes the shale to collapse and decrease in volume despite the temperature increase. An intermediate situation would be a slightly consolidated shale, which will initially expand, but as the yield surface shrinks for increasing temperatures, the shale will eventually yield and thus, it will undergo contraction. In our simulations, the shale is slightly overconsolidated. However, since the shale experiences a cooling path, rather than a heating path, the yield surface increases in size, so the observed elastic behaviour in our simulation results is coherent with the theory and observation of thermo-plasticity of shale.

Simulation results show that inelastic deformation is small in the modeled cases. However, thermal stresses are proportional, apart from the thermal expansion coefficient, to the rock stiffness and the temperature difference (Equation (1)). Thus, in the presence of stiffer reservoirs or a large temperature contrast, thermal stresses would be larger, which could lead to larger inelastic strain that could induce excessive microseismicity. Consequently, proper site characterization and site specific thermo-hydro-mechanical modeling are necessary to carry out safe CO_2 storage projects.

5. Conclusions

We have simulated cold CO_2 injection in deep saline formations in a normal faulting stress regime and investigated the effect of the contrast of the thermal expansion coefficient between the reservoir and the caprock, considering an elastoplastic constitutive law to account for inelastic strain. We found that irreversible strain occurs within the cooled region of the reservoir, but fracture instability does not propagate into the caprock in the geological setting considered in this study. However, the cooled region of the lower portion of the caprock may undergo some damage due to cooling when the thermal expansion coefficient of the caprock is greater than that of the reservoir. This damage occurs because thermal stresses are proportional to the thermal expansion coefficient and thus, high values of the caprock thermal expansion coefficient induce a higher thermal stress reduction, which leads to a lower mean effective stress and a higher deviatoric stress. These stress changes may yield inelastic strain in the reservoir, but they do not propagate into the caprock. At most, inelastic strain occurs in the lower portion of the caprock that undergoes cooling, so the overall caprock sealing capacity is not compromised and CO_2 leakage is unlikely to occur due to cooling.

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