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Effects of in situ stress measurement uncertainties on assessment of predicted seismic activity and risk associated with a hypothetical industrial-scale geologic CO₂ sequestration operation

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ABSTRACT

Carbon capture and storage (CCS) in geologic formations has been recognized as a promising option for reducing carbon dioxide (CO₂) emissions from large stationary sources. However, the pressure buildup inside the storage formation can potentially induce slip along preexisting faults, which could lead to felt seismic ground motion and also provide pathways for brine/CO₂ leakage into shallow drinking water aquifers. To assess the geomechanical stability of faults and the characteristics of potential injection-induced seismic events. Our modeling study is based on a hypothetical industrial-scale carbon sequestration project assumed to be located in the Southern San Joaquin Basin in California, USA. We assess the stability on the major (25 km long) fault that bounds the sequestration site and is subjected to significant reservoir pressure changes as a result of 50 years of CO₂ injection. We present a series of geomechanical simulations in which the resolved stresses on the fault were varied over ranges of values corresponding to various stress measurements performed around the study area. The simulation results are analyzed by a statistical approach. Our main results are that the variations in resolved stresses as defined by the range of stress measurements had a negligible effect on the prediction of the seismic risk (maximum magnitude), but an important effect on the timing, the seismicity rate (number of seismic events) and the location of seismic activity.

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1. Introduction

Carbon capture and storage (CCS) has been recognized as a promising option for reducing carbon dioxide (CO₂) emissions from large stationary sources (Pacala and Socolow, 2004). However, large amounts of CO₂ (several billions of tonnes per year over several decades) have to be stored in deep geologic formations before CCS has the desired beneficial effect on climate change (Zoback and Gorelick, 2012; Fuss et al., 2014). One main challenge is that injection of such large amounts of CO₂ into the deep subsurface may be associated with a number of environmental risks that should be assessed before commencing the operation. As injection begins, a CO₂-rich plume grows away from the injector, driven by pressure gradients and buoyancy forces (Rutqvist et al., 2007; White and Foxall, 2016). As the injected fluid displaces the in situ brine, a large overpressure plume also develops. This pressure buildup inside the storage formation might lead to slip and dilation along preexisting faults and fractures. Indeed, fluids can facilitate slip on fault at stress levels lower than those required under dry conditions. When fluids are present in fault zones, they can accumulate and increase the fluid pressure along the fault principal slip zone, and the effective normal stress across the fault will decrease. This effect will in turn reduce the fault strength according to the Coulomb failure criterion (Sibson, 1973; Scholz, 2002; Wibberley

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The fault reactivation could potentially lead to brine/CO2 leakage into shallow drinking water aquifers (Zheng et al., 2009; Apps et al., 2010; Keating et al., 2010; Viswanathan et al., 2012; Tillner et al., 2016). This risk is higher for mature fault zone with a well-developed and continuous damage zone parallel to the fault core than for minor fault zone where heterogeneities within the damage zone may limit the leakage (Jeanne et al., 2014; Rinaldi et al., 2014a, 2014b). In addition, the pressure buildup could also result in seismicity that might be felt by the local population and might even cause structural damage (Rutqvist et al., 2014). Therefore, it is extremely important to estimate the geomechanical fault stability and predict the seismic hazards along faults located in the vicinity of a potential geologic CO2 storage site (Vilarrasa and Carrera, 2015a, 2015b; Zoback and Gorelick, 2015).

To perform such a study, it is of crucial importance to measure and predict the in situ state of stress. Although in general the existing state of stress in the subsurface varies as a function of depth, there is no easy way to predict the depth-dependent variations in stress magnitudes and directions, which are potentially influenced by topography, tectonic forces, local geologic history (Jaeger et al., 2012) and rock constitutive behavior as variations in layer stiffness with depth result in a rotation of the horizontal stresses (Gunzburger and Cornet, 2007; Goodarzi et al., 2015; Hergert et al., 2015). Such complexity inhibits our ability to accurately predict in situ stresses. Some methods performed in boreholes (e.g. hydraulic fracturing, overcoring, and wellbore breakout) or the analyses of earthquake focal mechanisms can provide some information on the in situ state of stress, but they requires either an existing well or seismic events recorded in the past. Moreover, even if this kind of measurements are performed, their estimates of the in situ stress are either relatively accurate for a small volume of rock (up to 100 m3 for methods performed in boreholes) or of limited accuracy for a larger volume (up to 109 m3 for focal mechanisms) (Amadei and Stephansson, 1997). Such measurement difficulty can show a large variation in the results and lead to considerable uncertainties in the stress orientation and the relative stress magnitude to be used as input to geomechanical simulations.

In this paper, we investigate how the uncertainties in the stress state, as defined by the variation of stress measurements obtained within the study area, influence geomechanical estimates of fault stability, and particularly estimate of the potential for induced seismicity. Our modeling study is based on a hypothetical industrial-scale carbon sequestration project initially planned in the Southern San Joaquin Basin in California (Fig. 1a) (Birkholzer et al., 2011; Zhou and Birkholzer, 2011; Wainwright et al., 2013).

In the following, we first present the study area, including the geology and estimates of the stress field made in the area. Then, we present numerical simulations involving basin-scale coupled
multiphase fluid flow and geomechanics. In addition, we link several model domains, i.e. the reservoir system and fault system, to simulate the evolution of seismicity on a major reservoir-bound fault. We then develop 24 scenarios in which the applied stress on the fault is varied over a range of values corresponding to various stress measurements performed around the study area. We test two different stress regimes (strike-slip and reverse), three different orientations for the horizontal maximal stress \((S_{hmax})\) and four different gradients for \(S_{hmax}\). The ensemble of geomechanical simulations enable us to perform a principal component statistical analysis designed to extract strong patterns in the simulation results for evaluating the effect of the stress measurement uncertainties on seismic hazards.

2. Study area

2.1. Geological setting

The hypothetical injection site is located towards the center of the San Joaquin Basin (Fig. 1b). The stratigraphy in the region consists of Quaternary and Tertiary deposits resting on basement granite. The regional structure is a monocline dipping 7° toward the west (Fig. 1c). The targeted stress formation is the Vedder sand, which is divided into six alternating sand/shale layers. The Vedder sand layers are quite permeable providing sufficient injectivity and offer a viable storage option. The overlying Freeman which is divided into six alternating sand/shale layers. The Vedder shale intercalated with discrete turbidite sand beds. These tests indicated a strike-slip regime (with \(S_v = 25\) MPa, \(S_{hmin} = 20\) MPa, and \(S_{hmax} = 48–54\) MPa, where \(S_v\) is the vertical stress, \(S_{hmin}\) is the minimum horizontal stress, and \(S_{hmax}\) is the maximum horizontal stress) (Chanchani et al., 2003). From these measurements, Chanchani et al. (2003) attempted to assess the stress state prior to reservoir pressure depletion using the theory of poroelasticity (Biot, 1941) and found a transitional reverse/strike-slip faulting regime (with \(S_v = 25\) MPa, \(S_{hmin} = 26\) MPa, and \(S_{hmax} \geq 54\) MPa). These measurements also highlight the range of uncertainties on the in situ stress measurements that geomechanical studies have to face when dealing with fault stability analysis with: an uncertainty of ±20° on the \(S_{hmax}\) direction, the \(\sigma_1/\sigma_3\) ratio ranging from 2 to 2.7 (where \(\sigma_1\) is the principal compressive stress and \(\sigma_3\) is the minimal compressive stress), and an uncertainty related to the faulting regime with \(S_v \approx 0.96S_{hmin}\) (reserve faulting regime) or \(S_{hmin} \approx 0.8S_v\) (strike-slip faulting regime).

3. Numerical simulation

It is a major challenge to model basin-scale multivariate flow processes, the complex internal structure of a fault zone, and induced seismicity at high resolution in the same hydrogeomechanical model. Usually, a fault zone comprises a thin (centimeter-scale) low-permeability and deformable fault core where most of the fault slip is accommodated, surrounded by a wider (up to several hundred meters) damage zone with higher permeability (e.g. Chester et al., 1993; Caine et al., 1996). Recent results suggest that fluid pressurization within the damage zone can produce large (meter) slips in the fault core (Cappa and Rutqvist, 2011a). Here the approach is to utilize the flexibility provided by a sequential hydro-mechanical coupling approach, using different numerical grids for each sub-problem. A high-resolution basin-scale model is required to adequately represent the complex geometries of reservoir-bound faults and to calculate the pressure distributions within the fault damage zones. At the same time, a sufficiently fine-grid resolution is required within the fault core to simulate the evolution of low-magnitude seismicity. In the following Sections 3.1–3.3, we describe the sequential coupling approach used in this study, as illustrated in Fig. 2.

### Table 1

<table>
<thead>
<tr>
<th>Formation</th>
<th>Each formation outside</th>
<th>PPC fault</th>
<th>(\beta_v) (10^{-10}) Pa(^{-1})</th>
<th>(\alpha) (10^{-5}) Pa(^{-1})</th>
<th>(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleistocene</td>
<td>(3 \times 10^{-12})</td>
<td>(3 \times 10^{-10})</td>
<td>0.35</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Etcheoign</td>
<td>(1.2 \times 10^{-12})</td>
<td>(1.2 \times 10^{-10})</td>
<td>0.32</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Macona</td>
<td>(1.9 \times 10^{-12})</td>
<td>(1.9 \times 10^{-10})</td>
<td>0.31</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Santa Margarita</td>
<td>(2 \times 10^{-12})</td>
<td>(2 \times 10^{-10})</td>
<td>0.28</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Round Mountain</td>
<td>(2 \times 10^{-18})</td>
<td>(4 \times 10^{-16})</td>
<td>0.02</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Olcece</td>
<td>(1.7 \times 10^{-13})</td>
<td>(1.7 \times 10^{-11})</td>
<td>0.34</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Freeman</td>
<td>(1 \times 10^{-16})</td>
<td>(4 \times 10^{-16})</td>
<td>0.02</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Vedder sand</td>
<td>(5.5 \times 10^{-13})</td>
<td>(3.01 \times 10^{-11})</td>
<td>0.28</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Vedder shale</td>
<td>(1 \times 10^{-16})</td>
<td>(2 \times 10^{-14})</td>
<td>0.1</td>
<td>3.5</td>
<td>54</td>
</tr>
<tr>
<td>Tunemy</td>
<td>(2 \times 10^{-16})</td>
<td>(2 \times 10^{-16})</td>
<td>0.07</td>
<td>3.5</td>
<td>54</td>
</tr>
</tbody>
</table>

\(\beta_v\) is the pore compressibility, \(\alpha\) is the van Genuchten parameter for entry capillary pressure, and \(m\) is the van Genuchten parameter for pore-size distribution (van Genuchten, 1980).
3.1. Fluid flow simulations

This study uses the basin-scale reservoir model developed and used in previous studies (Birkholzer et al., 2011; Zhou and Birkholzer, 2011; Wainwright et al., 2013). The three-dimensional (3D) mesh extends to a depth of 3.5 km, and 84 km and 122 km in the eastern and northern directions, respectively. It is composed of 64,214 elements representing the 11 formations, from the crystalline basement to the shallow aquifer. As mentioned before, the storage formation (the Vedder sandstone) is divided into three sand model layers and three alternating shale layers (Vedder sand and Vedder shale). We explicitly account for the Greeley, PPC and New Hope faults in the fluid flow simulation grid (Fig. 2a) as vertical, 500 m wide zones. In addition to the model presented by Wainwright et al. (2013), we consider a hypothetical scenario in which two faults bound the reservoir to the northwest and southeast (faults in blue in Fig. 2a) to increase the pressure buildup and favor the PPC fault reactivation. In the basin-scale reservoir model, all the faults are assumed impermeable except the PPC fault (in red in Fig. 2a), which has an anisotropic permeability caused by an low-permeability fault core (acting as an impermeable barrier) and a permeability within the damage zone (along both strike and dip) two orders of magnitude higher than the adjacent host rock permeability (Table 1). Also, the porosity of the PPC fault is assumed to vary according to the initial properties of the adjacent host rock sedimentary layers. These assumed variations in permeability and porosity for the PPC fault are based on geologic observations and field studies on faults as reported in the literature. In high-porous layers, deformations are accommodated by micro-mechanisms at the grain scale leading to a progressive decrease in the porosity of the intact rock toward the fault core (Aydin et al., 2006; Tondi et al., 2006). Inversely, in low-porosity layers, deformations are accommodated toward the fault core by increases in fracture porosity and microcrack density, and by displacements along preexisting fractures (Jeanne et al., 2012). Justified by observations of such phenomena, the intact rock porosity is decreased within the initial high-porous layer and is increased within the initial low-porosity layers (Table 1).

The simulation assumes that CO2 is injected into the deep Vedder formation, which is a saline reservoir, in the center of the domain at a distance of more than 7.2 km from the PPC fault. Because of this large distance, we consider an industrial-scale
injection at a substantial rate of 20 million tonnes of CO$_2$ per year for a period of 50 years. In reality, such a high injection rate may not be realistic considering the amount of CO$_2$ produced in this area and also considering the required or regulatory limits on well pressure. Nonetheless, we use such a high injection rate in a compartmentalized reservoir to achieve a sufficient pressure buildup to reactivate the PPC fault, which is the focus of this study.

The multiphase basin-scale flow simulation is performed with the parallel multiphase simulator TOUGH2-MP (Zhang et al., 2008) with the ECO2N module to simulate injection and migration of supercritical CO$_2$ in the brine reservoir. The ECO2N module describes the thermodynamics and thermophysical properties of H$_2$O$-$NaCl$-$CO$_2$ mixtures, including phase transitions and dissolution (Pruess, 2005). We set the initial conditions assuming linear pore pressure and temperature gradients (9.81 MPa/km and 25 °C/km, respectively), with constant hydraulic boundary conditions (i.e. open to fluid flow). The simulation is isothermal, because we assume that CO$_2$ is injected under thermal equilibrium with the storage formation.

### 3.2. Geomechanical stability of the PPC fault

We use the numerical simulator TOUGH-FLAC (Rutqvist, 2011) to investigate the fault reactivation and the associated seismicity during CO$_2$ injection. TOUGH-FLAC links the TOUGH2 (finite volume) multiphase flow and heat transport simulator (Pruess et al., 2011) and the FLAC$^{3D}$ (finite-difference) geomechanical code (Itasca, 2009) for coupled thermo-hydro-mechanical analysis under multiphase flow conditions. This simulator has been successfully used for modeling fault activation associated with CO$_2$ injection in several previous studies (Rutqvist et al., 2007, 2014; Cappa and Rutqvist, 2011a, 2011b, 2012; Mazzoldi et al., 2012; Jeanne et al., 2014; Rinaldi et al., 2014a, 2014b, 2015).

To run a TOUGH-FLAC simulation, two numerical grids, one for each code, are constructed. Here, the TOUGH2 grid is a two-dimensional (2D) model representation of the PPC fault surrounded by 500 m of host rock on both sides of the fault, from 0 to 0.5 km and from 25.3 km to 25.8 km (Fig. 2b). The model is approximately 25 km long, 0.1 m wide and 3.5 km deep and it is discretized by 41,280 rectangular elements having a size of 50 m $\times$ 0.1 m $\times$ 50 m. Every 7 days during 50 years of injection, the pressure and CO$_2$ saturation within the damage zone of the PPC fault are extracted from the basin-scale reservoir model, interpolated into a more refined mesh grid and exported into the TOUGH2 2D grid of the fault. By this approach rupture along the fault has no influence on pressure evolution.

To run a FLAC$^{3D}$ simulation, three numerical grids, one for each code, are constructed. Here, the FLAC$^{3D}$ grid represents the PPC fault core (which has the exact same size as the TOUGH2 2D grid: 41,280 rectangular elements of 50 m $\times$ 0.1 m $\times$ 50 m). The model extends laterally about 25 km by 7.5 km and is 3.5 km deep. It is discretized by 371,520 (=41,280 $\times$ 9) elements (Fig. 2c). Only the fault core (from the surface to 3.5 km depth) is linked to the TOUGH2 2D fluid flow model (which provides the fluid pressurization within the damage zone) during the TOUGH-FLAC simulation. Unfortunately, by this approach the changes in stresses due to the forcing imposed by the expanding reservoir, the caprock and the damage zone due to the pore pressure increase are not considered, only changes in stresses along the fault core is considered. No fluid flow occurs between the fault and the surrounding host rock. This extended part of the 3D model is needed to initialize and to apply the in situ stress state and to allow the fault to slip when rupture nucleates. This part has a Young's modulus of 15 GPa and a Poisson's ratio equal to 0.25. On the top boundary, the ground surface is free to move, whereas stress on the other boundaries follows the lithostatic gradient. To assess how the uncertainty related to the stress state could affect the prediction of the geomechanical stability of the PPC fault during the CO$_2$ injection, we conduct several simulations in which the applied stress acting on the PPC fault is changed according to the range of in situ stress magnitudes and orientation reported from various stress measurements in the region.

1. We simulated the case of a strike-slip stress regime ($\sigma_1 = S_{\text{inmax}}, \sigma_2 = \sigma_3 = \rho gh$, with $\rho$ the rock density, $g$ the acceleration of gravity and $h$ the depth, where we assume that $\sigma_3 = 0.95\sigma_1$), and a reverse stress regime ($\sigma_1 = S_{\text{inmax}}$, where we assume that $\sigma_2 = 1.15\sigma_1$ and $\sigma_3 = S_0$ (Fig. 3a and b).

2. For each stress regime, we perform several simulations where $S_{\text{inmax}}$ is rotated 10° from N0 to N20. When $S_{\text{inmax}}$ is oriented N0, the segments AB and CD of the PPC fault are more critically oriented for shear reactivation than when $S_{\text{inmax}}$ is oriented N20 (the angles between $S_{\text{inmax}}$ and these two segments are 40° and 48° in the first case and 60° and 68° in the second, respectively (Fig. 3c).

3. Finally, for each orientation of $S_{\text{inmax}}$, we perform four simulations where the applied stress varies by changing the ratio $R = \sigma_1'/\sigma_3' = (\sigma_1 - P_3)/(\sigma_3 - P_3)$ from 2.3 to 2.6, where $P_3$ is the pore fluid pressure.

4. In summary, there are four strike-slip stress regimes and four reverse stress regimes with three different orientations of $S_{\text{inmax}}$, leading to a total of 24 scenarios.

In the basin-scale reservoir model, the PPC fault is vertical but in reality this fault dips 60° to the southwest. The simplification of a vertical fault does not have a significant effect on the pressure distribution along the fault but would have a significant effect on the stress distribution within the fault plane. For this reason, to assess the geomechanical stability of the PPC fault, the fault dips 60° to the southwest in the geomechanical model.

### 3.3. Assessment of the induced seismic activity

We consider a finite thickness fault (0.1 m) and use a Mohr-Coulomb elasto-plastic (ubiquitous joint) model with a strain-softening frictional law to model shear slip during fault activation. The strain-softening friction law enables sudden (seismic) slip to be simulated on the fault. When the failure criterion is reached in one element, plastic deformations occur and stresses are transferred to the surrounding elements composing the fault plane, which may or may not fail in rupture depending on the resolved stresses acting on these elements. Therefore, the slip and the size of the rupture area, and consequently the earthquake magnitude, will be influenced by the stress state. This approach allows calculating the seismic moments and magnitudes of slip events. The friction angle changes from an initial value of 31° to a residual value of 24° when the plastic shear strain on the fault core reaches a critical value of 10$^{-5}$. This change in friction (a drop in the coefficient of friction from 0.6 to 0.44) and the strain threshold were chosen to simulate a brittle (slip weakening) fault rheology that results in substantial and distinct seismic slips across areas of fault rupture. The static friction of 0.6 is in agreement with average values at considered depth (Byerlee, 1978), while the dynamic friction was calibrated to avoid unrealistic run-away rupture after activation.

Both the fault and the surrounding rock have a Poisson’s ratio of 0.25 and Young’s modulus of 5 GPa and 15 GPa, respectively. The three segments of the PPC fault AB, BC and CD strike N140°, N095° and N132°, respectively (Fig. 2c). We also assume that there is no seismic activity in the shallow region of our model (above – 500 m), since ruptures that nucleate within this low stress region are inhibited from propagating (Das and Scholz, 1983), corresponding to a displacement hardening friction law.
One geomechanical simulation is performed every week during the 50-year period of injection. To estimate the seismic activity, we compare each geomechanical simulation with the previous one. A seismic event during a simulation corresponds to shear failure (rupture) of cells within the fault plane that have not been activated previously. One or several seismic events can occur depending on the Euclidian distance between the cells that fail. For example, if failure occurs on two adjacent cells (Euclidian distance smaller than $\sqrt{(50\,\text{m})^2 + (50\,\text{m})^2} = 71\,\text{m}$), we consider that a rupture that nucleates on one patch propagates to the second one, representing a single seismic event. Conversely, failures that occur on two cells that are not in contact (Euclidian distance > 71 m) are considered as two separate events. This is illustrated in Fig. 4, which shows the seismic activity for week 1626. First, we look at the rupture distribution at the end of week 1625 (in blue in Fig. 4a and b) to deduce the new areas where the fault has been activated during week 1626 (in red in Fig. 4b) to calculate the associated seismic activity (Fig. 4c). Using this approach, the seismic activity is related only to the propagation of rupture along the fault in areas that were previously stable. The slip occurring in the previously activated area is considered to be aseismic. However, because we look at the rupture distribution only on a weekly basis, there is a possibility that what appears as one event is in reality a cluster of smaller events, which can lead to underestimation of the number of events.

For each event, we calculate the hypocenter location $(x, y, z)$, average slip, slip direction (rake), area of rupture, the average changes in fluid pressure responsible for the event, the seismic moment and moment magnitude, and the normal and shear stresses after rupture. The rake is determined by calculating the angle between the vector displacement and the $x$, $y$ and $z$ axes. The static seismic moment of an event is given by (e.g. Kanamori and Brodsky, 2004):

$$M_o = G A d$$

where $G$ is the shear modulus (2 GPa in our study), $A$ is the rupture area and $d$ is the slip. Moment magnitude is estimated using the equation (Hanks and Kanamori, 1979):

$$M_w = \frac{2}{3} \left( \log_{10} M_o - 16.1 \right)$$

where $M_o$ is in dyne cm ($10^{-7}$ N m).

The normal stress $\sigma$ (MPa) and shear stress $\tau$ (MPa) acting on the fault are...
\[ \sigma = l^2 \sigma_1 + m^2 \sigma_2 + n^2 \sigma_3 \]  
(3)

\[ \tau = \left( (\sigma_1 - \sigma_2)^2 l^2 m^2 + (\sigma_2 - \sigma_3)^2 m^2 n^2 + (\sigma_1 - \sigma_3)^2 l^2 n^2 \right)^{0.5} \]  
(4)

where \( l, m \) and \( n \) are the direction cosines of the normal to the fault plane with respect to the principal stress axes, \( \sigma_1, \sigma_2 \) and \( \sigma_3 \), respectively. At the end of 50 years of injection, once a seismic catalog is created (as shown in Fig. 5), we look at the empirical relation between the frequencies of occurrence and magnitudes of the simulated induced events (Eq. (5)) \( (\text{Gutenberg and Richter, 1954}) \):

\[ \log_{10} N = a - bM \]  
(5)

where \( N \) is the total number of earthquakes per unit time with magnitudes \( \geq M \). The \( a \)-value describes the seismic productivity, which depends on the area and time period of investigation, and the \( b \)-value describes the earthquake frequency-magnitude distribution.

4. Results

4.1. Pressure distribution along the PPC fault

Fig. 6 shows the pore pressure variations along the PPC fault during the injection at 10 years, 20 years, 30 years, 40 years and 50 years and Fig. 7 presents the pore pressure evolution at nine control points located along the three segments of the PPC fault (AB, BC and CD) in the targeted reservoir (top of the Vedder sand), in the upper caprock (Freeman–Jewell) and in an upper reservoir (Olcese) (locations in Fig. 6a). We observe that the pore pressure mostly increases where the targeted reservoir intersects the PPC fault. Indeed, despite that the fault permeability across the caprock is two orders of magnitude higher than the adjacent host caprock permeability, the pore pressure change in the upper reservoir is very limited. After 50 years of injection, the pressure change is approximately 4 MPa in the Olcese reservoir, about 250 m above the targeted reservoir (Fig. 7). Also, in Fig. 7 the curves showing the pore pressure evolution at six control points located on the three segments of the PPC fault in the reservoir formations: Vedder (curves 1–3) and Olcese (curves 7–9) are almost equal despite being located at different distances from the injection well. Inside the caprock (Freeman formation), curve 5 is somewhat different from curves 4 and 6 because of the variations of caprock thickness—only 75 m at point 5 versus 175 m at points 4 and 6. However, this difference in pore pressure variation is less than 1 MPa after 50 years of injection. The homogeneous pore pressure distribution along the fault over time is due to the high injection rate into a compartmentalized and thin (\( \approx 350 \) m) reservoir, and to the high permeability along its strike and dip, which allows for rapid pore pressure diffusion. This observation implies that the difference in seismic activity along the fault is not related to the pore pressure differences. Fig. 6f also shows that the CO₂ at the end of injection is confined within the targeted reservoir and no major leaks occur along the fault during the first 50 years.

Fig. 5. Seismic catalog calculated with \( S_{\text{hmax}} \) oriented N0 and \( s_1'/s_3' = 2.3 \), with (a) a strike-slip faulting regime and (b) a reverse faulting regime.
4.2. Geomechanical stability and induced seismic activity

To investigate how the uncertainties related to the measurements of the in situ stress state affect the seismic activity along the PPC fault, we did a total of 24 geomechanical simulations: 12 considering a strike-slip faulting regime and 12 considering a reverse faulting regime. These results were analyzed first by comparing the locations of the hypocenters of the seismic events (Section 4.2.1) and second by a statistical approach (Section 4.2.2).

4.2.1. Uncertainty on the in situ stress versus seismic event locations

Fig. 8 shows the locations of the seismic events over the range of stress states tested in this work ($S_{H_{\text{max}}}$ oriented N0 and N20, and $\sigma_1/\sigma_3 = 2.3$ and 2) considering both reverse and strike-slip faulting regimes. A first look at Fig. 8 reveals that most of the seismic activity occurs along the segment CD of the fault, which is the farthest from the injection well and not the most optimally oriented for promoting shear reactivation (oriented $48^\circ - 68^\circ$ from $S_{H_{\text{max}}}$ against $40^\circ - 60^\circ$ for segment AB, Fig. 3). The reason for this apparent paradox is that segment CD of the PPC fault intersects the targeted reservoir at the shallowest depth while pore pressure change is homogeneous over all three segments of the fault. Under these conditions, as illustrated in Fig. 9, rupture will nucleate first along segment CD.

Fig. 8a and b shows the results for the two simulations in which both the orientation of $S_{H_{\text{max}}}$ (N) and the $\sigma_1/\sigma_3$ ratio ($R = 2$) are the same, but under different stress regimes: a reverse faulting regime, $\sigma_2 = 1.1S_v$ (Fig. 8a) and a strike-slip faulting regime, $\sigma_2 = S_v$ (Fig. 8b). It appears that this slight variation in $\sigma_2$ strongly influences the location of the seismic activity. Indeed, segment AB is not activated under a reverse faulting regime but it is activated under a strike-slip faulting regime. However, the influence of the stress regime on the event locations decreases with the increase in the $R$ ratio. Segment AB is activated in both cases when $R$ is equal to 2.3 (Fig. 8c and d). This shows that uncertainty in the locations of seismic events that

Fig. 7. Pore pressure variations at nine control points (CP) located on the three segments of the PPC fault AB, BC and CD, within: the targeted reservoir (Vedder formations: curves 1–3), the caprock (Freeman formations: curves 4–6) and the upper reservoir (Olcese formation: curves 7–9).
nucleate on a fault plane related to uncertainties in the stress regime will become less important when the applied stress is close to the frictional strength of the fault. On the other hand, the uncertainty on $S_{\text{Hmax}}$ orientation is very important for assessing the location of a rupture nucleation. Fig. 8e–h show that when $S_{\text{Hmax}}$ is rotated $20^\circ$, no seismic activity occurs along segment AB regardless of faulting regime (reverse or strike-slip) and the applied stress ($R = 2$ or $R = 2.3$). Moreover, with $S_{\text{Hmax}}$ rotation from N0 to N20, segment BC becomes more optimally oriented for shear reactivation and consequently seismic events start nucleating along this part of the PPC fault.

Another interesting observation is when the applied stress is close to the frictional strength of the fault (fault critically oriented: $S_{\text{Hmax}}$ oriented N0 and $R = 2.3$), most of the induced seismic activity occurs outside the reservoir (Fig. 8c and d). Inversely, when the applied stress is far from the frictional strength of the fault ($S_{\text{Hmax}}$ oriented N20 and $R = 2$), the induced seismicity is mostly located within the reservoir (Fig. 8e and f). In the first case, the fault is so close to instability (near critically stressed) that the rupture propagates very easily over a larger area. Therefore, new parts of the fault where the rupture will nucleate are located outside the reservoir. Conversely, when the fault is less critically stressed, ruptures propagate over a smaller area confined within the reservoir.

### 4.2.2. Uncertainty on in situ stress versus seismic response

The simulation results are analyzed using principal component analysis (PCA), which is a statistical technique used to explore and visualize a dataset by emphasizing variations and highlighting strong patterns (Jolliffe, 2002). PCA can be thought of as finding the principal components we can visualize a dataset by emphasizing variations and highlighting strong patterns (Jolliffe, 2002). PCA can be thought of as finding the principal components we can use to evaluate the differences in the results among the 24 geomechanical simulations. Note, however, that the evolution of the calculated $a$ and $b$ values cannot be extrapolated to the real world, because in our simulation, the

<table>
<thead>
<tr>
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### 4.2.2. Uncertainty on in situ stress versus seismic response

The simulation results are analyzed using principal component analysis (PCA), which is a statistical technique used to explore and visualize a dataset by emphasizing variations and highlighting strong patterns (Jolliffe, 2002). PCA can be thought of as finding the principal components we can use to evaluate the differences in the results among the 24 geomechanical simulations. Note, however, that the evolution of the calculated $a$ and $b$ values cannot be extrapolated to the real world, because in our simulation, the

### Table 2

Seismic attributes obtained from the 12 geomechanical simulations under a reverse faulting regime and used in the factorial analyses.

<table>
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<tr>
<th>$S_{\text{Hmax}}$</th>
<th>$\sigma_1/\sigma_3$</th>
<th>Time (yr)</th>
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<th>$A_{\text{tot}}$ (m$^2$)</th>
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fault has homogeneous strength and stress properties (same friction coefficient and same ratio between normal and shear stresses), whereas in reality the a and b values are strongly influenced by the heterogeneous topography (and hence resolved stress distribution) and distribution of fracture properties of faults in nature (e.g. Mogi, 1962; Warren and Latham, 1970).

Tables 4 and 5 present the results of the factorial analyses performed on the simulated data in Tables 2 and 3. The PCA results for both datasets are very similar and only three axes (or three principal components) are needed to explain 93% of the underlying structure in the dataset (axes 1, 2 and 3, explain ~65%, ~20% and ~10%, respectively). The first axis is related to the positive correlations between the variables $S_{Hmax}$ time, and $M_{Tot}$, and to the negative correlation with the variables $N$, $a$, $A_{Tot}$, and $M_{Tot}$ in the case of Table 4 for the reverse faulting regime. This means that when $S_{Hmax}$ rotates from N0 towards N20, the angle between $S_{Hmax}$ and the fault increases (from 40° to 60° for segment AB for example), and the fault becomes less optimally oriented for shear reactivation. Therefore, we can observe that:

1. The time between the beginning of the injection and the first nucleation of a seismic event increases. For example, in the case of a strike-slip faulting regime with $R = 2.3$, the time is 11.5 years with $S_{Hmax}$ oriented N0 and 22.4 years with $S_{Hmax}$ oriented N20.

2. The total number of seismic events (and therefore the $a$-value) decreases. For the same example as before, with $S_{Hmax}$ oriented N0 and N20 there are 2670 events ($a = 3.1$) and 1037 events ($a = 2.49$), respectively.

3. The $b$ values tend to decrease, meaning that there are fewer smaller events and more larger events. This is why we observe that the total seismic moment released during injection increases when $S_{Hmax}$ rotates from N0 to N20. For the same example as before, with $S_{Hmax}$ oriented N0, $b = 1.24$ and $M_{Tot} = 2 \times 10^{30}$ N/m, while with $S_{Hmax}$ oriented N20, $b = 0.93$ and $M_{Tot} = 1 \times 10^{21}$ N/m.

(4) The total rupture area decreases. For $S_{Hmax}$ oriented N0 and N20, the total rupture area of the fault is $4 \times 10^{11}$ m² and $1 \times 10^{11}$ m², respectively.

Two additional observations can be made from this analysis. First, with rotation of $S_{Hmax}$ from N0 to N20, both $a$- and $b$-values tend to evolve from high towards low values (Fig. 10), such that the frequency–magnitude relationships intercept the magnitude axis at about the same value (about magnitude 3, Fig. 10). This means that, in terms of a probabilistic hazard forecast, an uncertainty of 20° on the $S_{Hmax}$ direction does not affect the prediction of the magnitude of the largest induced event. This is why the maximum magnitudes calculated during all of the geomechanical simulations are about the same ($M_w$ ranging between 3 and 3.5). The second observation is that the size of the total rupture area is inversely correlated with the total seismic moment released during injection. Evidently, according to Eq. (1), when the applied stress is close to the frictional strength of the fault ($S_{Hmax}$ oriented N0, $R = 2.3$), earthquakes nucleate and propagate across larger areas but have lower slips. On the other hand, when the fault is less critically stressed, events rupture smaller areas but have larger slips. This is why, as seen previously in Section 4.2.1, when the fault is optimally oriented and near critically stressed, most of the induced seismicity occurs outside the reservoir and vice versa.

Large values for the second axis in the PCA correspond to the positive correlation between the total seismic moment released during injection ($M_{Tot}$) and the maximum seismic magnitude calculated (max $M_w$), which is related to Eq. (1). This trend (the principal component) is more or less affected by the $\sigma_1' / \sigma_3'$ ratio. For the same $S_{Hmax}$ orientation, the higher the $\sigma_1' / \sigma_3'$ ratio is, the closer the applied stress is from the frictional strength of the fault and, as seen before, there are more small events than large events. It is why,
in some cases, we sometimes observe that the calculated maximum seismic magnitude is slightly smaller than that when the $\sigma_1/\sigma_3$ ratio is close to 2.3. Still for the same example (strike-slip regime and $S_{\text{max}}$ oriented N0) for $\sigma_1/\sigma_3 = 2$ and 2.3, the maximum seismic magnitudes are 3.19 and 2.29, respectively (see Table 3, row N0).

The second series of factorial analysis was performed on the seismic catalog obtained after each simulation. Therefore, 24 PCAs were realized on the 24 seismic catalogs calculated in this study. In these factorial analyses, each seismic event is characterized by: depth ($z$), area of rupture ($A$), average slip ($\text{Slip}$), rake, characterized by the angles $\theta_s$, $\theta_c$ and $\theta_q$ between the axis $x$, $y$ and $z$ and the slip vector, the average change in fluid pressure inducing the seismic event ($\Delta P$), $M_w$ and the normal ($\sigma$) and shear ($\tau$) stresses after rupture. Globally, the 24 PCAs show two main types of behaviors, so we only present two analysis results, both for a reverse faulting regime and with $S_{\text{max}} = 0$. The first one is with $\sigma_1/\sigma_3 = 2$ (Table 6), and the second one with $\sigma_1/\sigma_3 = 2.3$ (Table 7). Generally, three axes (or three principal components) explain 75% of the underlying structure in the seismic catalogs.

Axis 1 highlights the positive correlation between the changes in pore pressure and the ambient stress. This means that, for the same deviatoric stress, a higher change in pore pressure is needed to induce a seismic event when the stresses are more elevated. Also, the major difference found between the 24 PCAs (between Tables 6 and 7) is that when the applied stress is close to the frictional strength of the fault, then the rupture area is also correlated to the changes in pore pressure and to the normal and shear stresses acting on the fault.

Axis 2 shows the positive correlation between $z$ and $\theta_q$ and a negative correlation between $z$ and $\theta_c$. These correlations show that when the depth increases, the angle between the displacement vector and the $y$ axis decreases ($y$ axis is either normal (segment $AB$) and almost normal (82° on segment CD) to the fault). And inversely, the angle between the displacement vector and the $x$ axis increases with depth. This means that the normal component of the displacement vector decreases and its shear component increases with depth.

Finally, the third axis shows a correlation between the slip, magnitude and the angle between the displacement vector and the $z$ axis: $\theta_s$, and occasionally with $\theta_c$.

5. Summary and conclusions

This study is based on a hypothetical industrial-scale carbon sequestration project in the Southern San Joaquin Basin in California. Our goals were (1) to assess the geomechanical stability of the Quaternary PPC fault zone mapped at the surface, and (2) to investigate how the uncertainties related to the faulting regime, the $S_{\text{max}}$ orientation and the $\sigma_1/\sigma_3$ ratio, could influence our results.

Concerning the assessment of the PPC fault zone stability, we have assumed very unfavorable conditions for the fault stability, with a very high injection rate in a reservoir bounded by impermeable faults. Despite these conditions, the maximum earthquake magnitude simulated on the fault is around 3.5. However, we have not varied the rock and fault elastic parameters and the friction law in our simulations. These parameters control the amount of strain energy that can be stored during the inter-seismic period of strain accumulation. More work is needed to investigate how these different parameters could influence the seismic moment and the seismic activity calculating in our simulations.

In this study, our main finding is that the uncertainties related to $S_{\text{max}}$ direction and $\sigma_1/\sigma_3$ ratio that describe the stress regime measured with in situ measurements (wellbore breakout and hydraulic fracture tests) have a negligible effect on the maximum magnitude of an induced event. Indeed, the maximum magnitude is approximately the same in all our geomechanical simulations. On the other hand, the uncertainty related to the $S_{\text{max}}$ direction and applied stress magnitude have a strong influence on the prediction of the elapsed time between the beginning of injection and the initiation of seismicity, the seismicity rate, and the locations of the earthquakes along different segments of the fault, all of which influence seismic hazards. Uncertainties in these two factors also influence whether induced events occur on portions of faults inside or outside the targeted reservoir.

Table 6

Results of the factorial analysis made on the seismic catalog calculated during the simulation under a reverse faulting regime, $S_{\text{max}} = 0$ and $R = 2.3$, with the values in bold type showing the variables with a strong correlation with the axis, the percentage of explained variance, the accumulated percentage of explained variance (Tot.), and the significance of each axis.

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Table 7
Results of the factorial analysis made on the seismic catalog calculated during the simulation under a reverse faulting regime, $S_{\text{res}} = N_0$ and $R = 2$, with the values in bold type showing the variables with a strong correlation with the axis, the percentage of explained variance, the accumulated percentage of explained variance (Tot.), and the significance of each axis.

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Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References

Itasca. FLAC3D v4.0, fast Lagrangian analysis of continua in 3 dimensions, user guide. Minneapolis, MN, USA: Itasca Consulting Group; 2009.
Jolliffe IT. Principal component analysis. 2nd ed. New York, USA: Springer; 2002.
Rutqvist J, Cappa F, Rinaldi AP, Godano M. Modeling of induced seismicity and ground vibrations associated with geological CO2 storage, and assessing their...


Vilarrasa V, Carrera J. Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO2 could leak. Proceedings of the National Academy of Sciences 2015a;112(19):5938–43.

Vilarrasa V, Carrera J. Reply to Zoback and Gorelick: geologic carbon storage remains a safe strategy to significantly reduce CO2 emissions. Proceedings of the National Academy of Sciences 2015b;112(33):E4511.


Zoback MD, Gorelick SM. To prevent earthquake triggering, pressure changes due to CO2 injection need to be limited. Proceedings of the National Academy of Sciences of the USA 2015;112(13):E4510.

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