# Modeling Hydrological and Geomechanical Processes Related to $CO_2$ Injection in a Faulted Multi-Layer System

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## Introduction

Storage of $CO_2$ in deep brine formations has been suggested as one possibility for reducing greenhouse gases in the atmosphere. To trap $CO_2$ at depth, the underground disposal requires a sufficiently impermeable caprock layer—or a sequence of such layers for increased safety—that prevent upward migration from the target reservoir. However, caprock layers may contain imperfections, such as faults or fracture zones, which can act as high-permeability conduits for leakage of $CO_2$ from depth to the near-surface environment. Further, the hydraulic properties of a fault zone can be affected by the increasing fluid pressure during injection. If sufficiently large, the induced stresses may even cause rock failure, thereby creating new faults and fractures. In this paper, we simulate the hydrological and geomechanical processes during and after injection of supercritical $CO_2$ into a deep brine formation. We consider a faulted multi-layer system, where the injection reservoir is situated below a sequence of caprock and aquifer layers. The study aims at (1) understanding the upward migration of $CO_2$ in such a system, and (2) evaluating the impact of hydromechanical changes.

## Methodology and Results

The simulations are performed using the coupled computer code TOUGH-FLAC (Rutqvist et al., 2002, Rutqvist and Tsang, 2003), which considers multi-phase flow (in this case supercritical $CO_2$ and water with dissolved NaCl) together with rock deformation. An example of the hypothetical geologic settings assumed in our simulations is depicted in Figure 1. The injection reservoir is 200 m thick and situated under a low-permeability 100 m thick caprock, which, in turn, is overlain by a sequence of two additional caprocks and two additional aquifer layers. Various scenarios with different fault geometries and properties are analyzed, among them the case depicted in Figure 1 with a vertical fault zone. Transient numerical simulations are conducted for a time period of 500 years, with injection of $CO_2$ occurring over the first 30 years.

We start analyzing a multi-layer system with pre-existing faults while neglecting geomechanical processes. Here, we focus on (1) determining the $CO_2$ migration patterns as a function of given fault/formation properties and (2) evaluating the benefit of injecting into a multi-layer system with possible attenuation of the migrating $CO_2$. Our results demonstrate the importance of faults as first-order risks for $CO_2$ storage, allowing for significant leakage from the injection reservoir. Controlling parameters for $CO_2$ migration are fault conductivity and continuity. A multi-layer sequence reduces the risk of large amounts of $CO_2$ reaching the near-surface environment, because the upward flow in a fault zone may be blocked at

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secondary caprock layers. Even if a fault zone intersects the entire vertical sequence from depth, some fraction of the $CO_2$ may spread laterally into neighboring aquifers during upward migration.

In a second step, we account for coupled hydromechanical effects caused by injection and buoyancy pressure in the faulted multi-layer system. This study includes analysis of pressure-induced mechanical responses that may induce significant changes in $CO_2$ transport properties. The fault zones penetrating each caprock layer are envisioned as consisting of a network of closely spaced and connected fractures that result in an effective fault permeability significantly higher than the surrounding intact rock. At the initial ambient pressure conditions, the fault zones are considered either hydraulically open or closed (depending on the degree of fracture mineral filling).

Our results indicate that the most important process for the hydromechanical response in the multi-layered and faulted system is a reduction of the mean effective stress, caused by increasing fluid pressure during and after active injection. This reduction of mean stress within the fault zones is not only important for evaluating fault permeability changes caused by elastic fracture opening, but also very important for evaluating the potential for initiation of shear slip that could lead to irreversible changes. The simulation results show that pressure-induced fracture opening first occurs in the caprock immediately above the injection zone and thereafter continues in the overlying layers as increasing fluid pressure propagates upward. In each caprock layer, the opening first takes place in its lower part, while the opening in its upper part is delayed until the fluid pressure in the overlying aquifer increases. As the $CO_2$ moves upward, the coupled hydromechanical response to fluid-pressure increase tends to be larger in the upper parts of the multi-layer system, a result of buoyancy effects in combination with lower initial stresses at shallower elevations.

## Conclusions

We conducted a coupled hydrological and geomechanical simulation study of $CO_2$ injection into a faulted multi-layer system. Our analysis suggests that the upward migration of $CO_2$ through fault zones should be evaluated considering various vertical layers rather than just the injection reservoir and the overlying caprock. For example, hydromechanical effects of increasing fluid pressure and reducing effective stress—which result in opening of fractures and permeability increases—may be more important in the upper parts of the multi-layer system than in the injection layer itself.

## References

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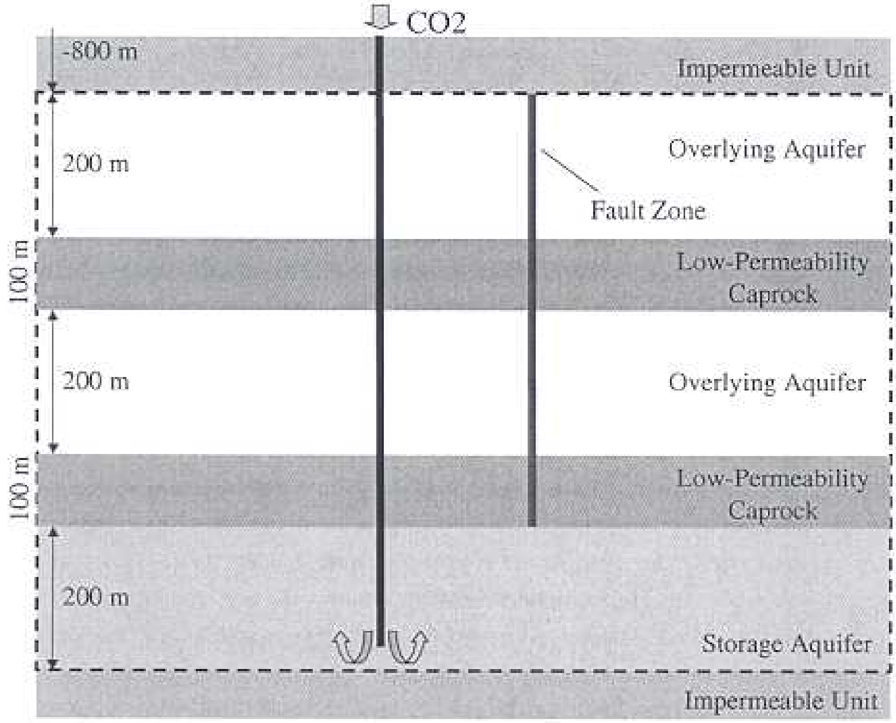


Figure 1. Schematic showing a simulation case with a multi-layer system intersected by a vertical fault