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Effect of Faults on Stress Path Evolution during Reservoir Pressurization

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Abstract

Fluid injection operations, such as CO₂ 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.

Keywords: Fluid Injection; Fault, Stress Path; Fault Reactivation; Shear Stiffness

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 CO₂ 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 CO₂ (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 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 CO₂ or storing CO₂ 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 CO₂ 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 CO₂ 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)

$$\begin{aligned}\gamma_h &= \frac{\Delta\sigma_h}{\Delta p_f} \\ \gamma_v &= \frac{\Delta\sigma_v}{\Delta p_f}\end{aligned}\tag{1}$$

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)

$$\gamma_h = \frac{\alpha(1-2\nu)}{1-\nu} \quad (2)$$

where α is the Biot coefficient and ν 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 Equation (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

$$\begin{aligned} \gamma_{dev} &= \frac{\Delta\sigma_{dev}}{\Delta p_f} \\ \gamma_{mean} &= \frac{\Delta\sigma'_{mean}}{\Delta p_f} \end{aligned} \quad (3)$$

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 (Figure 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 discontinuum. Although the models in this paper stay in the elastic domain, fault planes are defined as previously cracked elements aligned along a definite direction. It is important to note that fault surface will behave as an elastic material. The code uses the following constitutive model for discontinuities

$$\begin{aligned} F_s &= k_s u_s \\ F_n &= k_n u_n \end{aligned} \quad (4)$$

where F_α , k_α and u_α are, the force (N), stiffness (N/m) and displacement (m), respectively, in the α -direction, where α can be either n for the normal or s (shear) for the parallel direction to the fault plane.

Fig. 1 shows the model used in this study, which is a vertical 2 km * 2 km 2D plane-strain model. The reservoir layer has a thickness, D , of 40 m ($-20 \text{ m} < Y < 20 \text{ m}$ in Fig. 1) and variable length, L , in several scenarios. The maximum and minimum principal effective stresses, which are set constant on the boundaries, are $\sigma'_1 = 30 \text{ MPa}$ and $\sigma'_3 = 15 \text{ MPa}$, respectively. The direction of the principal stresses depends on the *in situ* stress regime, which can be either a normal faulting (the maximum principal stress is vertical) or a reverse faulting (the maximum principal stress is horizontal) stress regime, which are also called extensional and compressional stress regimes, respectively. There are examples of both normal and reverse faulting stress regimes in CO₂ storage sites. For example, Otway, Australia (Vidal-Gilbert et al., 2010), is an example of a normal faulting stress regime. But there are also cases of reverse faulting stress regime, like Tomakomai, Japan (Kano et al., 2013), or regions of the North Sea close to Snohvit, Norway (Chiaramonte et al., 2013). The Mohr circles corresponding to the initial stress states are identical in terms of size and position. Also, the stress path is independent of the *in situ* stresses and initial pore pressure in an elastic model. Since the presented results are in terms of stress path, it is possible to calculate the final stresses for any initial *in situ* stress and initial pore pressure.

The geomechanical material properties of the reservoir and the caprock are the same, with Young's modulus and Poisson's ratio equal to 15 GPa and 0.3, respectively. These values are in the range typical of rocks (e.g., Goodman, 1989). Furthermore, we analyze the effect of different rock properties between the reservoir and the caprock in Section 5. While reservoir properties are kept the same, the Poisson's ratio of the caprock is varied to 0.2 and 0.4.

We consider two scenarios, one with and another without fault. Each of these scenarios is investigated in compressional and extensional stress regimes. For each scenario, we consider three aspect ratios: 1, 0.5 and 0.067. The dip angle of the considered fault is 60°. The shear

stiffness (K_s) is assumed to be 0.066 GPa/m and the normal stiffness (K_n) is 66 GPa/m (Kulhawy, 1975). K_s is defined as $K_s=k_s/l_e$, where l_e is the effective element size in 2D, which is half of the element size. In the model, strength parameters of the intact rock and the friction angle of the fault are assumed to be high, so that the entire model including the faults will be in the elastic domain and failure does not occur.

We study the effect of the fault plane shear stiffness by solving two additional cases with a stiffer fault shear stiffness of 1.3 GPa/m and 13.3 GPa/m in a reservoir with an aspect ratio equal to 0.067. We also investigate the effect of the effect of caprock Poisson's ratio on the local stress path altered by fault presence. Moreover, effect of fault dip on the stress changes was studied by considering two additional fault dips of 45° and 30°, for both a compressional and an extensional stress regime. The models are constructed such that the location of the intersection of the fault and the reservoir-caprock interface coincide in the three fault dip cases. It is important to note that the stability investigations discussed in the paper mainly refer to the regions in the vicinity of the fault and not to the stability of the faults. Table 1 summarizes the scenarios performed in this paper.

The aim of the analyses is not to perfectly model CO₂ injection or any other injection operation, but to understand how the stresses may evolve and what the effects of different parameters are on the stress path evolution. Therefore, no fluid flow modeling is carried out. The pore pressure is increased by 10 MPa uniformly in the entire reservoir section.

Table 1 Summary of the scenarios simulated

Case	Aspect ratio (e)	Stress regime	Fault dip ($^{\circ}$)	K_s (GPa/m)	V_r	V_s
No fault	1	Compressional	-	-	0.3	0.3
		Extensional				
No fault	0.5	Compressional	-	-	0.3	0.3
		Extensional				
No fault	0.067	Compressional	-	-	0.3	0.3
		Extensional				
With fault	1	Compressional	60	0.066	0.3	0.3
		Extensional				
With fault	0.5	Compressional	60	0.066	0.3	0.3
		Extensional				
With fault	0.067	Compressional	60	0.066, 1.3, 13.3	0.3	0.3
		Extensional				
With fault	0.067	Compressional	45, 30	0.066	0.3	0.3
		Extensional				
With fault	0.067	Compressional	60	0.066	0.3	0.2, 0.3, 0.4

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 θ° 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.

3. EFFECT OF THE PRESENCE OF A FAULT

To achieve the main objective of the paper, i.e., to investigate the effect of the presence of faults on the stress redistribution after fluid injection, it is necessary to compare the stress paths with the cases where no fault exists.

3.1. No fault case

When injecting a fluid into a reservoir, the effective stresses decrease inside the reservoir due to pressure buildup. As a result, the reservoir rock unloads and expands. If the surrounding low-permeability caprock is isotropic-linear elastic and has the same elasticity parameters as the reservoir rock, the pore pressure remains constant in the surrounding caprock, but the expansion of the reservoir deforms it. The surrounding rock resists against the expansion of the reservoir, causing an increase or decrease of the stresses depending on the location. It is important to note that for reservoir and caprock having different elasticity parameters, the pore pressure will change in the caprock proportionally to the Skempton coefficient, which is caused by the undrained response of the caprock initially (Fjær et al., 2008).

Fig. 2 shows the stress paths (based on Eq. (1) and Eq. (3)) along a horizontal line crossing the reservoir center in a compressional stress regime. The horizontal total stress increases as a response to injection, presenting its maximum value at the center of the reservoir. This increase extends to the flanks, outside of the reservoir. In contrast, the vertical total stress decreases in the outer flanks, but it increases inside the reservoir. The greatest change in x -stress and y -stress are recorded at the center and at the edge (in the inner flanks) of the reservoir, respectively. These changes depend on the size of the reservoir. As the reservoir aspect ratio decreases, i.e., the width of the reservoir increases, the horizontal total stress increases more (Fig. 2c). In contrast, the vertical total stress increases less due to a lower arching effect in larger reservoirs (Fig. 2d). The

24 mean effective stress path inside the reservoir is independent of the aspect ratio (Fig. 2f), but the
 25 deviatoric stress path is not (Fig. 2e).

26
 27 Fig. 2. (a) Schematic representation of the model and the section where the results are plotted, (b) the stress
 28 regime, and profiles of (c) horizontal, (d) vertical, (e) deviatoric and (f) mean effective stress paths along
 29 the $Y=0$ m line crossing the reservoir center for several aspect ratios in the no fault and compressional
 30 stress regime. 'e' represents the aspect ratio.

31 Maintaining caprock stability is one of the main concerns in CO₂ storage projects in order to
 32 avoid CO₂ leakage. Therefore, it is essential to understand the stress paths in the caprock. Stress
 33 path in the caprock is defined based on the stress changes in the caprock per unit pore pressure

34 change in the reservoir. Though the stress paths vary with depth, the reservoir-caprock interface is
 35 of interest in these examples, and thus, the stress paths are investigated just above the interface in
 36 the caprock. Fig. 3 shows the stress path profiles along the line $Y=20.5$ m (in the caprock, just

37
 38 Fig. 3. (a) Schematic representation of the model, (b) the stress regime and profiles of (c) horizontal, (d)
 39 vertical, (e) deviatoric and (f) mean effective stress paths along $Y=20.5$ m line in the caprock for several
 40 aspect ratios in the no fault and compressional stress regime case. 'e' in the legend stands for aspect ratio.

41 above the reservoir). Fig. 3 clearly indicates that the horizontal total stress decreases in the
 42 caprock above the reservoir, but increases in the flanks and the changes are greater for higher
 43 aspect ratios (Fig. 3c). On the other hand, the vertical total stress shows the opposite behavior

(Fig. 3d). While the mean effective stress is almost constant and close to zero (Fig. 3f), the deviatoric stress decreases above the reservoir, experiencing greater changes for higher aspect ratios (Fig. 3e).

In an extensional stress regime, the x -stress, the y -stress and the mean effective stress paths are the same as those in a compressional stress regime. However, the same stress changes lead to an opposite deviatoric stress change, i.e., -1 times the deviatoric stress change in a compressional regime in Fig. 2e and Fig. 3e. This equivalency is valid as long as the deformation is elastic. If inelastic strain takes place, the stress path becomes dependent on the initial stress state and would be different for extensional and compressional stress regimes.

3.2. Fault case (60°)

In a compressional stress regime, a 60° fault is unfavorably oriented for shear failure, so fault slip is unlikely to occur (e.g., Vilarrasa et al., 2013b). Figure 4a-b shows the distribution of the horizontal and vertical stress path, respectively. Simulation results indicate that the greatest stress changes occur in the fault vicinity in the caprock-reservoir interface. Therefore, we focus on the changes along the $Y=19.5$ m (in the reservoir, just below the caprock, Fig. 5) and 20.5 m (in the caprock, just above the reservoir, Fig. 6) horizontal profiles. Fig. 5a shows a schematic representation of the model and the line where the stress path profiles are measured numerically at the top of the reservoir. Similar to the no fault case, pressure buildup increases the horizontal and vertical total stresses inside the reservoir. However, the presence of the fault in the model affects the stress changes in the vicinity of the fault in the caprock-reservoir interface. The increase in the horizontal stress is enhanced in the hanging wall and lowered in the footwall compared to the no fault model (Fig. 5c). Furthermore, the greatest vertical stress path takes place in the hanging wall of the fault, but the vertical stress change becomes negative in the footwall (Fig. 5d). Similar to the no fault models, these stress paths depend on the reservoir aspect ratio. While the mean effective stress is independent of the aspect ratio in the no fault cases (Fig. 2f), the lower the

aspect ratio, the greater the changes in the mean effective stress when a fault is present. Considering the fact that a lower mean effective stress and a greater deviatoric stress lead to a more unstable situation, the presence of the fault makes the reservoir less stable. This does not imply that the fault is weaker and more unstable, but it means that the existence of faults leads the stress changes in a different path than when no fault is present.

Fig. 4. Distribution of horizontal (a) and vertical (b) stress path in the presence of a 60° fault

Fig. 6 illustrates the stress path profiles in the caprock along the line $Y=20.5$ m. The horizontal stress path is negative in the caprock in the no fault case (Fig. 3c), meaning that the horizontal total stress decreases after reservoir pressurization. However, in the presence of a fault, the horizontal stress increases in the hanging wall for low aspect ratios, becoming positive around the fault (Fig. 6c). The shape of the variation of the vertical stress path is similar to that inside the reservoir, i.e., to the line $Y=19.5$ m shown in Fig. 5d. However, the stress path values are different. The x - and y -stress changes lead to negative and positive deviatoric stress paths in the

83 hanging wall and the footwall, respectively (Fig. 6e). Since the pore pressure remains unchanged
84 in the caprock, the mean effective stress path is supposed to be zero, as in the no fault case (Fig.
85 3f). However, the mean effective stress decreases in the footwall and increases in the hanging wall

86
87 Fig. 5. (a) Schematic representation of the model, (b) the stress regime and the profiles of (c) horizontal, (d)
88 vertical, (e) deviatoric and (f) mean effective stress paths along Y=19.5 m line crossing the reservoir for
89 different aspect ratios in the compressional stress regime with a 60° fault crossing through the central part
90 of the reservoir.

91 (Fig. 6f). Thus, the presence of a fault decreases the mean effective stress and increases the
 92 deviatoric stress in the footwall of the fault, making this zone less stable.

93
 94 Fig. 6. (a) Schematic representation of the model, (b) stress regime and the profiles of (c) horizontal, (d)
 95 vertical, (e) deviatoric and (f) mean effective stress paths along Y=20.5 m line crossing the caprock for
 96 different aspect ratios in a compressional stress regime with a 60° fault crossing through the central part of
 97 the reservoir.

98

The Mohr circles inside the reservoir and in the caprock are compared for both the 60° fault and the no fault cases in Figs. 7 and 8 for the compressional and the extensional regimes respectively. As shown in Section 3.2, the presence of the fault considerably decreases and increases the mean effective stress and deviatoric stress, respectively, in the footwall in a compressional stress regime in both the reservoir and the caprock. These changes shift the Mohr circle to the left and enlarge its radius, which makes the storage more unstable compared to the case where there is no fault in the model (Fig. 7). The minimum principal stress can even become negative if the fault is present,

Fig. 7. (a) Schematic representation of the reservoir and caprock and the location of the points where the Mohr circles are plotted, (b) the stress regime and comparison of the most unstable Mohr circles related to the 60° fault case and no fault case in (c) the reservoir and (d) the caprock in a compressional stress regime with a reservoir aspect ratio equal to 0.067.

which might lead to horizontal tensile fracture initiation inside the reservoir. Even though the fault is unfavorably oriented and is unlikely to fail, its presence influences the stress changes in its vicinity, decreasing rock stability both in the reservoir and in the caprock. Fig. 8 shows Mohr circles for the same locations as in Figure 7 for the no fault and the faulted cases in the reservoir and the caprock in an extensional stress regime. Fluid injection shifts the Mohr circle towards the failure surface in the reservoir for the no fault case, but the decrease in the deviatoric stress leads to a relatively stable situation. In the presence of the fault, the Mohr circle shifts even more to the left, but the deviatoric stress decreases, which maintains reservoir stability (Fig. 7c).

Fig. 8. (a) Schematic representation of the reservoir and caprock and the location of the points where the Mohr circles are plotted, (b) the stress regime, and comparison of the most unstable Mohr circles related to the 60° fault case and no fault case in (c) the reservoir and (d) the caprock in an extensional stress regime with a reservoir aspect ratio equal to 0.067.

In the caprock, the stress state becomes less stable in the no fault case, but stability improves slightly in the faulted case (Fig. 7d). Therefore, the presence of a 60° fault, which is favorably oriented for shear failure in an extensional stress regime, improves stability in its vicinity both in the reservoir and the caprock.

3. EFFECT OF FAULT PLANE SHEAR STIFFNESS

The stress path profiles along the lines $Y=19.5$ m in the reservoir ($e=0.067$) and $Y=20.5$ m in the caprock for a compressional stress regime for several fault shear stiffness are shown in Figs. 9 (c-f) and 10 (c-f), respectively. The x -, y -, deviatoric and mean effective stress paths vary significantly in the vicinity of the faults in the footwall and the hanging wall. The pattern of stress changes is the same regardless of the value of the fault plane shear stiffness, but the magnitude of the stress paths becomes greater for lower shear stiffness values. The zone affected by the presence of the fault becomes larger for lower shear stiffness values both in the reservoir and the caprock.

Figure 11c shows the Mohr circle inside the reservoir as a function of the fault shear stiffness in a compressional stress regime. The lower the shear stiffness, the higher is the risk of failure. This is due to the fact that the y -stress in the footwall decreases more in a softer fault plane (Fig. 9d). This effect leads to a lower minimum principal effective stress and a higher deviatoric stress for softer fault planes. As a result, the Mohr circle is much closer to the failure envelope. The stability of the caprock is also lower for smaller K_s values (Figure 11d). This is also caused by a greater reduction in the y -stress for the softer fault plane, which brings the Mohr circle towards the failure envelope, even though there is no pressure change in the caprock.

147
 148 Fig. 9. (a) Schematic representation of the model, (b) the stress regime and the profiles of: (c) horizontal,
 149 (d) vertical, (e) deviatoric and (f) mean effective stress paths along Y=19.5 m line crossing the reservoir for
 150 a compressional regime with a 60° fault crossing through the central part of the reservoir for several shear
 151 stiffness values.

152

153 Fig. 10. (a) Schematic representation of the model, (b) the stress regime and the profiles of: (c) horizontal,
 154 (d) vertical, (e) deviatoric and (f) mean effective stress paths along Y=20.5 m line crossing the caprock for
 155 a compressional regime with a 60° fault crossing through the central part of the reservoir for several shear
 156 stiffness values.

157

158 Fig. 11. (a) The schematic model of the reservoir and caprock and the location of the points where the
 159 Mohr circles are plotted, (b) the stress regime, and comparison of the most unstable Mohr circles related to
 160 the 60° fault case for two shear stiffness values in the (c) reservoir and (d) caprock in a compressional stress
 161 regime.

162 Figure 12 shows the shear stresses acting on the fault plane (60°) for several fault plane stiffness in
 163 a compressional stress regime. The dashed line shows the initial shear stress on the fault before
 164 injection. After reservoir pressurization, the shear stress acting on the fault increases in the
 165 reservoir ($Y < 20$ m) and decreases in the caprock sections ($Y > 20$ m). The shear stress evolution is
 166 dependent on the shear stiffness value of the fault plane. The greatest and the least shear stress on
 167 the fault in the reservoir are recorded for the $K_s = 13.3$ GPa/m and $K_s = 0.066$ GPa/m cases,
 168 respectively. Also, the decrease of the shear stress on the fault in the caprock is lower for the
 169 softer fault plane. It is interesting to see that the shear stress in the caprock ($20 \text{ m} < Y < 50 \text{ m}$)
 170 increases instead of decreasing for the softer fault plane. Fig. 12 basically indicates that if the fault

plane is more deformable, the stresses are concentrated in the fault's vicinity, but a lower shear stress concentrates on the fault plane. This is similar to a softer reservoir surrounded by a stiffer rock increasing the stress arching coefficient (Eq. 1) or stress concentration around a borehole (Fjær et al., 2008). Therefore, although a softer fault plane induces a less stable stress path around it (Fig. 11), it decreases the fault reactivation likelihood, because the shear stress decreases and the normal stress is independent of the shear stiffness.

Fig. 12. Shear stress on the 60° fault in the prior and post-injection stages for several shear stiffness values in a compressional stress regime. Y=20 m corresponds to the reservoir-caprock interface.

4. EFFECT OF POISSON'S RATIO

Three models with different Poisson's ratios of the reservoir section and its surrounding are performed. While the Poisson's ratio of the reservoir is constant and equal to 0.3, it is set to 0.2, 0.3 and 0.4 in the surrounding rock. Figure 13 shows the variation of stress path along Y=19.5 m inside the reservoir for the compressional regime. The stress paths are affected by the Poisson's ratio of the surrounding rock only for a close distance from the fault at the reservoir-caprock

186 interface. The greatest change of stress occurs for a model with lower Poisson's ratio in the
 187 caprock, except for the deviatoric stress change in the hanging wall. Figure 14 shows the variation
 188 of stress path along $Y=20.5$ m in the caprock of the same models than in Figure 13. In contrast to
 189 the reservoir, the greatest changes are observed for higher Poisson's ratio values (of the caprock),
 190 except for the deviatoric stress path, which presents a similar trend to that in the reservoir. The

191
 192 Fig. 13. The profiles of (a) horizontal, (b) vertical, (c) deviatoric and (d) mean effective stress paths along
 193 $Y=19.5$ m line crossing the reservoir for a compressional stress regime with a 60° fault crossing through the
 194 central part of the reservoir for several Poisson's ratio of the caprock.

195 results imply that both the caprock and the reservoir in the footwall experience a greater change
 196 for lower Poisson's ratio of the caprock.

197
 198 Fig. 14. The profiles of (a) horizontal, (b) vertical, (c) deviatoric and (d) mean effective stress paths along
 199 $Y=20.5\text{ m}$ line crossing the caprock for a compressional stress regime with a 60° fault crossing through the
 200 central part of the reservoir for several Poisson's ratio of the caprock.

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5. EFFECT OF FAULT DIP

Fault dip is relevant in fault stability analysis because while favorably oriented faults for shear failure are sub-vertical in an extensional stress regime, they are sub-horizontal in a compressional stress regime. Figures 15 and 16 plot the Mohr circles in the footwall (FW in the figures) and the hanging wall (HW) in the reservoir (with superscript R) and the caprock (with superscript C) for the three faults with dips of 60° , 45° and 30° for a compressional and an extensional stress regime, respectively. The Mohr circles are plotted at the points where the fault effect is the maximum. It is important to note that the Mohr circles shown in the FW and the HW do not necessarily correspond to the opposite locations with respect to the fault plane. The footwall is less stable compared to the hanging wall for the two stress regimes. Nevertheless, in general, both the hanging wall and the footwall become less stable after pressurization than before injection. In a compressional stress regime, the reservoir in the footwall is the least stable in the 60° fault case and the Mohr circle belonging to the 45° case is less stable than the 30° fault case (Fig. 15d). The stress state also becomes less stable in the hanging wall in the reservoir. However, opposite to the footwall, the 30° fault is the least stable and the 45° fault is the most stable in the hanging wall (Fig. 15c). Likewise, the footwall becomes less stable in the caprock. The stability decreases from the 30° , the 45° to the 60° fault cases in order (Fig. 15f). The hanging wall in the caprock becomes more stable in the 60° than prior to injection and stability slightly changes in the 45° and the 30° fault cases (slightly more stable in the 45° fault compared to the 30° case) (Fig. 15e).

In an extensional stress regime, the hanging wall in the reservoir in the 60° case becomes less stable after the injection, but it becomes more stable in the 45° and the 30° cases than prior to injection (Fig. 16c). For all fault dips, the Mohr circle in the footwall in the reservoir is shifted towards the failure surface, but the deviatoric stress decreases as the dip angle increases, leading to a stable situation in the 60° case (Fig. 16d). In the caprock, the mean effective stress increases in

Fig. 15. (a) Schematic representation of the reservoir and caprock and the location of the points where the Mohr circles are plotted, (b) the stress regime and comparison of the stability condition in the footwall (FW) and hanging wall (HW) of the fault in a compressional stress regime for several fault dips (c-d) inside the reservoir and (e-f) in the caprock, respectively.

all cases in the hanging wall and the deviatoric stress decreases in the 45° and the 30° cases, making them more stable than prior to injection. Nonetheless, the deviatoric stress slightly changes in the 60° case, which gives rise to a similar stability than prior to injection (Fig. 16e).

The caprock in the footwall becomes less stable due to a decrease in the mean effective stress,
being the 30° fault case the least stable and the 60° fault the most stable case (Fig. 16f).

Fig. 16. (a) The schematic model of the reservoir and caprock and the location of the points where the Mohr circles are plotted, (b) the stress regime and comparison of the stability condition in the footwall (FW) and hanging wall (HW) of the fault in an extensional stress regime for several fault dips (c-d) inside the reservoir and (e-f) in the caprock, respectively.

6. DISCUSSION

Fluid injection induces changes in the stresses around pre-existing faults. Fig. 17 shows a conceptual model of the effect of a fault crossing a reservoir-caprock system on the stress field when the reservoir is pressurized. Fig. 17a represents Mohr circles and the corresponding shear and normal effective stresses before (at point A) and after injection (at point A') acting on the fault shown in Fig. 17c. These stress changes modify the shear and normal stresses acting on the fault

Fig. 17. (a) Shear stress change on a plane due to fluid injection, (b) shear deformation of the fault plane and (c) the conceptual model of the reservoir, caprock and under burden, cut by a fault, and the stress redistribution around the fault.

plane during injection (Fig. 17a). The fault plane can deform either elastically or inelastically depending on the amount of the stress changes and the strength parameters of the fault plane. The amount of the fault plane deformation depends on the shear stiffness (K_s) of the fault plane (Fig. 17b). Since there is a pressure difference between the reservoir and the surrounding rock, the part of the fault inside the reservoir will deform differently than the parts outside of the reservoir. The differences in the deformation of the fault plane in the reservoir and in the surrounding rock may cause different stress redistribution in the reservoir-caprock interface compared to the case where

no fault is present. For example, in a compressional stress regime, as displayed in Fig. 17c, the shear stress applied on the fault plane increases due to injection and the hanging wall in the upper and the footwall in the lower interfaces are loaded (shown by compression in Figure 17c). On the other hand, the footwall and the hanging wall in the upper and the lower interfaces, respectively, are unloaded (shown by tension in Fig. 17c). The results (for $K_s=0.066$ GPa/m) indicate that the 60° fault makes the reservoir and the caprock less stable in a compressional stress regime, but not in an extensional stress regime (recall Figs. 7 and 8). The deviatoric stress change and the resulting deformation of the fault plane is a coupled phenomenon. The deviatoric stress change induced by injection deforms the fault plane and this deformation affects the stresses in response to it. Before fluid injection, the fault's hanging wall and the footwall, both in the reservoir and in the caprock, tend to move upward and downward, respectively, in a compressional stress regime. Apart from this, overpressure causes an increase in the deviatoric stress inside the reservoir, but a decrease in the caprock in a compressional regime. Therefore, the footwall inside the reservoir will move elastically downwards (along the direction that it would tend to before injection) and the footwall in the caprock will tend to move upward.

Figure 18 shows the displacement field (of nodes) around a 60° fault ($K_s=1.3$ GPa/m) in the reservoir-caprock interface. The displacement field is only showing the deformations due to the fault effect and the deformation of the intact rock in the reservoir and the caprock was excluded. The magnitude of the displacements vectors is below 1 mm and in the elastic domain. Figure 18 illustrates the tendency of the footwall to move downwards in the reservoir and upwards in the caprock, inducing unloading and consequently, decreasing the stresses in the upper reservoir-caprock interface in the footwall (Figs. 5c-d and 6c-d). Similarly, but in an opposite direction, the hanging wall in the reservoir and the caprock will tend to move upwards and downwards, respectively. Therefore, the interface in the upper hanging wall is loaded (compressed) and the stresses increase (Figs. 5c-d and 6c-d). The reduction of the stresses in the upper footwall significantly decreases the total, and consequently, the minimum principal effective stress. As a

result, the Mohr circle of the most unstable location becomes less stable compared to the no fault case in the reservoir, because it shifts to the left (lower mean effective stress) with a greater deviatoric stress (the Mohr circle radius increases). Therefore, the stability in the reservoir and also the caprock is reduced due to the fault effect (Fig.7c-d).

Fig. 18. Displacement field caused only by the fault effect ($K_s = 1.3$ GPa/m) due to stress field change induced by injection excluding the reservoir and caprock deformation.

In an extensional stress regime, the fault's hanging wall and the footwall both in the reservoir and in the caprock would tend to move downward and upward, respectively, before injection. After the reservoir is pressurized, the footwall and the hanging wall in the reservoir will deform in the opposite directions as they tend to before injection. In contrast, the footwall and the hanging wall in the caprock will deform in the same directions as they tend to before injection. After injection, the deviatoric stress will decrease inside the reservoir and will increase in the caprock. As a result, the footwall in the lower caprock and the upper reservoir will move upwards and downwards, respectively. These movements induce unloading or decrease of the stresses in the reservoir-caprock interface in the upper footwall. Conversely, the hanging wall tends to move upwards in the reservoir and downwards in the caprock after injection, which increases the stresses due to the

loading of the reservoir-caprock interface in the upper hanging wall. Therefore, the upper footwall and hanging wall are unloaded and loaded, respectively, regardless of the *in situ* stress regime.

The absolute value of the deviatoric stress change in the reservoir and the caprock is independent of the *in situ* stress regime (Section 3.2). However, the actual deviatoric stress has opposite sign in the two stress regimes. The deviatoric stress increases (positive) in a compressional stress regime and decreases (negative) in an extensional stress regime (Section 3.2), because the x - stress change is the change of the maximum and minimum principal stresses in a compressional and an extensional stress regimes, respectively. The fact that the absolute value of the deviatoric stress is independent of the stress regime, as well as the mean effective stress, causes the deformation of the fault plane in the caprock and the reservoir to be the same in both cases. Consequently, the amount of loading in the upper hanging wall and unloading in the upper footwall in the fault's vicinity in the reservoir-caprock interface are independent of the *in situ* stress regime. But the opposite sign of the deviatoric stress for each stress regime impacts stability differently in the two stress regimes. The presence of a 60° fault in the model decreases the stability in the reservoir-caprock interface around the fault both inside the reservoir and in the caprock in a compressional stress regime (Fig. 7). In contrast, the fault effect improves the stability in an extensional stress regime in the same locations (Fig. 8).

Comparison of the stress changes for the three fault dip angles in Figs. 15 and 16 shows that the change of the deviatoric stress acting on the fault plane is not enough to explain the amount of the stress path perturbation in the three fault angles. The shear stress change acting on a fault plane with dip Θ can be calculated by

$$\Delta \tau = \left| \Delta \sigma_{dev} * \sin (2\theta) \right| , \quad (5)$$

where $\Delta \tau$ and $\Delta \sigma_{dev}$ are the shear and the deviatoric stress changes after injection, respectively. Therefore, the amount of the shear stress is equal for the 30° and the 60° faults. Furthermore, the shear stress change for the 45° is greater than for the other two cases. Therefore, the stress path

perturbation is expected to be greater in the 45° model and to be equal for the 30° and the 60° faults. However, the y -stress change both in the footwall and the hanging wall is the greatest for the 60° and it is the least for the 30°. This behavior is the opposite in the x -stress change. The reason for this difference is that the elastic shear deformation of the fault plane in higher angles has a greater component in the vertical direction than the horizontal direction. Therefore, the stress changes are greater in the vertical and horizontal component of the stress in higher and lower fault angles, respectively (Figs. 15 and 16). In other words, the amount of the shear stress change is the driving force for the stress path perturbation in the vicinity of the fault in the reservoir-caprock interface, but the amount of the perturbation is controlled by the fault's dip. Therefore, a fault (in elastic domain) is a geometrical feature in terms of the stress path changes, i.e., it is the fault's inclination (geometry) that determines how much stresses should change around it.

The deformation of the fault plane in the reservoir section induces a different stress change in the fault vicinity in the reservoir-caprock interface compared to the other locations (Fig. 17). The amount of the induced perturbation is dependent on the amount of the displacement of the fault plane in the reservoir. The deformation of a fault/fracture plane has a direct relationship with the level of applied stress and the deformability or the shear stiffness (K_s) of the plane (Fig. 17b). Therefore, it is expected that lower shear stiffness values will cause a greater change in the stress values. Values for normal and shear stiffness for rock joints typically can range from 0.010 to 0.100 GPa/m for joints with soft clay in-filling, to over 100 GPa/m for tight joints in granite and basalt (Kulhawy, 1975). Therefore, the in-filling and morphology of discontinuities controls the deformability of pre-existing faults/joints. Fault shear stiffness is a stress and scale-dependent parameter and the reader is referred to Ostapchuk and Pavlov (2016), Kocharyan et al. (2014), Steer et al. (2011), Spivak (2011), and Yoshinaka and Yamabe (1986) for more details. Simulation results in Figs. 9 and 10 indicate that the stress paths perturbation in the reservoir-caprock interface is highly sensitive to the shear stiffness of the fault/joint plane. The softer the fault plane, the larger the deformation and stress changes. Both the vertical and horizontal stresses decrease in

the upper footwall and increase in the upper hanging wall (Figs. 9 and 10). Furthermore, softer fault planes lead to larger zones of influence. Larger zones of influence may imply a higher risk for fluid injection projects, in particular in CO₂ storage reservoirs because the risk of CO₂ leakage may increase.

Greater shear deformation is recorded for lower shear stiffness along the fault and the maximum shear displacement occurs at the center of the reservoir. Great shear deformation of a fault plane may also represent that the fault slips. At the same time, the decrease of shear stress on the fault plane with lower shear stiffness (Figure 12) is qualitatively similar to the results obtained by Faulkner et al. (2006). Using the field sampling and numerical modeling, they showed that for a damaged zone the stress state rotates and shear stress decreases from the far-field to the fault core. Therefore, the results of this paper can give an idea of the stress path perturbation due to the slip of a fault. However, fault slip also reduces the shear stress acting on the fault due to stress release. This leads to a more complicated stress perturbation which requires separate investigation.

Simulation results show that the fault effect is dependent on the reservoir's aspect ratio. We have utilized reservoir models with aspect ratios that, in general, are greater than potential CO₂ storage cases. However, there may be oil-fields like Elgin (Suiter et al., 2005) where some of the compartments have a very high aspect ratio. Thus, injection of CO₂ for Enhanced Oil Recovery (EOR) purposes may be performed in this type of reservoirs, so a better understanding of the stress changes is also required. Figs. 2d and 3d show that as the aspect ratio decreases, i.e., the reservoir length becomes larger, the y -stress path is reduced, meaning that the arching affect is negligible in the central part of the model. Actually, the vertical stress remains practically constant for reservoir lengths larger than 400 m (equivalent to $e=0.1$). According to Fig. 2, the x - and y -stress changes increase and decrease as the aspect ratio becomes smaller, respectively. Consequently, the deviatoric stress change becomes greater in a compressional stress regime and smaller in an extensional stress regime for decreasing aspect ratios. When a fault is present, greater stress changes occur in both stress regimes for larger reservoirs. Therefore, the fault effect

is expected to be more pronounced for extensive reservoir. The faults modeled in this study are placed in the central region of the model, and thus, the effect of reservoir boundaries are negligible in the stress path perturbation addressed in this paper.

The strength parameters of the faults were so high that the faults were stable in all the simulated cases. The 60° fault is favorably oriented for shear failure in an extensional stress regime. Conversely, the 30° fault is favorably oriented for shear failure in a compressional stress regime. However, the 45° fault is unfavorably oriented in the two stress regimes. In favorably oriented faults, the ratio of the shear stress over the normal effective stress is maximum and if it equals the friction coefficient, the fault will undergo shear failure.

In the reservoir, the upper footwall in a compressional stress regime (point FW^R in Fig. 15a) becomes less stable than the models where the fault is not considered explicitly for both the favorably (30°) and the unfavorably oriented (60° and 45°) faulted models (compare Figs. 7c and 9c-d). In the hanging wall (Fig. 12b), the stress state becomes less stable than prior to pressurization for all fault dips, but stability is not worsened compared to the no fault case. In an extensional stress regime, the unfavorably oriented faults (30° and 45°) make the stress state less stable after injection in the upper footwall of the reservoir, but more stable in the hanging wall (Fig. 16d). In contrast, the stability of the favorably oriented 60° fault does not decrease in the footwall, but it is slightly reduced in the upper hanging wall (Fig. 16c-d). Thus, while the presence of faults does not worsen reservoir stability in extensional stress regimes, faults may compromise reservoir stability in compressional stress regimes.

In the caprock, the stress state does not become less stable than prior to injection in the presence of favorably oriented faults for shear failure, but it may become less stable in some locations for unfavorably oriented faults in the two stress regimes (recall Figs. 15e-f and 16e-f). The stress state becomes less stable for the unfavorably and the favorably oriented faulted cases in the footwall in the caprock and for favorably oriented ones in the hanging wall in the caprock. For an extensional

stress regime, the footwall and the hanging wall become less stable in the unfavorably and the favorably oriented faulted cases, respectively. Comparison of Fig. 15c-f and Fig. 16c-f indicates that the stress state is less stable in the fault vicinity in the reservoir and the caprock in a compressional stress regime than in an extensional stress regime. Therefore, a compressional stress regime leads to a relatively less stable reservoir and caprock due to the fault effect on the stress paths.

The simulations, in this paper, are limited to a 2D problem. However, the same phenomenon occurs in 3D models, with the only difference that the stress path in the third dimension, i.e., out-of-plane direction, may present slightly different values between the 2D and 3D models. As long as there is deformation of the fault plane in the reservoir-caprock interface in the direction of interest, the stress path will be affected. Moreover, strike slip stress regime was excluded in this paper in order to present all the cases using the same model geometry. Nevertheless, a plan view could be used for the analysis of a strike slip stress regime because the maximum and minimum principal stresses are horizontal. In this case, critically stressed faults would be vertical and the regions of interest for fault stability would be at the flanks of the reservoir, rather than at the top and bottom.

The simulations in this study are isothermal. However, CO₂ will reach the storage formation at a colder temperature than that of the rock (Paterson et al., 2008). As a result, cooling will occur around injection wells, which will induce stress changes that may affect the rock stability (Goodarzi et al., 2015; Vilarrasa and Rutqvist, 2017). Nevertheless, cooling does not propagate over large distances, so it is usually a local effect around injection wells. If faults were affected by cooling, thermo-mechanical effects should be superposed to the stress changes shown in this study.

7. CONCLUSIONS

The stress path is affected by the presence of faults. Simulation results indicate that due to the stresses induced by overpressure, the reservoir-caprock interface may become less stable due to the fault's presence, even if the fault is completely stable. This is caused by the different shear deformations of the fault plane inside the reservoir and the caprock or the under burden induced by the different shear stress changes acting on the fault. The stresses in the upper hanging wall and the lower footwall in the reservoir-caprock interfaces increase. Conversely, the stresses decrease due to the unloading of the upper footwall and the lower hanging wall.

The stress path perturbation caused by the fault presence is independent of the stress regime if the rock behaves elastically. However, the impact on stability is not the same in compressional and extensional stress regimes. The faults that are unfavorably oriented for shear failure make the footwall in the reservoir and the caprock the least stable faulted cases in both a compressional and an extensional stress regime. In particular, the stress changes in a compressional stress regime in the faulted case can even lead to the minimum principal effective stress to become tensile in the reservoir in the upper footwall. Thus, either tensile fracturing or shear failure could occur in the intact rock. On the other hand, the hanging wall in the caprock and the reservoir becomes the least stable when favorably oriented faults are present in both stress regimes. The stress state is generally less stable in the vicinity of the fault in the reservoir section in a compressional stress regime than in an extensional stress regime. Furthermore, the caprock in the fault's vicinity also becomes less stable in compressional stress regimes. Therefore, a compressional stress regime leads to a relatively less stable reservoir and caprock than in an extensional stress regime due to the fault effect on stress paths.

Overall, the presence of faults alters the stress state around them, which can lead, in general, to a stress state that is closer to failure conditions than predicted by models that do not explicitly include faults. The fault effect on the stress path increases as the aspect ratio of the reservoir becomes lower in compressional stress regimes, but decreases in extensional ones. Therefore, the risk of failure initiation due to stress disturbance in the reservoir-caprock interface is higher in

extensive reservoirs in compressional than in extensional stress regimes. Furthermore, the magnitude and extension of the stress path perturbation around the fault are larger for faults with lower shear stiffness. 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.

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