Coupled Hydro-Mechanical Processes And Fault Reactivation Induced By Co₂ Injection In A Three-Layer Storage Formation

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Highlights

Hydro-mechanical (HM) fault reactivation has been analysed for a CO₂ reservoir
A single layer is not adequate to model the HM behaviour of a three-layer reservoir
A comprehensive parameter sensitivity analysis has been carried out
Key HM parameters have been identified for CO₂ storage site characterisation

Abstract

The interaction between mechanical deformation and fluid flow in fault zones gives rise to a host of coupled hydro-mechanical processes fundamental to fault instability, induced seismicity, and associated fluid migration. Fault stability is studied in the context of the Heletz site which was chosen as a test site for CO₂ injection experiment in the framework of the EU-MUSTANG project. The potential reservoir for CO₂ storage at the Heletz site consists of three sandstone layers that are approximately one, two and nine meters in thickness, separated by impermeable shale layers of various thicknesses, and overlaid by a five-meter limestone and a thick impermeable shale, which serves as caprock. The storage formation is intersected by two pre-existing sub-vertical normal faults (F1 and F2) on two opposite sides of the injection point. A hydro-mechanical model was developed to study the interaction between mechanical deformation and fluid flow in the two faults during CO₂ injection and storage. We evaluate the consequences caused by potential fault reactivation, namely, the fault slip and the CO₂ leakage through the caprock. The difference in the results obtained by considering the three-layer storage formation as an equivalent single-layer storage formation is analysed. It was found that for the two cases the pore pressure evolution is similar, but the differences in the evolution of CO₂ saturation are significant, which is attributed to the differences in CO₂ spread in a single and three-layer storage. No fault reactivation was observed in either case. A sensitivity analysis was made to study the influence of the fault dip angle, the ratio between the horizontal and vertical stresses, the offset of the layers across fault F2, the initial permeability of the fault and the permeability of the confinement formations. Results show that reactivation of faults F1 and F2 is most sensitive to the stress ratio, the initial permeability of the faults and the permeability of the confinement formations. The offset of the layers across the fault F2 was also found to be an important parameter, mainly because an offset leads to an increase in CO₂ leakage. Changes in permeability were found to be small because plastic shear strains induced by the reactivation of the faults and associated increase in volumetric strains and permeability, occur mainly in a fault section of only 10 m length, which is the approximate total thickness of the storage layers.

Keywords

Carbon dioxide CO₂, equivalent and three-layer storage formation, fault reactivation, hydro-mechanical effects

1. Introduction

Large-scale storage of CO₂ in deep underground reservoirs may cause considerable fluid pressure perturbation and concern has been raised over whether nearby faults, optimally oriented relative to *in situ* stress components, could be reactivated with shear failure (Davies *et al.*, 2013; Miller *et al.*, 2004; Sibson, 1992; Streit and Cox, 2001). Incidents of fault reactivation due to CO₂ injection are well known in such sites globally, e.g., Snipe Lake and Strachan (Alberta), Wilmington (California), Rangely and Denver (Colorado), and the mid-continental region of the United States (Baranova *et al.*, 1999; Ellsworth, 2013; Healy *et al.*, 1968; Hsieh and Bredehoeft, 1981; Milne, 1970; Nicol *et al.*, 2011; Raleigh *et al.*, 1976; Shemeta *et al.*, 2012; Suckale, 2010; Wyss and Molnar, 1972). CO₂ injection may also induce seismic events. The Midwest Geological Sequestration Consortium (MGSC) has a program of monitoring micro-seismicity during CO₂ injection on MGSC sites.

Coupled reservoir-geomechanical numerical modelling with TOUGH-FLAC (Rutqvist *et al.*, 2002; Rutqvist, 2011) to simulate faults reactivation induced by CO₂ injections (Rutqvist and Tsang, 2002; Cappa and Rutqvist, 2012; Rinaldi and Rutqvist, 2013) has been shown to be an effective tool for assessing the potential for fault instability and shear failure (Cappa and Rutqvist, 2011; Konstantinovska *et al.*, 2014). The potential for shear failure, and the type and orientation of failure, is to a large extent controlled by the three-dimensional initial stress regime. An extensional stress regime, in which the horizontal stresses are 0.7 times the vertical stresses, is shown to be favourable for shear failure along faults with high dip angle (dip > 60°) that may cut through overburden rock above the pressurized storage zone (Rutqvist *et al.*, 2008). Fault shear rupture and dilation may induce or enhance fault permeability, which in turn facilitates the rupture propagation across the overlying caprock (Cappa and Rutqvist, 2011; Rinaldi and Rutqvist, 2013).

The work reported in this paper aims to study the consequences of potential fault reactivation caused by underground CO₂ injection in a three-layer storage formation, focusing on the integrity of the CO₂ repository after 5 years of CO₂ injection, and hence on the potential leakage of CO₂ through the caprock to shallow formations. The geological setting on which the study has been conducted is that of the Heletz site in Israel that was chosen as a test site for CO₂ injection experiments in the framework of the EU-MUSTANG project (Niemi *et al.*, 2012). The Heletz site is located at the southern Mediterranean coastal plain of Israel and the geological structure is an anticline fold with a crest of about 4 km by 2 km. The structure is gently dipping to the east, truncated by a pinch-out line to the west and subdivided into a number of blocks bounded by sub-vertical normal faults with small displacements. An areal sketch of the site with the elevation of the caprock and the location of the borehole that has been chosen for the CO₂ injection experiment is presented in Fig. 1.

The potential reservoir for CO₂ injection at the Heletz site consists of three high-permeability sandstone layers, named K, W and A, approximately one, two and nine meters thick respectively, separated by impermeable shale layers of various thickness. This sequence of layers is overlaid by an additional limestone (LC) with 5 m thickness, which is the main geological marker in the entire region. The limestone layer (LC) is in turn overlaid by an impermeable shale and marl section with 45 m thickness which probably serves as a caprock for oil accumulation. The storage formation is underlain by an impermeable dolomite layer (Fig. 1). The confinement formations, located above the caprock and below the dolomite layer, are constituted essentially by limestone.

The CO₂ injection is made only in two permeable layers (W and A), approximately at an average depth of 1630 m (Fig. 1). At a distance away on both sides of the CO₂ injection point, the storage formation is intersected by the pre-existing faults F1 and F2. A vertical offset of 55 m in the layers is found across fault F1, but no offset data are found across the fault F2.

Five main sources of uncertainty were identified: the normal faults are sub-vertical but the exact dip angle is unknown; there is no stress measurements data available; no elevation data are available east of F2, and hence, the vertical offset of the layers across the fault F2 is not known; the initial permeability of the faults is unknown; and the permeability values of the confinement formations are unknown. In this paper, a base case is considered in which the key parameters discussed above are fixed at reasonable values. The difference in the results obtained by considering the three-layer as an equivalent layer storage formation is analysed. Secondly, a sensitive analysis is made to study the influence of these parameters on the obtained results. These results are followed by a discussion and some concluding remarks.

2. FLUID PRESSURE-STRESS COUPLING AND FAULT INSTABILITY

Fault reactivation is here defined by the occurrence of slip (plastic) displacement when the shear stress acting on the fault plane is high enough to exceed its shear strength. Fault slip displacement is defined by the difference between the displacement in the hanging wall and the foot wall, calculated in the fault plane.

Because of poro-elastic effects, stresses change during CO₂ injection (Altmann *et al.*, 2010; Safari *et al.*, 2013; Kim and Hosseini, 2014). As a consequence of fault reactivation with shear failure, the normal stress increases and the tangential stress decreases (Cappa and Rutqvist, 2011). To estimate the fluid pressure required for the reactivation of a fault, normal stress acting on the fault is reduced to an effective value according to the effective stress law of Terzaghi (1923):

$$\sigma'_n = \sigma_n - p, \quad (1)$$

where σ'_n is effective normal stress, σ_n is total normal stress and p is fluid pressure. In a failure analysis of a fault with a given orientation, the most fundamental relationship describing fault slip, considering hydro-mechanical interactions, is derived from the effective stress law given by equation (1) and the Coulomb failure criterion (Jaeger *et al.*, 2007), according to the following equation:

$$\tau = c + \mu_s \sigma'_n, \quad (2)$$

where τ is the critical shear stress for slip occurrence, c is cohesion, and μ_s is the static friction coefficient defined as:

$$\mu_s = \tan(\varphi), \quad (3)$$

where φ is the friction angle.

The shear and normal stress acting on the fault plane can be calculated from the two-dimensional principal stresses, by the following equations:

$$\tau = \frac{\sigma_1 - \sigma_3}{2} \sin(2\delta), \quad (4)$$

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos(2\delta), \quad (5)$$

where σ_1 is maximum compressive principal stress, σ_3 is minimum compressive principal stress and δ is the angle between the fault plane and the σ_1 direction.

To accurately estimate the potential for fault reactivation, both fluid pressures and stresses need to be constrained. Fault instability is frequently evaluated in terms of the ratio of shear stress to effective normal stress (τ/σ'_n) which is called “slip tendency” or “ambient stress ratio” acting on the fault plane (Streit and Hillis, 2004). According to equation (2), for a cohesionless fault ($c=0$), slip will be induced once the ambient stress ratio exceeds the coefficient of static friction:

$$\frac{\tau}{\sigma'_n} \geq \mu_s. \quad (6)$$

The potential for fault slip may also be expressed in terms of the fluid pressure required to induce slip. The maximum sustainable injection pressure, or the critical pressure P_c , can be calculated from equations (1) and (2) as:

$$P_c = \sigma_n - \frac{\tau}{\mu_s}. \quad (7)$$

Comparing the critical pressure P_c with a reference *in situ* pore pressure p , the critical pressure perturbation p_{cp} can be obtained, which indicates how close a particular section of a fault is to slipping. Typically, the coefficient of static friction μ_s ranges approximately from 0.6 to 0.85. By using a frictional coefficient of 0.6 in equation (7), which is a lower-limit value observed for the most hydraulically fractured rock masses, a conservative estimate of the maximum sustainable fluid pressure during CO₂ injection is obtained (Rutqvist *et al.*, 2007).

If considering the Mohr-Coulomb model in the fault, the potential for shear slip can be evaluated in terms of effective principal stresses, according to the following equation:

$$\sigma'_1 = c + q\sigma'_3, \quad (8)$$

where c is the cohesion, σ_1' is the maximum principal effective stress, σ_3' is the minimum principal effective stress and q is the slope of the σ_1' versus σ_3' line, which is related to μ_s according to the following equation:

$$q = \left[\left(\mu_s^2 + 1 \right)^{\frac{1}{2}} + \mu_s \right]^2. \quad (9)$$

By substituting a zero cohesion into equation (8) and a static coefficient of friction of 0.6 into equation (9), the following equation is obtained (Rutqvist *et al.*, 2007):

$$\sigma_1' = 3\sigma_3'. \quad (10)$$

Equation (10) means implies that shear slip is induced whenever the maximum principal effective stress exceeds three times the minimum compressive effective stress. The critical pore pressure P_c to induce shear slip on an arbitrarily oriented fault can be derived from equation (10) by considering that shear slip occurs when $\sigma_1' = \sigma_1 - P_c$ and $\sigma_3' = \sigma_3 - P_c$:

$$P_c = \frac{3\sigma_3 - \sigma_1}{2}. \quad (11)$$

3. HYDRO-MECHANICAL MODEL

In this section we briefly introduce the TOUGH-FLAC simulator and the coupled hydro-mechanical fault-permeability model adopted in this study.

3.1 TOUGH-FLAC simulator

TOUGH-FLAC (Rutqvist *et al.*, 2002; Rutqvist, 2011) is a simulator linking a finite-volume multiphase flow code TOUGH2 (Pruess *et al.*, 2011) and a finite-difference geomechanical code FLAC3D (Itasca, 2010). In a TOUGH-FLAC analysis of coupled thermo-hydro-mechanical problems, TOUGH2 and FLAC are executed on compatible numerical grids and linked through external coupling modules, which serve to pass relevant information between the field equations that are solved in the respective codes. A TOUGH-to-FLAC link takes multiphase pressures, saturation, and temperature from the TOUGH2 simulation and provides the updated temperature and pore pressure information to FLAC3D. After data transfer, FLAC internally calculates thermal expansion and effective stresses. Finally, a FLAC-to-TOUGH link takes the element stress and deformation from FLAC3D and updates the corresponding element porosity, permeability, and capillary pressure to be used by TOUGH2. A separate batch program controls the coupling and execution of TOUGH2 and FLAC3D for the linked TOUGH-FLAC simulator.

The calculation is stepped forward in time with the transient thermo-hydraulic analysis initialized in TOUGH2, and at each time step or at a TOUGH2 Newton iteration level, a quasi-static mechanical analysis is

conducted with FLAC3D to calculate stress-induced changes in porosity and intrinsic permeability. The resulting thermo-hydro-mechanical analysis may be explicitly sequential, meaning that the porosity and permeability is evaluated only at the beginning of each time step, or implicitly sequential, with permeability and porosity updated on the Newton iteration level towards the end of the time step, using an iterative process. A coupled hydro-mechanical fault model can be developed within the framework of TOUGH-FLAC by utilizing existing capabilities within TOUGH2 and FLAC3D codes, and by developing specially designed coupling modules for faults.

The mechanical behaviour of faults and fault zones can be represented in FLAC3D by special zero-thickness mechanical interfaces, by an equivalent continuum representation using solid elements, or by a combination of solid elements and ubiquitous-joints oriented as weak planes. Our analysis is made by discretizing the fault using finite-thickness elements which is the least complex approach. This approach has the ability to account for cross fault heterogeneity, and enables to simulate properly the fluid pressure-induced geomechanical reactivation in faults (Cappa and Rutqvist, 2011).

3.2 Model to consider shear-slip-induced fault permeability changes

A fault could have different architectures ranging from a single slip surface to a more complex geometry with a fault core and damage zone. Depending on the specific fault architecture, different approaches may be applied for estimating permeability changes associated with fault reactivation (Cappa and Rutqvist, 2011; Rinaldi *et al.*, 2014). In this study, a model was adopted for permeability correction that relates first the porosity ϕ at a given stress to the volumetric strain variation ε_v . Volumetric strains in the fractures are defined as the ratio of the change in volume of the fracture elements to its original volume. These volumetric strains include elastic and plastic components, in which plastic strain occurs after shear failure along the fault. Then, the permeability k at a given stress is related to changes in porosity, according with the following equations:

$$\phi = 1 - (1 - \phi_i) e^{-\varepsilon_v}, \quad (12)$$

$$k = k_i \left(\frac{\phi}{\phi_i} \right)^n, \quad (13)$$

where ϕ_i is the initial porosity, k_i is the initial permeability and n is a power law exponent.

The empirical relation between permeability and porosity expressed in equation (13) has been shown to be widely applicable to geological materials. The exponent n could vary between 3 and 25 for consolidated geological materials (David *et al.*, 1994). In Chin *et al.* (2000), a value of n equal to 5.6 was determined to fit permeability and porosity changes for experimental data in highly permeable sandstones. In the present study, we use a value of 15 for n as suggested by Cappa and Rutqvist (2011) for modelling shear-induced fault-permeability changes.

The plastic shear strain is associated with shear dilation, causing the volumetric strain and permeability to increase. The final permeability enhancement upon shear activation depends on the total shear strain and shear dilation and consequently the value of the dilation angle applied to the elasto-plastic model.

4. NUMERICAL MODEL AND CONDITIONS OF THE HELETZ SITE

4.1 Model setup

A coupled hydro-mechanical structural model within the framework of TOUGH-FLAC was developed to study the interaction between mechanical deformation and fluid flow in the faults during CO₂ injection at the Heletz site. Generally a 3D numerical model is desirable if at all possible. However a global 3D model would be very large and the necessary fine refinement close to the storage layers and faults would require a great computational effort. A simplified two dimensional model was developed instead. This is adequate from a mechanical perspective, particularly for investigating the potential for shear fault reactivation, because this is driven by changes in pore pressure in the storage reservoir that can be simulated explicitly with a 2D model.

This model considers the section A-B-C-D (Fig. 1) chosen to be representative of the geometry of the storage layers and their geology in a vertical cross-section for several kilometres. The model is executed in a plane strain analysis. Because no elevation data of the layers are available on the east side, the layers in the model were extended to the right side of fault F2, and it was assumed no offset of the layers across this fault. The section A-B-C-D is not collinear because it was chosen to be perpendicular to the two faults on the two sides of the injection well. The perpendicular line is the fastest pathway for CO₂ to arrive at the respective faults. A collinear plane would imply an increase in arrival time of the CO₂ to the two faults. The non-collinearity is not so critical in the scope of the hydro-mechanical analysis presented in this paper. Further studies will be carried out to consider a 3D geometry in the study of coupled hydro-mechanical effects due to fault reactivation, which is the best way to address that issue.

This model is a 5 km×2.5 km vertical cross section with 1 m thickness (Fig. 2), and includes the layers described in section 1. The horizontal size of the model was chosen from a sensitivity study which indicated that at this size it does not significantly affect results in the zone of interest. The top boundary is set 328 m below land surface. The water table is located at 300 m below the land surface. In Fig. 2, d is the offset of the layers across the fault F2, and α is the dip angle of the faults relatively to the horizontal plane. The dip of the both faults was set to 80°. It was assumed that the vertical stress is due to gravity loading and is one of the principal stresses. It was also assumed that the maximum horizontal principal stress is normal to the plane of the model, which is justified by the approximate perpendicularity between this plane and the faults. The angle between the normal to the fault F1 and the plane of the model between the points A and B (Fig. 1) is approximately 15°, which is relatively small.

The mesh constitutes of 15000 elements with refined elements close to the faults and storage formations. The width of the faults is assumed to be 10 m and is represented by five finite-thickness solid elements (Cappa and Rutqvist 2011, 2012). The injection point is located 550 m and 150 m from faults F1 and F2, on the left and right sides, respectively. The points I1 and I2 are located in the fault F2 section located in the W and A storage layers, respectively. In our simulations, CO₂ is injected with a constant rate, as a point source within a vertical column of elements with high-permeability (10^{-8} m²), that connects the two permeable layers (W and A) (Fig. 2). This is used to roughly represent the impact of the injection well connected to both layers, simultaneously. The size of the elements where CO₂ is injected is quite small. If the permeability of elements was much smaller than 10^{-8} m², the initial increase in pore pressure in those elements would be very large, and numerical problems would occur

during TOUGH-FLAC simulations. At the depth of the injection, the initial pore pressure and temperature are 13.16 MPa and 66.99 °C, respectively, and they assure supercritical conditions for CO₂. The initial temperatures T_0 at 328 m and 2828 m below ground surface are 44.14 °C and 87.58 °C respectively, resulting in a depth gradient of 17.4 °C/km. The initial fluid pressures P_0 at 328 m and 2828 m below ground surface are 1.65 MPa and 23.51 MPa respectively, considering a hydrostatic gradient of 9.81 MPa/km.

Constant pressure, saturation, and temperature conditions are assumed at the boundaries, and hence, they are open to fluid flow. Simulations are conducted in an isothermal mode, which implies that the thermal gradient is maintained according to the initial conditions. Null displacements conditions were set normal to the left and bottom boundaries, while a stress was set to the right and top boundaries (Fig. 2). The vertical stress σ_v is given by ρgh , where ρ is the density, and h is the depth below ground surface. It was assumed that the stress regime is extensional in which the horizontal stress σ_h is 0.7 times the vertical stress σ_v .

4.2 Layers properties

The layers are considered to be elastic, whereas the faults follow an elasto-plastic behaviour, described by a Mohr-Coulomb mechanical model. Hydraulic and mechanical properties are shown in Table 1.

The mechanical properties of the layers (elastic modulus E and Poisson's ratio ν) which are typical for sedimentary rocks were taken from Cappa and Rutqvist (2011, 2012). The elastic modulus of a fault zone may vary significantly with distance from the principal slip zone itself, that is, from the core through the fractured damage zone and to the less fractured host rock. Generally, the elastic modulus is lower in the fault core (~1 to 10 GPa) than in the damage zone (~10 to 70 GPa) (Faulkner and Rutter, 1998; Gudmundsson, 2004). Here we set the elastic modulus of the fault zone to 5 GPa (Cappa and Rutqvist, 2011). The initial permeability of the faults was considered to be 10^{-16} m^2 , which is representative of the damage zone permeability (Gudmundsson, 2000; Faulkner *et al.*, 2006). This permeability is four orders of magnitude higher than the permeability of the surrounding caprock. Thus, some fluid may penetrate the fault which in turn may trigger fault reactivation. The initial equivalent fault permeability is about three orders of magnitude lower than the permeability of the reservoir sandstone. Thus, the fault acts as a partial flow barrier in the reservoir, but a conduit through the caprock. The other mechanical and hydraulic properties of the faults were extracted from Cappa and Rutqvist (2011, 2012).

Density measurements were conducted which yield a value of 2645 kg/m³. Analysis of field data (Niemi, under preparation) indicates a permeability of the layers K, W and A of about 10^{-13} m^2 . The permeability of confinement formations, constituted by limestones, was set to a value of 10^{-15} m^2 . The permeability of the dolomite and shale layers was set to 10^{-20} m^2 . Field experiments indicates the values of 14.5%, 16.3% and 13.3% for the porosity of the layers K, W and A, respectively, and 7.3% for the porosity of the limestone layer. The porosity of the shale and dolomite layers was set to 6% and 7.3%, respectively.

The fluid-property module ECO2N (Pruess and Spycher, 2007) was employed for modelling the thermodynamic and thermophysical properties of water-NaCl-CO₂ mixtures. The relative permeability of gas and liquid phases is calculated from Corey's function (1954), while capillary pressure is governed by the van Genuchten's function (van Genuchten, 1980). The parameters of these functions were taken from Cappa and Rutqvist (2011, 2012).

4.3 Injection rate

To estimate the injection rate to be applied in our simplified 2D model, a 3D independent model was developed (Fig. 3) to study the pore pressure build-up close to the faults. This model is a 60 km×60 km with a 14 m vertical thickness corresponding to the total thickness of the sandstone layers W and A with the shale layer between them. In Fig. 3, the limits of our 2D simplified model is represented by points 1 and 2. The mesh has 2760 elements, is more refined between the two faults, and is very coarse on the left and right sides of faults F1 and F2, respectively. Five elements were used in the vertical thickness of the model. Although this mesh is very coarse, it is adequate to estimate the pore pressure build-up close to the faults and the extent of the pore pressure build up from the injection well.

The pore pressure was assumed to be constant across the layer thickness, because the pore pressure gradient is negligible in a 14 m thick layer. Thus, a single layer was considered. Further, it is shown that the maximum difference in pore pressure build-up obtained with representation of this two-layer storage by a single layer with an equivalent permeability is smaller than 1.0 MPa. Between the two faults and on the right side of the fault F2, the equivalent permeability of the two sandstone layers (W and A) and the isolating shale layer between them, was assigned. To take into account the offset of the layer across the fault F1, the permeability of the limestone (10^{-15} m^2) was assigned to the region located on the left side of this fault (Fig. 3).

The top and bottom boundaries are assumed to be impermeable, which is justified by the existence of the caprock and the impermeable dolomite layer located above and below the storage formation, respectively. The lateral boundaries are considered to be open to flow. However, results of our simulations showed that since the boundary conditions are imposed very far away from the injection point, they do not influence the pore pressure values obtained close to the faults.

The amount of CO₂ injected may vary from site to site. For example, at the In Salah (Algeria) CO₂ storage project the injection occurred over three horizontal 1 to 1.5 km long wells in a 20 m thick storage formation at a rate of about 0.5-1.0 million tons/year, which corresponds to an average injection rate per well of about 10-15 kg/s (Shi *et al.*, 2012; Rinaldi and Rutqvist, 2013). Based on this injection rate per well, in our simulations with the 3D model, the CO₂ is injected with a constant rate of 10 kg/s which is approximately 10 times the injection rate used for the CO₂ field experiments at Heletz site. Results of our simulations showed that injection rates higher than this value could lead to large pore pressure values close to the faults, mainly when the permeability of the faults is very small (10^{-18} to 10^{-20} m^2). The pore pressure evolution close to each fault obtained during 5 years of CO₂ injection was monitored. Then, we ran the 2D simplified model for several injection rates to find the 2D injection rate that leads to similar evolution in pore pressure close to the faults. Results of our simulations showed that, at 5 years after CO₂ injection, the pore pressure achieved for an injection rate of 0.005 kg/s in the vertical 2D model of 1 m thickness is consistent with the pore pressure obtained with an injection rate of 10 kg/s applied in the 3D model. The discrepancy in the pore pressure obtained close to the faults with the two models was found to be about 1.0 MPa, and this is acceptable, considering the uncertainties associated with both models.

Calculation of the equivalent 2D injection rate to maintain same pore pressure increase at the fault in the 3D model depends on the site parameters assumed, such as the value of the initial fault permeability, and layer offset across fault. Hence, this value is recalculated for each case if necessary.

4.4 Representing the three-layer formation by an equivalent single layer

To study the difference in the pore pressure build-up close to the faults and the evolution of the CO₂ plume, when the three-layer storage formation is represented by a single-layer storage, three scenarios are considered: in scenario 1, a three-layer (K, W, A) storage with injection into the layers W and A, is considered; in scenario 2, a single layer with an equivalent permeability k_{eq1} of the three storage layers (K, W and A) is considered; in scenario 3, a single layer with an equivalent permeability k_{eq2} of the two storage layers W and A (where injection takes place) is considered, but layer K is considered to have the permeability of the sandstones ($1 \times 10^{-13} \text{ m}^2$) and is considered to be opened to flow.

Let us assume that k_1 is the permeability of the three sandstones K, W and A, with thickness d_2 , d_4 and d_6 , respectively, and k_2 is the permeability of the separating shale layers with thickness of d_1 and d_3 (Fig. 4).

In scenario 2, the permeability k_{eq1} of the equivalent single layer is given by the following equation:

$$k_{eq1} = \frac{k_1(d_1 + d_3 + d_5) + k_2(d_2 + d_4)}{d_1 + d_2 + d_3 + d_4 + d_5}. \quad (14)$$

In scenario 3, the permeability k_{eq2} of the equivalent single layer is given by the following equation:

$$k_{eq2} = \frac{k_1(d_3 + d_5) + k_2(d_4)}{d_3 + d_4 + d_5}. \quad (15)$$

By using the equations (14) and (15) the values of $6.7 \times 10^{-14} \text{ m}^2$ and $7.8 \times 10^{-14} \text{ m}^2$ were obtained for the permeability k_{eq1} and k_{eq2} , respectively.

5. RESULTS

5.1 Comparison between the results obtained by representing the three-layer as a single-layer storage

The results presented in this section were obtained by considering a base case where the fault dip angle α is 80°, the horizontal stress is 0.7 times the vertical stress (stress extensional regime), there is no offset of the layers across the fault F2 ($d=0$) (Fig. 2), the initial permeability k_0 of the faults is 10^{-16} m^2 , and the permeability of the confinement formations is 10^{-15} m^2 . In the next section, the results of a sensitivity analysis that was made to study the influence of the above parameters on the obtained results, are presented.

The variation with time of the pore pressure and CO₂ saturation at the injection point, and points I1 and I2 (Fig. 2), was obtained with TOUGH-FLAC code. A comparison between the curves obtained in the three scenarios, presented in section 4.4, is shown in Fig. 5. In this figure, the solid and the dashed lines represent the pore pressure and CO₂ saturation, respectively. Fig. 6 shows the CO₂ saturation obtained after 5 years of

injection with consideration of the three cases described in section 4.4. In this figure, the upper limit of the caprock is shown.

Fig. 5 shows that at the injection point, in scenario 1, the pore pressure increases during approximately 1.3 years and reaches a value of 23.5 MPa. After this period, the pore pressure progressively decreases and reaches approximately 21.5 MPa after 5 years of injection. Also, at the injection point CO₂ saturation increases quickly at the start-up of injection and then increases at a slower rate until the end of the injection to reach a value of 55%. At points I1 and I2, changes in pore pressure are more sensitive to CO₂ saturation. First, in point I₁ pore pressure increases during the first 8.5 months of injection. Then, accelerated inflow and increased pressure into the fault occurs when CO₂ saturation abruptly increases. The increase in CO₂ saturation is faster than that of pore pressure, because CO₂ is much less viscous than brine, and therefore its mobility increases as CO₂ saturation increases. CO₂ spreads quickly through the fault F2, until reaching a steady state CO₂ saturation value. The instant when the pore pressure starts to decrease coincides with the period during which injected CO₂-rich fluid reaches the fault F2. Because the injected CO₂ is much less dense than water, it migrates up along fault F2 and overrides over the water. This leads to a decrease in pore pressure and an increase in CO₂ saturation until a steady state is attained.

At the three points referred above, the pore pressure curves obtained in the scenarios 1 and 3 are quite similar, which enables to conclude that the flow in the upper layer K is not prevalent. After 5 years of CO₂ injection, the discrepancy in pore pressure obtained in these two cases is smaller than 1.0 MPa. This discrepancy is larger when the curves of the pore pressure obtained in scenarios 1 and 2 are compared (the maximum discrepancy is approximately 2 MPa). This discrepancy results from injecting CO₂ in two permeable layers (W and A) and in scenario 2 the equivalent permeability of the single layer is calculated by considering also the upper layer K, where the CO₂ flow is not prevalent (see Fig. 6a). If there was more CO₂ flow in layer K originated by buoyancy effects, this discrepancy would be smaller.

At the injection point the CO₂ saturation is generally larger when a single layer is considered (scenarios 2 and 3). This is because in these scenarios the equivalent permeability of the single layer is smaller than the permeability of the three-layer storage formation, and in this way, the spread of the CO₂ is slower. The discrepancy in CO₂ saturation obtained in the three scenarios becomes smaller than 10% after 5 years of CO₂ injection. Also, because of this, in scenarios 2 and 3, the CO₂ arrives at the point I1, approximately 7 and 2 months later, respectively, than in scenario 1. In scenarios 1 and 3, the CO₂ arrives at the point I2 practically at the same time (approximately after one year of CO₂ injection), and its variation with time is very similar. But, in scenario 2, the CO₂ arrives one year later and the CO₂ saturation is smaller than the obtained in scenarios 1 and 3. This is because in scenario 2, the thickness of the single layer is larger, and the buoyancy force that causes CO₂ to migrate upwards is larger than in scenario 3. In all scenarios, the CO₂ arrives quickly at the point I1. The discrepancy in the arrival time of the CO₂ at the points I1 and I2 is justified by the different lateral extensions of the CO₂ plume in the layers W and A. In the three-layer storage (scenario 1), the lateral extent of the CO₂ plume is greater in the layer W than in the layer A (Fig. 6). This is explained by a buoyancy force which causes CO₂ to propagate more in the layer W. Then, CO₂ reaches faults F1 and F2 and propagates upwards. In the layer K, the lateral extension of the CO₂ plume to the left side of the fault F2 is much smaller than that observed in the layers W and A, which shows that the flow in this layer is not prevalent. When a single layer with an equivalent

permeability of the layers K, W and A (scenario 2) is considered, the major changes in CO₂ saturation occur in the mid and upper part of this single-layer storage. The CO₂ reaches the fault F1 that is located farther away from the injection, but does not propagate upwards. When a single layer with an equivalent permeability of the layers W and A is considered (scenario 3), the later extension of the CO₂ plume is slightly larger than in scenario 2. In this case, the CO₂ reaches the fault F1 and propagates upwards. In all studied scenarios, it was found that after 5 years of injection, the CO₂ only escapes through fault F2 towards ground surface, which is the closest fault to the injection point.

Figs 7 and 8 display the vertical profiles of the pore pressure build-up and slip displacement along the section of faults F1 and F2 (in the elements next to the reservoir), respectively, obtained after 5 years of CO₂ injection, for the three considered scenarios. The location of the layers K, W and A is delimited by two horizontal dashed lines. Fig. 7 shows that at the location of both faults the pore pressure build-up occurs mainly in the fault section located in the storage formation. This concludes that because the permeability of the faults (10^{-16} m^2) is one order of magnitude smaller than the permeability of the surrounding confinement formations (10^{-15} m^2), and three orders of magnitude smaller than the permeability of the storage layers (10^{-13} m^2), the vertical fluid penetration along the faults is not significant. It is also noted that for the three scenarios the maximum increase in the pore pressure obtained in faults F1 and F2 is similar: the difference was found to be smaller than 1.0 MPa. This concludes that, although the maximum pore pressure build-up value is not very sensitive to the offset of the layers across the fault F1, the increase in pore pressure is slightly larger in fault F2 than in fault F1, in a region located above the storage formation. In the fault F1, the pore pressure cannot build-up in shallower parts because fluid leaks off into the high permeable formations on the left side of this fault and hence, the pressurized section is smaller than in fault F2.

No fault reactivation was observed because in the fault section located in the storage formation, the total pore pressure is approximately 20.9 MPa, which is smaller than the critical pore pressure of 23.7 MPa, obtained with the equation (11), where $\sigma_1 = 0.7 \sigma_3$ and σ_1 is equal to the vertical stress at 1630 m depth. In this way, the slip displacement is caused only by variation in the elastic strain along the faults. Fig. 8 shows that the maximum displacement obtained in faults F1 and F2 is similar (the discrepancy is smaller than 1.0 mm).

The above analysis shows that, because of the significant differences observed mainly in CO₂ spread and the arrival times of CO₂ to the fault F2, the representation of the three-layer storage as an equivalent storage layer may not be adequate. This is not obvious because due to buoyancy effects, CO₂ propagates in the fault F2 and in layer K. If there was more CO₂ in layer K, these discrepancies would be smaller. For this reason, the three-layer storage (scenario 1) is considered in further analysis.

Let us now analyse the permeability changes along the faults. Fig. 9 displays the profile along the faults F1 and F2 of the ratio between the permeability k obtained after 5 years of CO₂ injection and the initial permeability k_0 of the faults, and its evolution with time at the point I2 (Fig. 2). These profiles were obtained in the elements next to the storage reservoir. The location of the layers K, W and A is delimited by the two vertical dashed lines. Fig. 9 shows that in both faults, the major changes in permeability are concentrated in the fault section located in the storage formation, where the major pore pressure build-up occurs. The maximum fault permeability occurs in the fault section located in the storage formation, and is approximately 1.15 times the fault initial permeability, which is not significant because no plastic strains are induced by shear fault reactivation. The figure also shows

that, at the point I2 (Fig. 2) the major changes in permeability occur approximately after 1.3 years of CO₂ injection, which corresponds to CO₂ arrival at this point. After this period, the initial permeability of the fault decreases with time, but this decrease is not significant. A period of five years is considered in further analysis, because after this period changes are more moderate.

5.2 Sensitivity analysis

A sensitivity analysis was done to study the influence of the fault dip angle α , the ratio SR between the horizontal and vertical stress components, the vertical offset d of the layers across the fault F2, the initial permeability k_0 of the faults and the permeability k_f of the confinement formations on the obtained results. The values of the key parameters used in the sensitive study are presented in Table 2 together with those used for the base case. The results of this sensitivity analysis were compared with those obtained in the base case study, presented in the last section.

In the sensitive study, to be consistent with the observance of sub-vertical normal faults, the fault dip angle was set to two additional values, 70° and 90°. The stress ratio was set to 0.55, 0.6, 0.7 and 1.0, on both sides of the base case value. A stress larger greater than 1.0 was not considered, because this is not consistent with the observance of normal faults. A small stress ratio (e.g. SR equal to 0.5) was not considered because it was found that for gravity loading, shear failure already occurs along the fault, so that the fault slip is triggered immediately upon the CO₂ injection and the entire fault reactivates. The permeability k_f of the confinement formations, located above the caprock and below the dolomite layer (Fig. 2) was set to 10⁻¹⁶, 10⁻¹⁸ and 10⁻²⁰ m² in the sensitive study. An offset d of 50 m, which is similar to the offset (55 m) of the layers across the fault F1, was considered as an additional value. The additional values of fault initial permeability k_0 are 10⁻¹⁸ and 10⁻²⁰ m². For these two latter parameters (d and k_0), the pore pressure build-up obtained close to the faults with the 2D model is found to be larger than the obtained with the assumed field injection rate of 10 kg/s applied in the 3D model (Fig. 3). Thus, the methodology described in section 4.3 was used to re-calculate the appropriate injection rate that would lead to a similar increase in pore pressure obtained in the 3D model.

5.2.1. Effect of fault dip angle

In this section, the results of a sensitivity analysis to study the influence of the fault dip angle α on the obtained results, are presented. The vertical profiles of the pore pressure build-up and slip displacement along the faults F1 and F2 obtained with the three fault dip angles were found to be similar to those in Figs 7 and 8, and a comparison between those profiles is not presented in this section.

Table 3 shows a comparison of the maximum pore pressure build-up P_{max} , the maximum slip displacement δ_{max} , the length L of the shear failure section, and the maximum ratio k/k_0 , where k is the permeability after 5 years of CO₂ injection, and k_0 is the initial permeability of the fault. These maximum values presented for the fault elements next to storage layers.

The table shows that for the three considered fault dip angles, the maximum pore pressure build-up close to the faults F1 and F2 and the fault slip displacement, is similar. It was found that in the three cases the pore

pressure build-up close to the faults is not enough to induce their reactivation, and hence, in the absence of plastic shear strains, the slip displacements are small. The CO₂ plume obtained with a fault dip angle of 70° and 90° is similar to that obtained with 80° (Fig. 6a).

5.2.2. Effect of ratio between the horizontal and vertical stresses magnitude

In this section, the results of a sensitivity analysis to study the influence of the ratio (*SR*) between the magnitude of the horizontal stress σ_h and the vertical stress σ_v on the obtained results, are presented. Table 4 shows a comparison of the results obtained for a stress ratio of 0.55, 0.60, 0.70 and 1.0. Fig. 10 shows the profiles of the pore pressure build-up, slip displacement and change in the tangential stress along fault F2 (in the elements next to the reservoir), obtained after 5 years of CO₂ injection. The profiles obtained along fault F1 are similar and are not displayed. The location of layers K, W and A is delimited by the two horizontal dashed lines.

Table 4 shows that the maximum pore pressure build-up ranges between approximately 6.8 and 7.3 MPa, in fault F1, and between 7.1 and 7.8 MPa, in fault F2, when the stress ratio ranges between 0.55 and 1.0. The slip displacement ranges between approximately 3 and 6 mm, in fault F1, and between 3 and 9 mm, in fault F2, when the stress ratio decreases from 1.0 to 0.55. This shows that a higher confinement provided by the horizontal stresses leads to a slight increase in pore pressure because of coupled hydro-mechanical effects. A higher confining stress reduces the length of the shear failure section with the result of smaller slip displacement. Fault reactivation only occurs for a stress ratio equal or smaller than 0.6. When the stress ratio decreases from 0.6 to 0.55, the length of the shear failure section increases approximately 950 and 930 m in faults F1 and F2, respectively, which is significant. The stress ratio has a significant impact on the length of the shear failure section because when the magnitude of the horizontal stress and consequently the stress ratio decreases, the stress normal to the fault decreases in all along its extent, and shear failure is more likely to occur with an increase in pore pressure due to CO₂ injection. In the limit, if the horizontal stresses are 0.5 times the vertical stresses, all the faults section is in shear rupture. However, the total maximum slip displacement along the faults and changes in permeability are not significant. This is because, as mentioned before, the pore pressure build-up occurs mainly at the storage formation, and hence, the flow penetration into the faults is not prevalent. In this way, the decrease in the tangential stress and fault slip displacement is observed mainly in the fault section located in the storage formation (Fig. 10). This implies that although the shear failure occurs in more a fault section than 2 km long, the shear plastic strains are more prevalent in the fault section of approximately 10 m length. Because the major shear dilation occurs in this short fault section, no significant changes in the volumetric strains and associated permeability were found.

A comparison between CO₂ plumes obtained with consideration of the several stress ratios showed that they have similar lateral and vertical extensions. Thus the size of the CO₂ plume has low sensitivity to the confinement provided by the horizontal stresses.

5.2.3. Effect of offset magnitude at fault F2

In this section, the results of a sensitivity analysis to study the influence of the magnitude of the offset *d* (Fig. 2) of the storage layers across the fault F2 on the obtained results, are presented. Table 5 shows a comparison of

the results obtained with a null offset and a 50 m offset. Fig. 11 shows the profiles of the pore pressure build-up, change in the tangential stress ($\Delta\tau$) and the ratio k/k_0 obtained along the fault F2 (in the elements next to the reservoir) after 5 years of CO₂ injection. The location of the layers K, W and A is delimited by two horizontal dashed lines.

Table 5 shows an increase in the maximum pore pressure build-up of approximately 1.4 and 1.6 MPa in faults F1 and F2, respectively, when the offset of the layers across the fault F2 is changed from 0 to 50 m. In both cases, the difference in the maximum pore pressure build-up observed in faults F1 and F2 is smaller than 1.0 MPa. With the consideration of a 50 m offset, the pore pressure increases more (see Fig. 11), because of the impermeable caprock located on the right side of the fault F2. Only fault F2 is reactivated, but the length of the shear failure section is only 10 m, which corresponds approximately to the thickness of the layers W and A. Consequently, the maximum increase in the slip displacement is only 1.0 mm. In this fault, for a null offset and for a 50 m offset, the maximum decrease in the tangential stress is approximately 1.0 MPa. The induced maximum permeability is approximately 1.2 times the initial permeability of the fault F2 (Fig. 11).

Fig. 12 shows the CO₂ saturation obtained after 5 years of CO₂ injection with consideration of an offset of 50 m of the layers across the fault F2. A comparison with the results obtained by considering a null offset (Fig. 6a) enables to conclude that the offset of 50 m limits the lateral extension of the plume to the right side of the fault F2. As a consequence, the CO₂ is forced to migrate upwards and there is a major leakage through the caprock at location of the fault F2. In fault F1, the CO₂ saturation is practically unaffected by the offset of the layers across the fault F2 and no leakage through the caprock is observed.

5.2.4. Effect of fault initial permeability

In this section, the results of a sensitivity analysis to study the influence of the initial permeability k_0 of the faults on the obtained results, are presented. Table 6 shows a comparison of the results obtained with an initial permeability of the faults of 10^{-16} , 10^{-18} and 10^{-20} m², results for the fault section located in the storage formation. Fig. 13 shows the profiles of the pore pressure build-up, change in the tangential stress ($\Delta\tau$) and the ratio k/k_0 obtained along the fault F2 (in the elements next to the reservoir) after 5 years of CO₂ injection. The location of the layers K, W and A is delimited by the two horizontal dashed lines.

At the location of the storage formation, the pore pressure build-up obtained with a fault initial permeability of 10^{-20} m² was found to be larger by approximately 4 MPa than the case of a fault initial permeability of 10^{-18} m². However, as Table 6 shows, at location of both faults, the pore pressure build-up is larger when the initial permeability of the faults is 10^{-18} m². This is because it is easier for fluid to propagate into the faults when their initial permeability is larger; in other words, the pore pressure and the length of the pressurized section in the faults decrease as they become more impermeable (see Fig. 13). Hence, when the initial permeability of the faults is set to 10^{-20} m², only the fault F2, being close to the injection well, is reactivated. Both faults are reactivated when the initial permeability of the faults is 10^{-18} m². The major decrease in the tangential stress is approximately 5.0 MPa and is observed when the initial permeability of the fault F2 is 10^{-20} m² (see Fig. 13). When the initial permeability of the faults is 10^{-18} and 10^{-20} m², the maximum slip displacement occurs in the fault section located in the storage formation and is approximately 1 cm. Maximum changes in permeability are

found to occur in fault F2 when its initial permeability is 10^{-18} m^2 . In this case, the maximum permeability of the fault F2 obtained after 5 years of CO_2 injection is approximately two times its initial permeability.

5.2.5. Effect of the permeability of the confinement formations

In this section, the results of a sensitivity analysis to study the influence of permeability k_f of the confinement formations on the obtained results, are presented. Table 7 shows a comparison of the results obtained with a permeability of the confinement formations of 10^{-15} , 10^{-16} , 10^{-18} and 10^{-20} m^2 . Fig. 15 shows a comparison of the vertical profiles of the pore pressure build-up, change in the tangential stress and the ratio k/k_0 obtained along faults F1 and F2 (in the elements next to the reservoir) for the considered values of k_f . The location of the layers K, W and A is delimited by the two horizontal dashed lines.

Table 7 shows that when the permeability of the confinement formations is set to 10^{-16} m^2 , only fault F1 is reactivated, but the length of the shear failure section is very small (approximately 3 m). Both faults are reactivated when their initial permeability is set to 10^{-18} and 10^{-20} m^2 . In these two cases, a major increase in pore pressure is observed because the confinement formations are more impermeable than the faults. Hence, the fluid is constrained to propagate more in the faults, with the result of an increase in the length of the pressurized section (see Fig. 15) and length of shear failure section (see Table 7). Fig. 15 also shows that the vertical profile of the pore pressure build-up along the fault F1 is non-symmetrical with respect to the depth level of the storage layers. In the fault F1, the pore pressure cannot build-up in the shallower part because fluid leaks off into the high permeable formations on the left side of this fault and hence, its pressurized section is smaller than in fault F2. This profile obtained in the fault F2 section is more symmetric because there is no offset between the layers across this fault.

In fault F1, the maximum decrease in the tangential stress is approximately 0.9 MPa and 1.5 MPa when the permeability of the confinement formations is 10^{-18} and 10^{-20} m^2 , respectively. In fault F2, this decrease is approximately 1.7 MPa and 1.4 MPa, for a permeability of the confinement formations of 10^{-18} and 10^{-20} m^2 , respectively. Changes in permeability were found to be more significant in fault F1. The maximum permeability obtained after 5 years of CO_2 injection is approximately 1.7 and 2.1 times the initial permeability, when the permeability of the confinement formations is 10^{-18} and 10^{-20} m^2 , respectively.

The CO_2 saturation obtained 5 years after CO_2 injection, with consideration of a permeability of the confinement formations of 10^{-20} m^2 is presented in Fig. 16. The figure shows that the lateral and vertical extension of the CO_2 plume obtained with consideration of a permeability of 10^{-20} m^2 is smaller than the obtained with a permeability of 10^{-15} m^2 (Fig. 6a), because the influence of the buoyance forces on the CO_2 spread is smaller in the former case. As a result, the CO_2 does not reach the fault F1, and there is no leakage through the caprock at location of the fault F2.

6. CONCLUSIONS

This paper presents a hydro-mechanical model within the framework of TOUGH-FLAC to analyse the consequences of potential reactivation of two sub-vertical normal faults (F1 and F2) on either side of a CO_2

injection point. The work was focused on the integrity of the CO₂ storage, induced by CO₂ injection in a three-layer storage formation at the Heletz site, which has been chosen for a CO₂ injection experiment as part of the EU-MUSTANG project.

Five main sources of data uncertainty were identified: the fault dip angle, the ratio between the horizontal and vertical stresses, the vertical offset of the layers across the fault F2, the initial permeability of the faults and the permeability of the confinement formations. In a base case study, these parameters were set to reasonable values. The main key points of the findings are summarized in Table 8.

The work reported in this paper was focused on the study of the potential consequences of fault reactivation in the context of Heletz site, where the thickness of the storage layers of about 10 m is fixed. Fault slip displacement and changes in permeability were found not to be significant because the plastic shear strains occur mainly in a fault section that is only about 10 m in length, corresponding to the thickness of the storage formation. Because shear plastic strains and changes in permeability are larger in thicker storage reservoirs, it is proposed that further work should be conducted to evaluate the influence of storage formation thickness on the hydro-mechanical behaviour of faults located nearby CO₂ injection zones.

As a concluding remark, the present study indicates three parameters of significant interest for the fault zone hydromechanics associated with CO₂ injection and storage. These are offset of storage layer across faults, permeability of confinement layers, and thickness of storage formation, which have direct relation with the extent of any potential fault reactivation. These are parameters which have not received sufficient attention but should be included among the key parameters to be evaluated in site characterization for CO₂ storage.

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Tables

Table 1 Material properties used to simulate CO₂ injection. Note that the permeability is expressed in m² (1×10⁻¹⁵ m² is equal to 1 millidarcy)

Parameters	Sandstones (K, W, A)	Limestone Confinement formations	Shale	Dolomite	Faults
Young's modulus E (GPa)	10	10	10	10	5
Poisson's ratio ν	0.25	0.25	0.25	0.25	0.25
Rock density ρ_s (kg/m ³)	2645	2645	2645	2645	2645
Friction angle φ (°)	-	-	-	-	25
Dilation angle ψ (°)	-	-	-	-	20
Porosity ϕ	0.145 (K) 0.163 (W) 0.133 (A)	0.073	0.060	0.073	0.100
Permeability k (m ²)	1×10 ⁻¹³	1×10 ⁻¹⁵	1×10 ⁻²⁰	1×10 ⁻²⁰	1×10 ⁻¹⁶
Residual CO ₂ saturation (-)	0.05	0.05	0.05	0.05	0.05
Residual liquid saturation (-)	0.3	0.3	0.3	0.3	0.3
van Genuchten (1980), P_0 (KPa)	19.9	19.9	621	621	19.9
van Genuchten (1980), m (-)	0.457	0.457	0.457	0.457	0.457

Table 2 Values of the key parameters considered in the sensitive study

Key parameter	Parameter value	
	Base case	Sensitive study
Fault dip angle α (°)	80	70, 90
Stress ratio SR	0.7	0.55, 0.60, 1.00
Offset d (m)	0	50
Permeability k_0 (m ²)	10 ⁻¹⁶	10 ⁻¹⁸ , 10 ⁻²⁰
Permeability k_f (m ²)	10 ⁻¹⁵	10 ⁻¹⁶ , 10 ⁻¹⁸ , 10 ⁻²⁰

Table 3 Influence of the fault dip angle α on the maximum pore pressure build-up P_{max} , maximum slip displacement δ_{max} , length L of the shear failure section, and maximum ratio k/k_0 , where k_0 and k are the initial and final permeability of the faults, respectively (results obtained after 5 years of CO₂ injection)

α (°)	Fault	P_{max} (MPa)	δ_{max} (mm)	Fault reactivation	L (m)	k/k_0
70	F1	7.87	3	No	-	1.16
	F2	8.27	3	No	-	1.16
80	F1	7.31	3	No	-	1.14
	F2	7.79	3	No	-	1.15
90	F1	7.38	3	No	-	1.15
	F2	7.85	2	No	-	1.15

Table 4 Influence of the stress ratio (SR) on the maximum pore pressure build-up P_{max} , maximum slip displacement δ_{max} , length L of the shear failure section, and maximum ratio k/k_0 , where k_0 and k are the initial and final permeability of the faults, respectively (results obtained after 5 years of CO₂ injection)

SR	Fault	P_{max} (MPa)	δ_{max} (mm)	Fault reactivation	L (m)	k/k_0
0.55	F1	6.81	6	Yes	2220	1.55
	F2	7.14	9	Yes	2220	1.55
0.60	F1	6.93	3	Yes	1267	1.40
	F2	7.36	4	Yes	1293	1.15
0.70	F1	7.31	3	No	-	1.14
	F2	7.79	3	No	-	1.15
1.00	F1	7.32	3	No	-	1.14
	F2	7.79	3	No	-	1.15

Table 5 Influence of the offset d of the layers across the fault F2 on the maximum pore pressure build-up P_{max} , maximum slip displacement δ_{max} , length L of the shear failure section, and maximum ratio k/k_0 , where k_0 and k are the initial and final permeability of the faults, respectively (results obtained after 5 years of CO₂ injection)

Offset d (m)	Fault	P_{max} (MPa)	δ_{max} (mm)	Fault reactivation	L (m)	k/k_0
0	F1	7.31	3	No	-	1.12
	F2	7.79	3	No	-	1.17
50	F1	8.69	3	No	-	1.12
	F2	9.36	4	Yes	10	1.19

Table 6 Influence of the fault initial permeability k_0 on the maximum pore pressure build-up P_{max} , maximum slip displacement δ_{max} , length L of the shear failure section, and maximum ratio k/k_0 , where k_0 and k are the initial and final permeability of the faults, respectively (results obtained after 5 years of CO₂ injection)

k_0 (m ²)	Fault	P_{max} (MPa)	δ_{max} (mm)	Fault reactivation	L (m)	k/k_0
10^{-16}	F1	7.31	3	No	-	1.12
	F2	7.79	3	No	-	1.12
10^{-18}	F1	23.26	10	Yes	27	1.75
	F2	23.71	12	Yes	33	2.04
10^{-20}	F1	20.95	11	No	-	1.49
	F2	21.02	12	Yes	6	1.50

Table 7 Influence of the permeability k_f of the confinement formations on the maximum pore pressure build-up P_{max} , maximum slip displacement δ_{max} , length L of the shear failure section, and maximum ratio k/k_0 , where k_0 and k are the initial and final permeability of the faults, respectively (results obtained after 5 years of CO₂ injection)

k_f (m ²)	Fault	P_{max} (MPa)	δ_{max} (mm)	Fault reactivation	L (m)	k/k_0
10^{-15}	F1	7.31	3	No	-	1.12
	F2	7.79	3	No	-	1.12
10^{-16}	F1	9.94	3	Yes	3	1.19
	F2	9.83	3	No	-	1.20
10^{-18}	F1	12.02	6	Yes	163	1.66
	F2	11.60	5	Yes	126	1.52
10^{-20}	F1	12.16	15	Yes	400	2.09
	F2	11.73	12	Yes	546	1.63

Table 8 Summary of the main results: α is the fault dip angle, SR is the ratio between the horizontal and vertical stresses, d is the offset of the layers across fault F2, k_0 is the initial permeability of the faults, k_f is the permeability of the confinement formations

Case		Main findings
Representing the three-layer formation by an equivalent single layer		The discrepancies in the pore pressure build-up close to the faults are small
		The discrepancies in the CO ₂ spread are significant, mainly because CO ₂ flow in the upper layer of the three-layer storage formation is not large and most of it will then flow into the other layers
		An equivalent single layer may not be adequate to represent a three-layer storage formation in hydro-mechanical modelling, mainly because of the differences in CO ₂ spread, and thus the multiple layers should be taken into account
Base case		After 5 years of CO ₂ injection, the faults are not reactivated
		A small leakage through the caprock is observed at one of the faults which can be explained by a buoyance force that causes CO ₂ to migrate upwards through the permeable fault
Sensitive study	α (°)	The results are not very sensitive to the fault dip angle, because no fault reactivation is observed at alternative values of dip angles
	SR	Both faults are reactivated for $SR \leq 0.60$
		The pore pressure build-up is observed mainly in the storage formation with a thickness relatively small
		The impact of fault reactivation is not significant: the pore pressure build-up close to the faults is not enough to induce significant shear plastic strains along the faults
	d (m)	Only fault F2 is reactivated when d is increased to 50 m
		The maximum fault slip displacement and changes in permeability are not significant
		The offset d is an important parameter because it limits the lateral extension of the CO ₂ plume and the CO ₂ leakage through the caprock increases
	k_f (m ²)	Both faults are reactivated for $k_f \leq 10^{-18} \text{ m}^2$
		The maximum pore pressure is about two times the initial pore pressure
		The maximum fault slip displacement is 1.5 cm
		The maximum fault permeability is increased by only two times its initial value
		No CO ₂ leakage through the caprock was observed because the lateral and vertical extensions of the CO ₂ plume are more limited
	k_0 (m ²)	Both faults are reactivated when $k_0 = 10^{-18} \text{ m}^2$, but only fault F2 is reactivated when $k_0 = 10^{-20} \text{ m}^2$
		The maximum pore pressure is about three times the initial pore pressure
		The maximum fault slip displacement is 1.2 cm
		The maximum fault permeability is increased by only two times its initial value

		No CO ₂ leakage through the caprock was observed because the lateral and vertical extensions of the CO ₂ plume are more limited
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Fig. 13 Vertical profiles of the pore pressure build-up (left), change in the tangential stress ($\Delta\tau$) (middle) and ratio k/k_0 (right), along the fault F2, obtained after 5 years of CO_2 injection, for a fault initial permeability k_0 equal to 10^{-16} , 10^{-18} and 10^{-20} m^2

Fig. 14 shows the CO_2 saturation obtained after 5 years of injection when the fault initial is 10^{-20} m^2 . A comparison with the results obtained with consideration of an initial fault permeability of 10^{-16} m^2 (Fig. 6a) enables to conclude that when the faults are more impermeable, the lateral extension of the CO_2 plume is much smaller, and the CO_2 does not reach the location of faults F1 and F2.

Fig. 14 CO_2 saturation (in percentage) obtained after 5 years of injection with consideration of an initial permeability k_0 of the faults of 10^{-20} m^2

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Fig. 16 CO₂ saturation (in percentage) obtained after 5 years of injection with consideration of a permeability k_f of the confinement formations of 10^{-20} m²