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GHGT-12

## Improving our knowledge on the hydro-chemo-mechanical behaviour of fault zones in the context of CO<sub>2</sub> geological storage

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### Abstract

A possible risk of geomechanical nature related to deep injection of CO<sub>2</sub> is the shear reactivation of faults, hence potentially leading to the creation of new leakage pathways and eventually inducing earthquakes felt at the surface. Current practices to evaluate fault stability in the domain of CO<sub>2</sub> storage still remain limited regarding two issues: 1. Faults are complex and heterogeneous geological systems, which do not correspond to discrete surfaces as already postulated by many authors. Reservoir-scale faults in a priori low-deformed reservoirs targeted for CO<sub>2</sub> storage can present high complex architecture, which might influence the hydro-mechanical behaviour of the fault system; 2. Chemical interactions (dissolution and precipitation processes, chemically-induced weakening, etc.) between CO<sub>2</sub>-enriched brine and the minerals constituting the fault zone can affect the mechanical stability and the transport properties of the faulted/fractured system. The research project FISIC ([www.anr-fisic.fr](http://www.anr-fisic.fr), funded by the French National research Agency) intends to overcome those limitations by accurately modelling the hydro-chemo-mechanical complexity of a fault zone. The main goal is to improve the stability analysis of a fault both undertaking pressure increase and alteration due to the presence of an acidic fluid. The progress of this research project is presented here.

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## 1. Introduction

A primary criterion for careful selection of CO<sub>2</sub> storage sites relies on the distance of the injection zone to potentially seismically-active large faults ([1]) in order to minimize the risk of fault slip re-activation and triggered seismicity ([2]) induced by pore pressure increase due to CO<sub>2</sub> injection. Such major faults can be identified by seismic data, whereas small-scale fractures are characterized by well data. However, structures at intermediate spatial scales, i.e. at the reservoir scale, can also exist, so that reservoirs targeted for CO<sub>2</sub> storage, even though expected to be located in low-deformed tectonic settings, can still present reservoir-scale faulted structures. Such faulting at the medium sub-seismic scale can play a significant role regarding several risk issues related to the injection-induced fluid pressure increase: enhancing fluid flow or producing compartmentalization ([3]), loss of integrity in reservoir–caprock systems, ([4]), potentially associated with triggered seismicity and generation of leakage pathways ([5]) that may lead to the contamination of fresh water aquifers.

Several methods exist to model hydro-mechanical behaviour of fault zones. A first “conventional” approach aims at evaluating the fault response by directly post-processing the results of the large-scale coupled hydro-mechanical simulations (e.g., [4]). This consists of: i) estimating the changes of the effective stress field in the reservoir-caprock system during CO<sub>2</sub> injection; ii) computing changes of shear and normal stresses acting on the fault plane; and iii) comparing them to a fault reactivation criterion. However, this approach does not account for the effects of the presence of the fault on the stress and pressure field in the surrounding rock matrix. More sophisticated (and physically more realistic) modeling strategies have been proposed, which explicitly integrate the fault zone as a distinct element in the large-scale simulation, i.e. by representing it as a linear discontinuity with various hydraulic and mechanical properties (e.g., [2]). From a CO<sub>2</sub> storage perspective, such a model still remains limited regarding two issues:

- Faults are complex and heterogeneous geological systems, which do not correspond to discrete surfaces as already postulated by many authors ([6] and references therein). A fault zone is composed of an inner core made of fine material, often impermeable, and where slip is concentrated. It is surrounded by an outer damage zone that often acts as a hydraulic pathway, because of the presence of a fracture network, whose characteristics (fractures’ orientation, connectivity, lengths, density, number of fractures’ families, etc.) depend on the distance to the core ([7]);
- Chemical interactions (dissolution and precipitation processes, chemically-induced weakening, etc.) between CO<sub>2</sub>-enriched brine and the minerals constituting the fault zone can affect the mechanical and transport properties of the faulted/fractured system (e.g., [8]). In particular, chemo-mechanical processes can either stabilize the system if the compaction rate is increased or destabilize it if new micro-fractures are created.

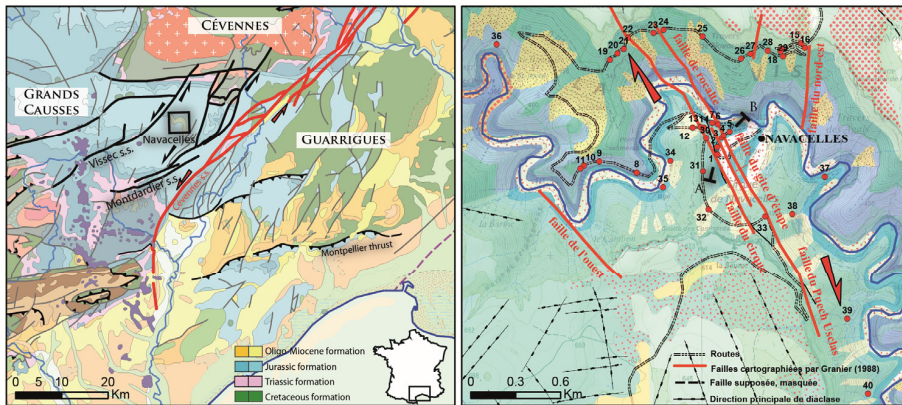
The research project FISIC ([www.anr-fisic.fr](http://www.anr-fisic.fr), funded by the French National research Agency) intends to overcome those limitations by accurately modelling the hydro-chemo-mechanical (HCM) complexity of a fault zone. The main goal is to provide appropriate theoretical and numerical models for accurate evaluation of fault stability in the context of CO<sub>2</sub> geological storage, i.e. improving the stability analysis of a fault both undertaking pressure increase and alteration due to the presence of an acidic fluid. Three questions are addressed and the progress regarding each of them is presented in the present communication:

- How to represent faults and fractures in a tectonic setting, which has a priori been selected far from major potentially seismically-active faults, i.e. a moderate-to-low-deformed setting;
- What is the impact of the fault zone's complex architecture on its hydro-mechanical behaviour? And if so, is it significant in terms of induced seismicity?
- What are the dominant chemo-mechanical processes resulting from aqueous CO<sub>2</sub> in fractured/faulted systems?

## 2. Complexity of fault zones in reservoirs targeted for CO<sub>2</sub> storage

A carbonate outcrop, in a region with low deformation, was chosen as an analogue of a CO<sub>2</sub> repository reservoir. Geological surveys were conducted at the Cirque de Navacelles located in the late Jurassic platform carbonates of Languedoc (southern France). The tabular Mesozoic carbonate series from middle Oxfordian to Uppermost Jurassic are mainly constituted of almost unfossiliferous lithographic limestones, sometimes partially dolomitized, and rhythmic alternations of small banks of mudstone and thin clayey horizons. The plateau is now deeply incised from over 350 m depth by late Miocene canyons, allowing the exceptional observation of the vertical distribution and variations of the fault structures.

A)



B)

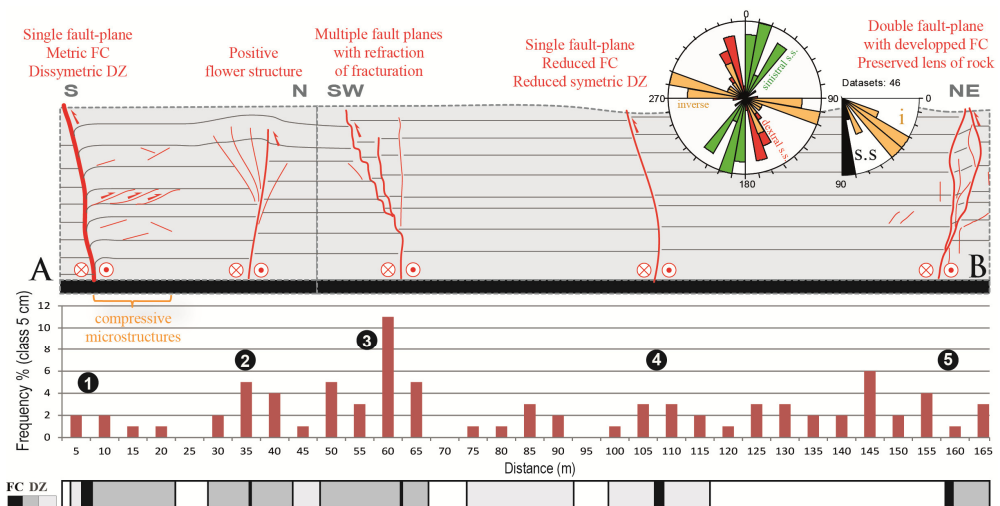


Fig. 1. (A) Regional (left) and local (right) geological and tectonic setting of the studied site of the Cirque of Navacelles. Numbers refer to the investigated outcrops. s.s. indicate strike-slip fault. (B) Detailed structural mapping across the Navacelles fault corridor revealing a large diversity of the fault architectures present at the reservoir scale (the outcrop is in average 6-m thick). Data orientation (azimuth and dip) are synthesized on the rose diagram for dextral (red), left-lateral (green) strike –slip and inverse (orange) faults. Adapted from [9].

The studied fault systems are located just north of the Cevennes major fault, which separates the tabular “Grands Causses”, less affected by the Eocene Pyrenean tectonics, and more to the SE the faulted “Garrigues” area. The analysed region is bounded by two kilometric regional faults corresponding to NE-SW left-lateral strike-slip faults: the Vissec and Montdardier faults. Hence, they delimit an a priori “deformation-preserved” compartment which has accommodated low-to-moderate tectonic deformation (Fig. 1A).

Nevertheless, in the field, we have identified and characterized numerous different fault structures at the reservoir scale, which do not correspond to discrete surfaces: the most prominent local structure is the NW-SE dextral strike-slip fault corridor of Navacelles. This zone exhibits several fault cores (denoted FC), mainly corresponding to NW-SE dextral major strike-slip fault, and damage zones with variable thickness, texture and fault rock properties (Fig. 1, adapted from [9]). At smaller scale (cm), there are also compressive fractures which run in a N100° direction, heterogeneously distributed in the cross-section. The magnitude of horizontal displacements could be estimated at around 40 m for around 3 m of cumulative vertical displacement across the section.

This study underlines the complexity of the reservoir-scale fault zones, whether in terms of FC geometry (curvature, number of branches) or in terms of width and asymmetry of the damage zone. In particular, it should be noticed that all the fault zones at the study site were characterized by the typical “damage zone – fault core – damage zone” structure, but symmetry of the damage zone (denoted DZ) was rarely observed (Fig. 1B, structures on the left-most part) as also reported by numerous studies (e.g. [10])

### 3. Influence of the fault zone's architecture complexity on the fault stability

In this section, we question whether the dissymmetry in the internal structure of the fractured damage zone DZ may play a role in the induced seismicity during deep injection. Here, we focused on “blind” 1,000-m-long normal faults (with shear displacement <10 m), which can hardly be detected using conventional seismic surveys, but might potentially induce seismicity felt on surface ([11]). The fault system was assumed to follow the “conduit-seal” model described by [12].

The question is numerically investigated by using 2-D plane-strain finite-element simulations of a 1,500-m-deep fluid injection (modeled by a constant increase of pore pressure of 10 MPa) into a porous reservoir by considering a synthetic storage system as depicted in Fig. 2A. Summary of the materials' properties is provided in Table 1. Initial stress state is defined by  $\sigma_H = 0.70 \times \sigma_v$ . A parametric study was undertaken by varying the width values of the hanging wall DZ (Fig. 2B), whose properties (elastic modulus and intrinsic permeability) vary as a power-law function (with exponent  $df$ ) of the distance to FC. The field equations were solved through fully coupled hydro-mechanical simulations using the finite element code Code\_Aster ([www.code-aster.org](http://www.code-aster.org)), whereas materials' properties update (permeability and coefficient of friction) as a function of plastic shear strain was conducted in a sequential manner. Full details are provided in (Rohmer, 2014).

This simulation-based study revealed the key role of a highly-fractured thick damage zone (degree of fracturing varying  $df$  from 1-low to 3-high), which both enhances the extent of the rupture area (Fig. 2C) and the slip magnitude (Fig. 2D). This could eventually induce a low-to-moderate earthquake ( $M \sim 2.0$ ) given the assumptions made on the fault system's characteristics (arbitrary chosen fault dimensions in the out-of-plane direction of 1km) and rupture behaviour (2-D static numerical simulations). This could not have been predicted by neglecting the thickness of the damage zone as it is done in traditional fault stability analysis. Therefore, this result supports the justification for deeper characterization of such blind faulted systems either through detailed mapping and microstructural observations on outcrops in geological settings of comparable stratigraphy, lithology and facies to those found at depth or through advanced seismic surveys combining well data, tectonic deformation history interpretation.

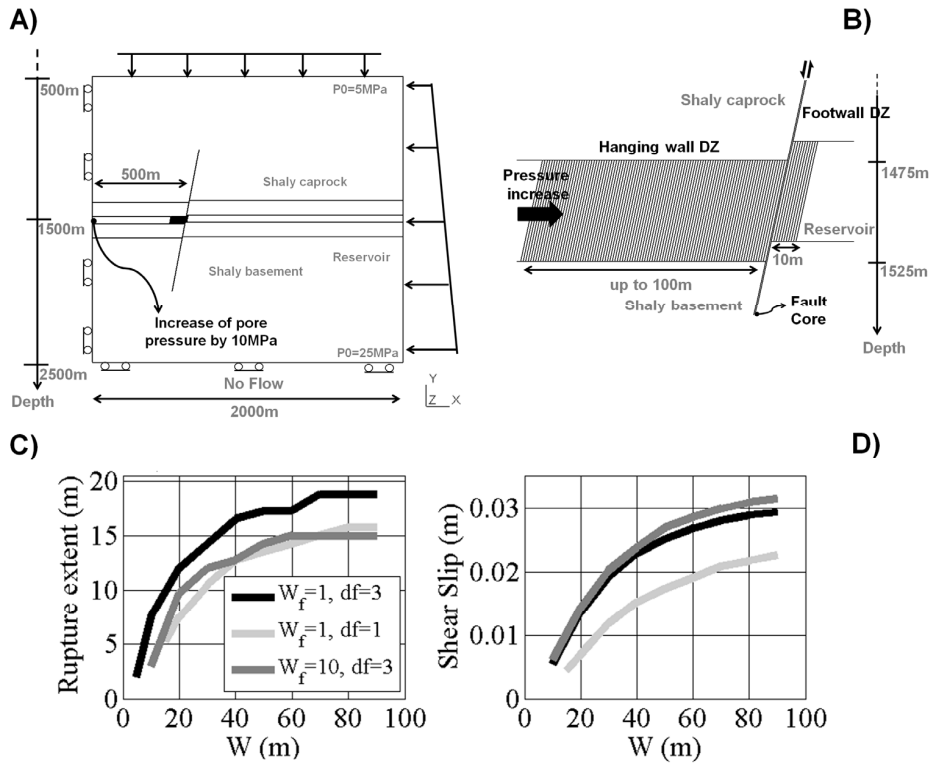


Fig. 2. (A) Model geometry and boundary conditions; (B) Discretization of the hanging wall's and footwall's DZ into 1-m-thick parallel zones; Relationship between the thickness  $W$  of the hanging wall's DZ and the spatial extent of rupture area along the fault plane (C); the average slip over the rupture area (D).  $W_f$  corresponds to the width of footwall DZ and  $df$  corresponds to the degree of fracturing of the hanging wall DZ. Adapted from [13].

Table 1. Properties of rock formations used in the numerical simulations of [13].

Property	Overburden	Caprock	Reservoir	Basement	Core
Young's modulus (GPa)	15	5	15	35	12
Poisson's ratio (-)	0.30	0.25	0.30	0.30	0.30
Intrinsic permeability (m <sup>2</sup> )	10 <sup>-13</sup>	10 <sup>-19</sup>	10 <sup>-13</sup>	10 <sup>-16</sup>	10 <sup>-17</sup>
Porosity (%)	15	1	15	15	1

#### 4. CO<sub>2</sub>(aqueous)-induced effect in a fractured system

The point is addressed at laboratory scale focusing on two effects (potentially combined) related to dissolved CO<sub>2</sub> and to the reservoir fluid chemistry composition. Two fracturing mechanisms were investigated: i) slow growth of cracks (subcritical fracturing) and their potential healing; ii) chemical degradation of mechanical properties such as fracture toughness (property which describes the ability of a material containing a crack to resist fracture).

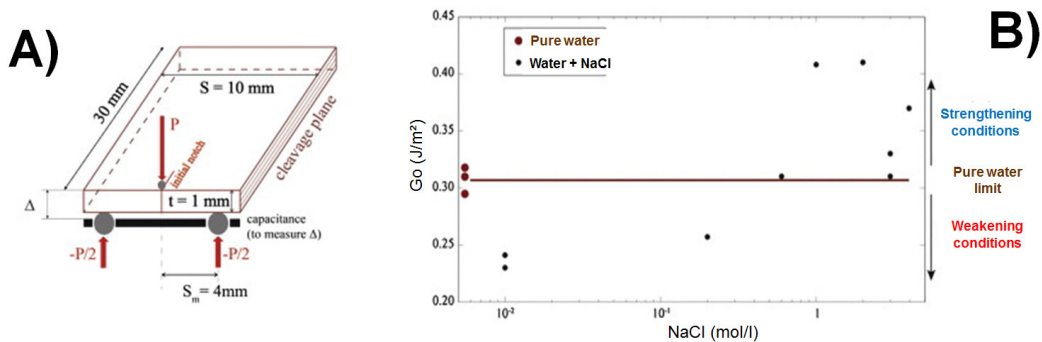


Fig. 3. (A) Schematic view of the double-torsion apparatus: the calcite sample is exposed to fluid with different salinities; (B) Values of the energy threshold  $G_0$  determining the onset of crack subcritical propagation as a function of NaCl concentration. The red line corresponds to the average pure water reference ( $G_0=0.31 \text{ J/m}^2$ ). Adapted from [14].

The first fracturing mechanism is studied using a double-torsion technique (see sketch of the lab experiment in Fig. 3A) to measure the effect of fluid chemistry on the slow propagation of cracks in calcite single crystals at room temperature (see [14]). Time-lapse images and measurements of force and load-point displacement allowed accurate characterization of crack velocities ( $10^{-8}$  to  $10^{-4}$  m/s) as a function of elastic energy-release rates. Different fluid compositions, varying  $\text{NH}_4\text{Cl}$  and NaCl concentrations were used. Rostom et al. [14] showed the presence of a threshold in fluid composition, separating two regimes: weakening conditions where the crack propagation is favored, and strengthening conditions where crack propagation slows down as shown in Fig. 3B. Keeping in mind that most reservoirs targeted for  $\text{CO}_2$  storage are saline, this experimental study highlights the key role of salt content in the stabilization or destabilization of the reservoir depending on its concentration.

The second mechanism is investigated by focusing on an analogue for rock formations targeted for  $\text{CO}_2$  storage, namely an oolitic limestone (porosity of 14.5%) “Pierre de Lens”, composed of 99% of calcite. Suhett-Helmer [15] developed the following protocol: rock samples resided for a time period of four weeks in contact of dissolved  $\text{CO}_2$  in a batch reservoir at conditions of  $60^\circ\text{C}$  and 15 MPa. A series of different mechanical lab tests, including Central Crack Brazilian Disc (CCBD) and Semi-circular Bend (SCB) have been performed on both intact and degraded samples to evaluate the mode I (tensile failure) rock fracture toughness (Fig. 4). These experiments have been coupled with advanced digital image correlation analysis for evaluation of the fracture toughness ([16]).

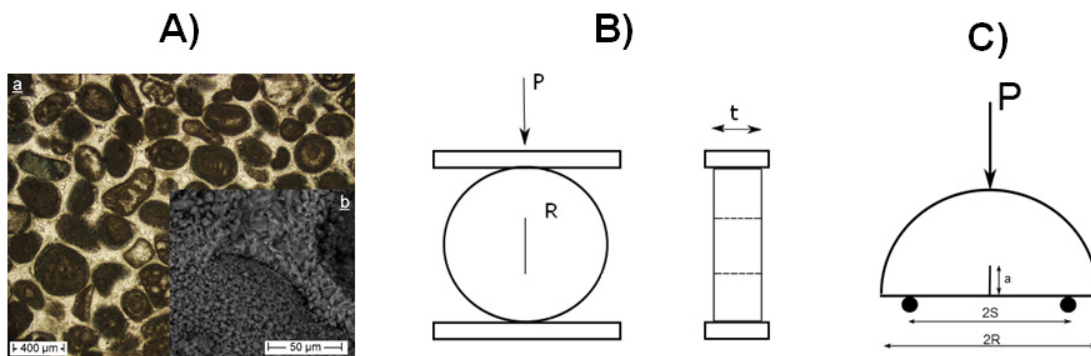


Fig. 4. (A) Microstructure of the oolitic limestone “Pierre de Lens” observed with (a) optical microscope and (b) ESEM ([18]); Schematic view of: (B) Central Crack Brazilian Disc test; (C) Semi-circular Bending test used by Suhett-Helmer (2014) for measuring the fracture toughness in mode I.

The experimental results revealed a moderate effect of dissolved CO<sub>2</sub> on rock fracture toughness with a decrease of about 10% for the studied degradation conditions (4 weeks in dissolved CO<sub>2</sub>, 60°C, 15MPa) (Table 2). This study is still ongoing and three issues are currently tackled: i. the effect chemical degradation on mode II (shear-failure) fracture toughness ; ii. the effect of confinement; iii. influence of water-saturation on the rock fracture toughness.

Table 2. Laboratory results of the effect of dissolved CO<sub>2</sub> on the fracture toughness of the Oolitic limestone (Pierre de Lens), Adapted from [15,16]

Type of tests	Number of samples	Mode I rock fracture toughness, $K_{IC}$ (MPa.m <sup>0.5</sup> )		
		Mean	Min	Max
SCB on intact sample	14	0.65	0.51	0.77
SCB on degraded sample	14	0.58	0.46	0.69
CCBD on intact sample	11	0.61	0.55	0.68
CCBD on degraded sample	4	0.58	0.54	0.66

### Concluding remarks and further work

Regarding the issue of fault architecture, the first investigations ([9]; [13]) revealed the key role of the damage zone (surrounding the fault core) in the size of the induced earthquake during injection (here focusing on blind undetected normal faults). To date, an ideal evolution of the damage zone's properties with the distance to the fault core has been assumed. An important question is then related to the fractures' organization within the damage zones of faults, i.e. their spatial distribution, which might influence such properties and eventually the fault stability during injection. To address this problem, a geostatistical approach is currently conducted based on observations of fault structures at Navacelles ([17]).

Regarding the issue of CO<sub>2</sub>(aqueous)-induced degradation, the first investigations ([14]) the key role of the composition of the fluid on the slow crack propagation. Future work should focus on the combined effect of CO<sub>2</sub>(aqueous) and fluid composition on crack propagation. On the other hand, the experimental work of [15,16], though requiring further investigations, suggest that the strength of carbonate rock materials are moderately influenced when exposed to dissolved CO<sub>2</sub> (under batch conditions, i.e. without percolation).

Those research studies (current and ongoing) ultimately aim at providing scientific foundations to decide on the necessity for the integration of such HMC processes in current practices for fault stability in the domain of CO<sub>2</sub> storage.

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