Long-term modeling of thermo-hydro-mechanical processes of geologic carbon storage

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Non-isothermal processes are relevant in geologic carbon storage

Carbon dioxide (CO_2) storage in deep geological formations is a solution for reducing emissions to the atmosphere. Pressure and temperature conditions of deep geological formations are such that CO_2 remains in a relatively dense state (Bachu, 2003). It is widely accepted that a pressure buildup is needed to inject the CO_2 into the rock, but it is usually assumed that CO_2 will be injected at the same temperature as that of the storage formation. However, CO_2 may not be in thermal equilibrium with the medium when it enters the formation because pressure and temperature injection conditions at the wellhead can be diverse and CO_2 may not equilibrate with the geothermal gradient if the flow rate is high (Paterson et al., 2008; Vilarrasa et al., 2013). Actually, CO_2 usually reaches the storage formation at a much colder temperature than that of the rock: 45 ºC colder at In Salah, Algeria, and 55 ºC colder at Cranfield, Mississippi (Vilarrasa and Rutqvist, 2017). This temperature contrast cools down the rock around the injection well, forming a cold region with temperature similar to that of the injected CO_2. Figure 1 illustrates the form of the cold region, which advances following the shape of the buoyancy driven CO_2 plume. Even though the extension of the cold region is quite limited around the injection well (compare the radii of CO_2 plume and cold region in Fig. 1), thermo-hydro-mechanical (THM) effects may be significant given the large temperature contrast and stiffness of rocks. Indeed, there is a certain fear that hydraulic fractures, which could serve as leakage pathways for CO_2, might be formed in the caprock as a result of the thermal stress reduction induced by cooling (Gor et al., 2013; Goodarzy et al., 2015).

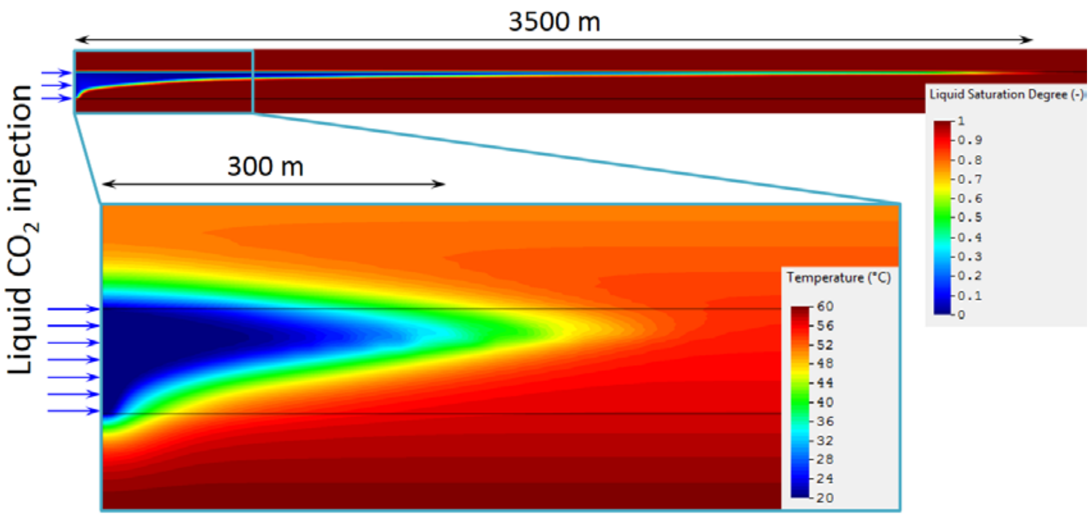

Fig. 1: CO_2 plume and temperature distribution after 30 years of injecting 1 Mt/yr of CO_2 at 20 ºC through a vertical well into a 100 m-thick saline aquifer (Figure modified from Vilarrasa et al., 2014)

Understanding the subsurface coupled THM response

To investigate thermal effects on the coupled hydro-geomechanical processes that occur during long-term injection, we perform fully coupled THM simulations of cold CO_2 injection using CODE_BRIGHT (Olivella et al., 1996). We simulate generic scenarios using realistic geological setting and material properties. Through a comprehensive study, we identify the processes that may control reservoir stability and caprock integrity.

We find that the cold region that develops around the injection well as a result of cold CO_2 injection causes the reservoir to contract, thus inducing thermal stress reduction. This stress reduction, which is proportional to the rock stiffness, temperature difference and thermal expansion coefficient, takes place in all directions. As a result, in fractured reservoirs, the normal stress acting on the fractures is reduced, which opens up fractures and enhances injectivity (Vilarrasa et al., 2017). Additionally, the stress reduction in the vertical direction causes a stress unbalance in this direction, because the overburden remains constant. Since the stress equilibrium and displacement compatibility has to be satisfied, stress redistribution occurs, inducing an increase of the horizontal total stress in the lower portion of the caprock (dome effect, Vilarrasa et al., 2013, Pujades et al., 2017). These stress changes have a varying effect on caprock stability depending on the in situ stress state (Vilarrasa, 2016). In normal faulting stress regimes, in which the maximum principal stress is vertical, the increase in horizontal stress at the lower portion of the caprock reduces the deviatoric stress (the size of the Mohr circle is reduced), tightening the caprock and improving its stability. As a result, cooling is unlikely to damage the caprock in such stress regime. In strike-slip stress regimes, the maximum and the minimum principal stresses are horizontal and, as a result, the deviatoric stress is maintained because the increase in the horizontal stress in the lower portion of the caprock caused by stress redistribution equally affects both stresses. Thus, cooling shifts the Mohr circle towards the failure envelope in strike-slip stress regimes, which may induce microseismicity if failure conditions are ultimately reached. Despite the shift towards failure conditions, the increase in the horizontal stresses caused by stress redistribution partly compensate the thermal stress reduction, limiting the possibility of reaching tensile stresses in the caprock. Finally, in reverse faulting stress regimes, in which the vertical stress is the minimum principal stress, the increase in horizontal stress in the lower portion of the caprock enhances the deviatoric stress. Nevertheless, the high confining stress found in reverse faulting stress regimes leads to a small increment of the deviatoric stress.

The effect of the stress regime on caprock stability highlights the importance of performing a proper site characterization, including measurements of the stress state as a function of depth, to determine the maximum sustainable injection pressure and maximum allowable temperature drop that will maintain the caprock sealing capacity and will not compromise fault stability. Knowledge of the in situ conditions will allow performing site specific studies to achieve a safe CO_2 storage. Overall, injecting cold CO_2 should not be feared because of the thermal stresses reduction, though care should be taken to avoid excessive induced microseismicity.

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