In Salah CO₂ Storage JIP: Hydromechanical Simulations of Surface Uplift due to CO₂ Injection at In Salah

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Abstract

Large-scale carbon capture and storage projects involve injecting CO₂ into a porous, permeable formation that is overlain by an impermeable “caprock”. The In Salah Project (a joint venture of BP, Statoil and Sonatrach) includes a CO₂ sequestration effort that has successfully injected just over three million tons of CO₂ into a deep saline formation close to a producing gas field in Algeria. We have performed detailed simulations of the hydromechanical response in the vicinity of the KB-502 CO₂ injector specifically because the morphology of the observed surface deformation differed from that above the other injectors at the field. Associated with the injection, we have simulated the mm-scale uplift of the overburden and compared the results with observed deformation using InSAR data. Our results indicate that the best fit is obtained through a combination of reservoir and fault pressurization (rather than either alone). However, our analysis had to make assumptions regarding the mechanical properties of the faults and the overburden. These results demonstrate that InSAR provides a powerful tool for gaining insight into fluid fate in the subsurface, but also highlight the need for detailed, accurate static geomodels.

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1. Introduction

In order for geological carbon sequestration to achieve substantial reductions of greenhouse gas emissions, many large injection projects will be required. Each project is likely to require multiple wells, each injecting millions of tons of CO₂ over many years. For storage in saline formations, this is likely to create a large and increasing pressure anomaly that will grow over the duration of the injection stage of the project. The In Salah Project (a joint venture of BP, Statoil and Sonatrach) includes a CO₂ sequestration effort that has successfully injected just over three million tons of CO₂ into a deep saline formation close to a producing gas field in Algeria [1, 2]. Since 2004, CO₂ has been separated at the Krechba gas field from extracted natural gas at In Salah, Algeria, and re-injected along the limbs of the trapping anticline as a supercritical fluid. Three injection wells have been used, targeting depths on the order of 1.8 km.

Surface deformation has been observed associated with the injection at the Krechba field at In Salah via interferometric synthetic-aperture radar (InSAR). In addition, CO₂ breakthrough has been observed at a suspended
appraisal well (see Ringrose et al. [3] for details). The first work regarding surface deformation at Krechba was to invert the observed surface deformation to obtain permeability estimates within the Krechba reservoir [4, 5]. More recently, Rutqvist et al. [6] used a sequentially coupled hydromechanical simulation to model injection into the Krechba reservoir using a model that consisted of homogeneous layers of rock with and without a vertically oriented fault zone and was able to match the magnitude, of surface displacement observed above the KB-501 CO₂ injector. However, in response to the different morphology of uplift above the KB-502 injector, several teams have developed progressively more complicated models for deformation associated with the KB-502 injector [7, 8, 9].

In contrast with previous interpretations of the InSAR data from Krechba, in this work we present our attempts to perform forward models based upon the best available data and compare against observed surface uplift. We have assumed best estimate values for reservoir and overburden mechanical properties and fault shear properties in order to understand mechanical responses to injection pressure. We have performed detailed simulations of the hydromechanical response in the vicinity of the KB-502 CO₂ injector specifically because the morphology of the observed surface deformation differed from that above the other injectors at the field (Figure 1). Our results indicate that the best fit is obtained through a combination of reservoir and fault pressurization (rather than either alone). However, our analysis had to make assumptions regarding the mechanical properties of the faults and the overburden. These results demonstrate that InSAR provides a powerful tool for gaining insight into fluid fate in the subsurface, but also highlight the need for detailed, accurate static geomodels.

![Figure 1](image.png)

**Figure 1** InSAR surface relative displacement observed above the KB-502 well (black line) after one year of injection. Surface displacements exhibit a distinct two-lobed structure.
2. Combined Multiphase Flow and Geomechanical Analysis

It is well established that fractures and faults that are favorably oriented for slip (so-called critically stressed fractures) tend to provide conduits for fluid flow [10]. Streit and Hillis [11] describe in detail how fault stability and sustainable fluid pressures can be estimated for a range of sequestration sites. Wiprut and Zoback [12] discuss a specific example of fault activation in the North Sea due in part to elevated pore-pressures. In addition, many sequestration targets are effectively closed on one or more sides by non-critically stressed (impermeable or sealing) faults.

We performed critical stress analyses of the influence of pore pressure on stability of fault stability within the Krechba reservoir, using an approach similar to Chiaramonte et al. [13]. These results used the estimated in situ stresses corresponding to the KB-502 area. Figure 2 shows our predictions for fault stability in terms of the coefficient of friction required for stability and the change in pore pressure anticipated to induce slip. It is typically assumed that as the required coefficient of friction approaches 0.6, the fault fails in shear and becomes a conduit for flow. For example, it can be seen that the F12 fault which cuts the KB-502 injector is predicted to be a flow conduit at relatively low changes in pore pressure. In contrast, the F9 fault which runs to the south of and almost parallel to KB502 is predicted to be more stable and potentially act as a flow barrier.

A three-dimensional multiphase flow and transport model, implemented using LLNL’s NUFT simulator, has been developed for the reservoir using porosity and permeability data provided by the JIP. NUFT has been previously demonstrated in the prediction of CO₂ storage performance [14, 15]. In our reservoir scale modeling we mainly focused on the KB-502/KB-5 area in order to understand the early CO₂ breakthrough at the KB-5 and the observed surface uplift. The preliminary fault map at KB-502/KB-5 was incorporated into our model. Based upon the fault stability analysis, several faults were identified in the vicinity of KB-502 that could be fast flow paths and flow barriers. Figure 3 shows the how the current model includes these features. This particular model includes a hypothetical extension of the F12 fault above and below the reservoir by 200m. All simulations we have performed that include the conductive F12 fault feature indicate that the fault leads to early arrival of CO₂ at KB-5, consistent with field observation (Figure 3).

We are interested in understanding the induced displacement at the surface due to fluid displacement in the subsurface in order to use the InSAR data to constrain our model. This requires identifying geomechanical treatments for the deformation due to both the fluid in the reservoir and that within the fault. In the analysis
presented here, it is assumed that the permeability field and mechanical response are not tightly coupled. As discussed above, a geomechanical analysis was performed to identify which faults are permeable features and which are seals. The subsequent NUFT simulation accommodates this information by employing constant permeable or impermeable cells along the fault traces. The NUFT model then predicts the pore-pressure changes within the reservoir and faults (Figure 3).

Changes in pore-pressure induce local strains within the rock that are transmitted through the overburden to the surface. It is vitally important that we utilize appropriate modes of induced deformation if we are to accurately predict the surface displacements. In this study, we employed the code SYNEF, which achieves a rapid prediction of the surface displacement through superposition of appropriate volume change and tensile source terms. SYNEF (unpublished) is a general purpose 3D elastic deformation code based on half-space Green's functions for tensile, shear and dilatational dislocation sources [16, 17].

It is clear from Figure 3 that the NUFT model predicts pressurization of both the reservoir level and fault portions of the storage domains. This begs the question: Is the observed surface deformation due to:
1) Pressurization of the reservoir? or
2) Pressurization of the fault portion of the storage domain? or
3) Combination from both fault and reservoir?

The geomechanical responses of reservoir and fault are distinct and must be treated appropriately. Specifically, the reservoir rock is approximately isotropic and consequently, locally the reservoir rock will respond to the increase in fluid pressure by attempting to expand volumetrically in proportion to the fluid pressure change. In reality, the induced strain field is more complicated, but in this work we assume the volume change due to poro-elastic effects within the reservoir results in local isotropic expansion. The contribution from reservoir expansion leads only to uplift at the surface (Figure 4) and no relative subsidence or double-lobed deformation as observed in the InSAR data (Figure 1).

The second hypothesis assumes that pressurization of the fault induces the observed surface deformation. In contrast with the reservoir, a fault or other fracture-like feature corresponds to a very weak plane and, consequently, has a highly anisotropic response to hydromechanical stress perturbations. The simplest appropriate representation
for the mechanical response of the fault to pressurization is to assume that it undergoes mode I (tensile) opening. The consequential surface displacements are shown in Figure 5. The surface deformation induced by the fault is both qualitatively and quantitatively different from that due to pressurization of the reservoir (Figure 4). Although the induced deformation due to the fault results in a dual-lobed structure at the surface, the spacing of the lobes and the region of subsidence between them is not consistent with observation (Figure 1).

These results indicate that the details of the surface uplift are captured by neither the fault induced or reservoir induced displacement alone. The surface deformation due to the reservoir alone (Figure 4) lacks the morphology observed in the InSAR data, although the magnitude is reasonably correct. Additionally, these results indicate that the uplift lobes associated with the fault alone (Figure 5) exhibit greater separation than those in the data. Additionally, the pressurization of the fault alone leads to a surface depression which is not observed in the data. The third hypothesis is that the observations are due to the combined effect of pressurizing the reservoir and the fault portion of the storage domain. This solution is shown in Figure 6, alongside the corresponding InSAR data. Combining the influence of the fault with that of the reservoir has two effects:

a. The peaks of the lobes are brought closer together, to be more consistent with the data; and
b. The depression is cancelled by uplift due to the reservoir pressurization.

Consequently, with this model, it is only when the hydromechanical effect of the hypothetical vertical extension of F12 is added to the deformation due to the reservoir that the surface deformation adopts the shape and magnitude observed via satellite.

The previous discussion has established that pressurization of a fault leads to better agreement with observed surface uplift. A key question, then, is how well we can constrain the vertical location of the fluid-filled fault, based on the InSAR data? Figure 7 shows a comparison between the surface displacements calculated from the baseline
model presented in the previous section with those calculated from the same model but with the fault extending 400m into the underburden only. It can be seen that the influence this change has upon the surface deformation is quite subtle. Consequently, it could be argued that the data could be just as well fit by a hypothetical fluid filled fault entirely below the injection interval.

![Image](image1.png)

**Figure 7** Comparison between predicted uplift for the baseline case of a fault that persists 200m above and below the reservoir (left) with a fault that persists only 400m below the reservoir (right).

### 3. Conclusions

We have performed detailed simulations of the hydromechanical response in the vicinity of the KB-502 CO₂ injector in an attempt to explain why the morphology of the observed surface deformation differed from that above the other injectors at the field. Our analysis took the best available data for the permeability within the reservoir and included forward models of CO₂ injection and hydromechanical response for comparison against InSAR data. Associated with the injection, we have simulated the mm-scale uplift of the overburden and compared the results with observed deformation using InSAR data. By including conducting and bounding faults into the model we achieve better agreement with the observed net uplift at the ground surface, but not the shape of the observed uplift. However, by including flow into a hypothetical fault, our simulations better match the morphology of the surface deformation observed via InSAR. Our results indicate that the best fit is obtained through a combination of reservoir and fault pressurization (rather than either alone).

These results demonstrate that InSAR provides a powerful tool for gaining insight into fluid fate in the subsurface. However, we have also identified some of the limitation of such a methodology. Firstly, our work indicates that at the depth in question, it is difficult to determine the precise vertical depth of the fault. In addition, our analysis had to make assumptions regarding the mechanical properties of the faults and the overburden, highlighting the need for detailed, accurate static geomodels. Our future work will focus upon reducing the uncertainty by including new detailed overburden data as it becomes available. In addition, tilt meter and GPS measurements will be included as they are made available by the In Salah JIP.

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