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Effect of faults on stress path evolution during reservoir pressurization

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ABSTRACT

Fluid injection operations, such as CO_2 storage and enhanced oil recovery (EOR), imply reservoir pressurization, which changes the effective and total stresses due to poroelastic effects. These stress changes control the geomechanical stability of discontinuities like faults and fractures. Though the effect of these pre-existing discontinuities on stress path is sometimes neglected, the stress state is altered around them. We investigate the effect of a fault on the stress path evolution when pressurizing a reservoir using an in-house hybrid FEM-DEM code called “MDEM”. Simulation results indicate that the stress path is affected by the presence of faults considered to deform elastically, especially in the vicinity of the fault in the reservoir-caprock interfaces. The stress path perturbation is caused by the shear deformation of the fault plane, which is different in the reservoir and the caprock sections. Actually, the magnitude and the extension of the stress path perturbation around a fault become larger for faults with lower shear stiffness. The upper hanging wall and the lower footwall of the fault in the reservoir-caprock interface experience a higher stress path in the horizontal and the vertical directions. Furthermore, the stress paths decrease (negative in the vertical direction) in the upper footwall and the lower hanging wall in the reservoir-caprock interfaces. The fault effect on the stress path increases as the aspect ratio of the reservoir becomes lower. Moreover, the results indicated that both the caprock and the reservoir in the footwall experience a greater change for lower Poisson’s ratio of the caprock.

These stress changes are independent of the *in situ* stress regime as long as the fault deforms elastically. However, the impact of the stress path perturbation on the stability of the reservoir and the caprock is different in a compressional (reverse faulting) and an extensional (normal faulting) stress regimes. The stress state becomes less stable in the vicinity of the fault in the reservoir and in the caprock in a compressional stress regime than in an extensional stress regime. Therefore, a compressional stress regime leads to a less stable situation due to the fault effect on the evolution of the stress path. Overall, the presence of faults alters the stress state around them, which may lead to a stress state that is closer to failure conditions than predicted by models that do not explicitly include faults.

1. Introduction

Geologic carbon storage, like any other fluid injection activity, causes the pressurization of the reservoir. This pressurization reduces the effective stresses, causing deformation and approaching the stress state to failure conditions. To avoid reaching failure conditions that could compromise the caprock sealing capacity or fault stability, a good understanding of the hydro-mechanical couplings induced by injection is necessary (e.g., Streit and Hillis, 2004; Vilarrasa et al., 2010; Kim and Hosseini, 2015; Figueiredo et al., 2015). This understanding should allow determining the maximum sustainable injection pressure that would avoid causing geomechanical issues such as CO_2 leakage or felt induced seismicity (Rutqvist et al., 2007; Vilarrasa and Carrera, 2015).

Reservoir pressurization is proportional to the injected flow rate and is inversely proportional to permeability. Additionally, overpressure is dependent on the reservoir boundaries. Extensive reservoirs, like the Utsira formation at Sleipner, Norway (Zweigel et al., 2004), and the Mount Simon Sandstone in the Illinois Basin, US (Zhou et al., 2010), lead to an overpressure evolution that is relatively constant with time and relatively low due to the low viscosity of CO_2 (Vilarrasa et al., 2013a). On the other hand, closed reservoirs, like the Tubåen Formation at Snøhvit, Norway (Hansen et al., 2013), induce an overpressure that increases linearly with time (Zhou et al., 2008; Mathias et al., 2011). Thus, extensive reservoirs are preferable to closed reservoirs because their storage capacity will not be limited, in general, by overpressure (Szulczewski et al., 2012). Nevertheless, extensive

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reservoirs may not be always available (Castelletto et al., 2013), like in hydrocarbon basins, where reservoirs are usually closed, and may be used for enhanced oil recovery (EOR) using CO_2 or storing CO_2 in depleted reservoirs. Furthermore, even in extensive reservoirs, the pressure perturbation front will extend over large distances, in the order of hundreds of kilometers after decades of injection, so faults in the far-field may be eventually affected by overpressure (Chang et al., 2013).

Fault stability analysis related to CO_2 injection is receiving increased attention lately due to the increasing number of felt induced earthquakes that are occurring recently as a result of wastewater injection (Ellsworth, 2013). Though a few numerical studies include faults in the model (e.g., Vidal-Gilbert et al., 2010; Cappa and Rutqvist, 2011; Rinaldi et al., 2015; Gheibi et al., 2016; Rutqvist et al., 2016), most of the studies related to geologic carbon storage do not explicitly include faults in the models and thus assume that the presence of a fault would not affect the stress changes around the fault as a result of fluid injection (e.g., Vilarrasa et al., 2010; Alonso et al., 2012; Bao et al., 2013; Goodarzi et al., 2015). However, pre-existing faults, which have different geomechanical properties than the surrounding rocks, as shown by petroleum engineering studies (e.g., Orlic and Wassing, 2013), lead to local stress changes around the fault that can only be captured by explicitly including faults in the model. Hirano and Yamashita (2011) have developed a mathematical method for the analysis of quasi-static in-plane deformation due to a fault of arbitrary geometry embedded in a bi-material medium to calculate the static stress change nearby after stress drop on the fault.

The aim of this paper is to investigate how the presence of a fault (in elastic domain) affects the static stress path evolution in reservoir-caprock systems under normal and reverse faulting stress regimes. Furthermore, we analyze the effects of the fault plane shear stiffness, caprock's Poisson's ratio and the fault dip on the stress changes induced by overpressure. From the numerically calculated stress changes, we evaluate the influence on the stability of the fault and the caprock and assess the most favorable conditions for achieving a geomechanically stable CO_2 storage.

2. Methods

2.1. Stress path

During depletion or injection, not only does the change in pore pressure modify the effective stresses, but also the total stresses. The distribution of the total stress changes is caused by the resistance of the surrounding rocks against the deformation of the portion of the rock which has been subjected to pore pressure change. The stress changes can be quantified by stress path coefficients that are defined as the change in total stress $\Delta\sigma$ per unit change in pore pressure Δp_f (Hettema et al., 2000)

$$\gamma_h = \frac{\Delta\sigma_h}{\Delta p_f}$$
$$\gamma_v = \frac{\Delta\sigma_v}{\Delta p_f} \tag{1}$$

where subscripts v and h denote vertical and horizontal directions, respectively. We refer to γ_h as horizontal or x- stress path and to γ_v as vertical or y- stress path. γ_v is also known as stress arching coefficient. For reservoirs with very small aspect ratio, i.e., small thickness compared to the lateral extension of the reservoir, the stress arching coefficient becomes negligible (but it cannot be neglected for high aspect ratio) and γ_h can be estimated as (Fjær et al., 2008)

$$\gamma_h = \frac{\alpha(1-2\upsilon)}{1-\upsilon} \tag{2}$$

where α is the Biot coefficient and υ is Poisson's ratio. However, extensive reservoirs may not always be available for geologic carbon storage (Castelletto et al., 2013) and thus, the approximation given by Eq. (2) will not be applicable in general. Furthermore, we define two other stress path coefficients that are dependent on the vertical and horizontal stress path coefficients: the deviatoric and the mean effective stress paths

$$\gamma_{dev} = \frac{\Delta\sigma_{dev}}{\Delta p_f}$$
$$\gamma_{mean} = \frac{\Delta\sigma'_{mean}}{\Delta p_f} \tag{3}$$

where γ_{dev} is the deviatoric stress path, $\Delta\sigma_{dev} = \frac{(\Delta\sigma_1 - \Delta\sigma_3)}{2}$ is the deviatoric stress change, and $\Delta\sigma_1$ and $\Delta\sigma_3$ are the maximum and minimum principal stress changes induced by pressure change, respectively. γ_{mean} is the mean effective stress path and $\Delta\sigma'_{mean} = \frac{(\Delta\sigma_1 + \Delta\sigma_3)}{2} - \Delta p_f$ is the mean effective stress change. The deviatoric and the mean effective stress paths quantify the Mohr circle's size and position change, respectively.

The stress path depends on the geometry (reservoir inclination, aspect ratio and fault offset etc.), stiffness contrast between the reservoir and its surrounding rock and plastic deformation (Holt et al., 2016; Lynch et al., 2013; Fjær et al., 2008; Holt et al., 2004; Santarelli et al., 1998). We consider a reservoir of variable length, i.e., variable aspect ratio, embedded in a low-permeable rock or caprock, which may be crossed by a fault with no offset (Fig. 1). Note that the term reservoir is defined as the region where pore pressure changes. The aspect ratio of the reservoir is the geometric parameter. The fault plane is also a geometric parameter and can be an inelastic feature if the fault plane reaches failure conditions. We assume that the stiffness of the reservoir and its surrounding rock are equal except for models in Section 5.

2.2. Numerical model

To investigate the stress path evolution due to fluid injection in a reservoir of limited size that may be crossed by a fault, a numerical model was set up in a hybrid FEM-DEM (Finite Element Method-Discrete Element Method) in-house code called MDEM (Alassi, 2008; Lavrov et al., 2015). If only elastic strain occurs, the calculation is equivalent to FEM. The problem becomes discrete if cracks are about to form. MDEM can also model plasticity (softening-hardening) after the material reaches its yield point. Therefore, it can handle the linear elastic, softening and discrete behavior of materials. Moreover, MDEM can be coupled to TOUGH2 (Pruess et al., 1999) and MRST (Krogstad et al., 2015) flow simulators. Faults can be considered as discrete features. DEM allows a discrete feature to shear, open and close depending on the loading conditions. Therefore, it is beneficial to model faults as

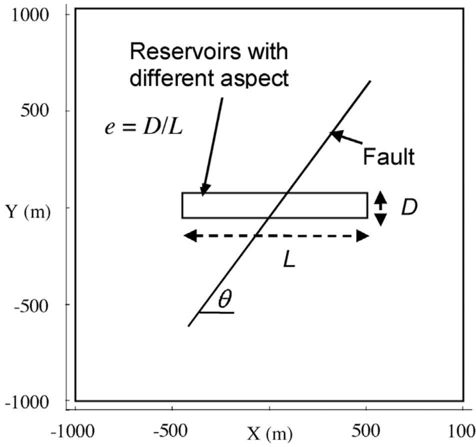

Fig. 1. Schematic representation of the 2D model used in the analyses. The rectangle with length L and thickness D illustrates the reservoir section. The black inclined line represents a fault with a dip of $\theta°$ crossing through the central part of the reservoir. Aspect ratio 'e' is the ratio of the reservoir thickness over its length. The reservoir is pressurized on both sides of the fault.