Structural and hydraulic properties of a small fault zone in a layered reservoir

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Abstract. This paper focuses on a small fault zone (too small to be detected by geophysical imaging) affecting a carbonate reservoir composed of porous and low-porous layers. In a gallery located at 250-m depth in the Underground Low Noise Laboratory, hydraulic properties of a 20-m thick section of the reservoir affected by the studied fault are characterized by structural measurements and by a hydraulic injection in boreholes. Main result is that the damage zone displays contrasted permeability values (up to two orders of magnitude) inherited from the differential alteration of the intact rock layers. To characterize the impact of these hydraulic properties variations on the flow of fluids, numerical simulations of supercritical CO_2 injections were performed with the TOUGH2 code. It appears, the permeability variations inside the fault zone favor the appearance of high fluid overpressure located in the layers having the highest permeability and storativity.

1. Introduction

In this paper we focus on a small fault zone. This kind of fault can play a tremendous role in loss of integrity of the reservoir-caprock systems related to the fluid pressure increase generated by a carbone dioxide (CO_2) geological storage. Fault zones can act either as barriers or conduits for fluid circulations [1]. There are strong interactions between fault zones architecture and their hydraulic properties. Faults zone are composed by a highly fractured volumes (i.e. the fault damage zones) encompassing a core zone. In the fault damage zone, the permeability is mainly governed by the fracture network. In porous formations, the deformations are mainly accommodated at the matrix scale leading to a porosity reduction [2] and by few fractures development. Inversely, in low porosity formations, fault damage zones are characterized by a high fracturing degree leading to an increase in permeability [3]. In the fault core, the permeability is influenced by the presence of fault gouges leading to a significant permeability drop. When fluids are present in fault zones, they can escape or accumulate depending on their hydraulic behavior. In this last case, the appearance of a fluid pressurization can facilitate the fault rupture. Here, we focus on small fault zone hydraulic properties affecting carbonate series. The questions that we address are: (1) how do the hydraulic properties evolve? (2) Can the fault zone architecture favor the appearance of fluids overpressure?
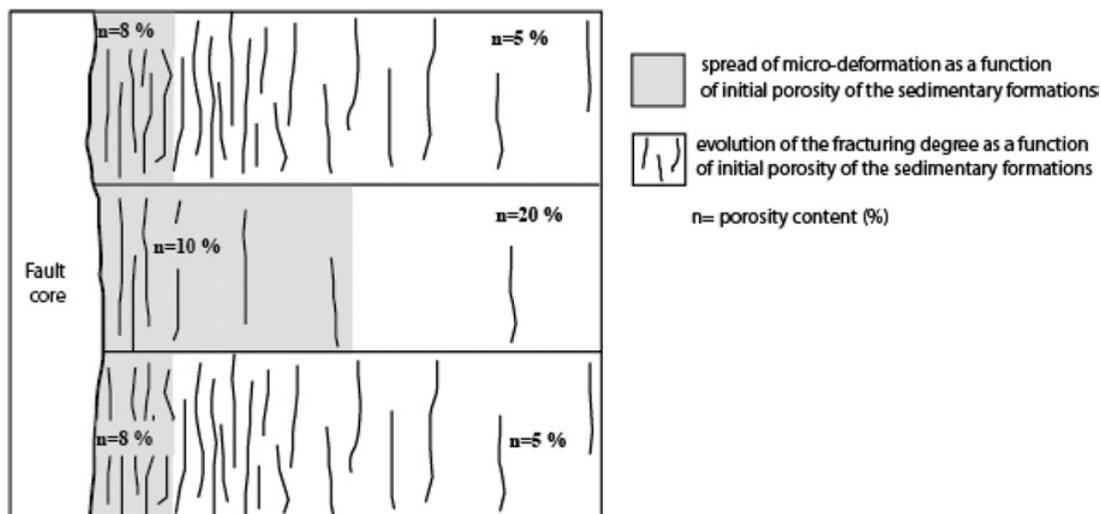
Figure 1. Conceptual model of the porosity variations along the fault zone in a carbonate reservoir.

2. Fault zone structural properties

We focused on a N030 fault that we investigated over a 35-m × 4-m × 26-m volume. The explored stratigraphic sequence is composed of three mechanical units: a porous layer ($\phi = 20\%$) with few fractures intercalated between two low-porosity highly fractured layers ($\phi = 3\%$). In the low-porosity layers, the fracturing degree extends from the fault core over a distance of 17-m. In the porous layers, there is a rapid attenuation of the fracture porosity over a distance of 5-m related to an important accommodation of the deformations by micro-mechanisms resulting in a progressive decrease in the micro-porosity to 10%. The fault core is composed of a fault gouge. From these observations, a porosity conceptual model was proposed: in low-porosity layers, the macro- and micro-fracture porosities increase toward the fault core; whereas in the porous layers, the micro-porosity decreases toward the fault core and the fracture porosity increases slightly very close to the fault core (Fig. 1).

3. Experimental and numerical protocol

Three wells located at different distances from the fault core to the host rock (5-m, 14-m and 18-m relative to the main fault plane) and the "outcropping" gallery walls allow to study the evolution of the deformation of the 20-m thick carbonate series intersected by the fault zone. The objectives were to highlight the relationships between the fault zone architecture and the hydraulic properties evolution. The hydraulic properties were evaluated with hydraulic injection tests in wells. These tests were analyzed with the numerical code TOUGH2 and compared to the rock mass properties describe by using the Q-value geological method [4]. The Q-value is defined as:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \tag{1}$$

where RQD is the percentage of intact drill-core segments ≥ 100 mm in length in a selected domain (a RQD $< 25\%$ indicates very poor rock quality, 25–50% indicates poor rock quality and 50–75% indicates fair rock quality), J_n is the rating for the number of joint sets (9 for 3 sets, 4 for 2 sets, etc.) in the same domain, J_r is the rating for the roughness of the least favourable of these joint sets or filled
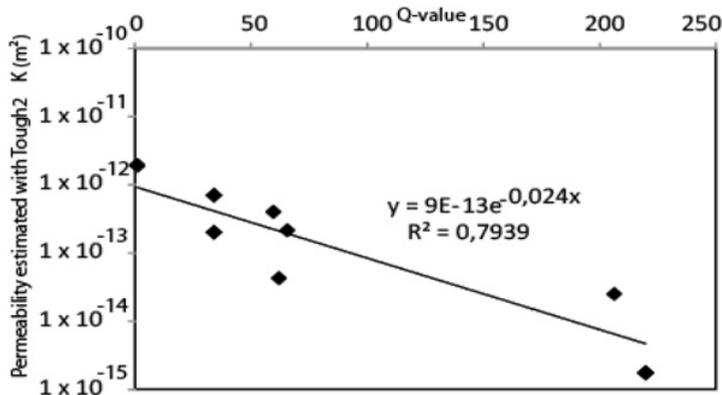
Figure 2. Correlation between Q-Value and the permeability.

discontinuities, J_a is the rating for the degree of alteration or clay filling of the least favourable joint set or filled discontinuities, J_w is the rating for the water inflow and pressure effects, which may cause outwash of discontinuities infillings, and *SFR* is the rating for the stress state.

The Q-system has been applied to more than 300 cases and it corresponds to one of the few methods to in-situ estimate fractured rock masses hydraulic parameters. Indeed, empirical correlations based on such a large number of case studies were proposed [4] between the Q-value, the rock mass strength and the Lugeon value (L = 1/min/m $\approx 10^{-7}$ m/s, which is a rough in-situ estimation of rock hydraulic permeability, Eqs. (2)–(3).

$$L = 1/Q_c \tag{2}$$

$$Q_c = Q \times 100/\sigma_c. \tag{3}$$

The uniaxial compressive strength σ_c was also estimated in-situ with a Schmidt hammer. It gives a local measurement of σ_c for a small volume of rock from the number of rebounds (R) (Eq. (4) [6]).

$$L\sigma_c = 2.21 \exp^{(0.07 \times R)}. \tag{4}$$

In this study, a measure of σ_c has been achieved every 10-cm and an average σ_c value was established every meter and affected to the corresponding area where the Q factor was estimated. The σ_c correlates strongly with the intact rock porosity, and so it contributes to better describe the intact rock quality and the evolution of the micro-damages occurring along the fault zone.

4. Results

4.1 Correlation between Q-Value and the permeability

The plot of Q-versus-K shows a best-fitting logarithmic trend line (Fig. 2): the higher the rock quality, the lower the permeability is. Significant matrix properties variations (porosity and specific storage coefficient) were also highlighted. From this study three layers units can be distinguished:

- "Unit 1": layer of low porosity ($\leq$ 9%), low specific storage coefficient (up to 6.9×10^{-3} m^{-1}), low permeability (up to 1.75×10^{-15} m^2) and no fracture (Q_c up to 219).
- "Unit 2": layer of high porosity (20%), high specific storage (2.0×10^{-2} m^{-1}), average permeability values (up to 3.0×10^{-13} m^2) and no fractures (Q_c close to 60).
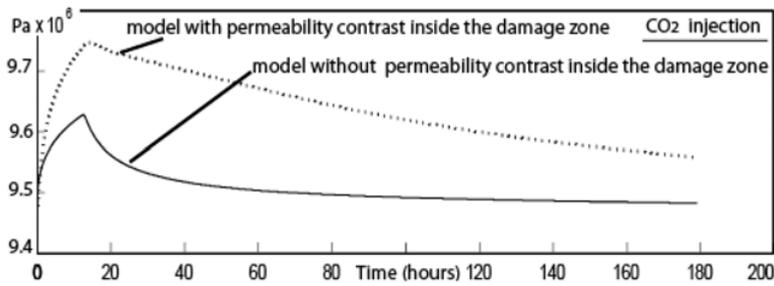
Figure 3. Fluid pressure evolution in the damage zone.

- "Unit 3": layer of low porosity (10%), low specific storage coefficient (9.8×10^{-3} m^{-1}), high permeability (up to 1.8×10^{-12} m^2) and well fractured (Q$_c$ up to 1.1).

Using Q-values, the permeability variations across the fault zone was estimated. Horizontal and vertical variations clearly appear showing many similarities with the conceptual porosity model. The horizontal variations are related to the fracturation degree of the layers toward the fault core. In low-porosity and fractured layers, the lowest permeability contrast between the host rock and close to the fault core is of one order of magnitude: 10^{-8} m/s in the host rock and 10^{-7} m/s close to the fault core. In the porous and unfractured layers, there is no significant permeability variation. Permeabilities are of 10^{-9} m/s close to the fault core and in the host rock. In the host rock the lowest permeability contrast is of one order of magnitude between the porous and un-porous mechanical units: 10^{-9} m/s and 10^{-8} m/s, respectively; and of two orders of magnitude close to the fault core (10^{-9} m/s in the porous layer and 10^{-7} m/s in the low-porous layers). Finally, the fault zone is characterized by strong permeable bodies more or less extended within the stratigraphic layers intercalated with low permeable bodies.

4.2 Impact of the fault zone architecture on fluid overpressure

To investigate the influence of the contrast of vertical and horizontal permeability inside a fault zone on the generation of fluid overpressures, we simulated a CO_2 injection (4.0 L/s) into a saline aquifer with initial conditions (P = 9.5 MPa, T = 32 °C, and a salinity of 5% by weight) that assure a supercritical state for CO_2. The injection point is located at 900m-depth in a fractured layer. The 2D geological model is enough large to consider infinite boundary conditions. The boundaries are impermeable.

The reservoir where is located the injection is composed by an alternation of fractured and un-fractured layers of 10-m thickness. The fault damage zone is 21-m thick in both sides of the fault core and the injection well is located in the host rock at 1-m from the damage zone. A control point is located in the damage zone at 11-m of the injection point and 11-m of the fault core. To highlight the influence of the permeability contrasts inside a fault zone, we compare results obtained by two different models: one with contrasted permeability values inside the damage zone (Model 1) and one where permeability of the fault damage zone was considered constant and homogeneous (Model 2). The hydraulic properties and their evolution across the fault zone (permeability and storativity) used for the fluid flow simulations are deduced from the in-situ characterizations.

The permeability contrasts are present inside the damage zone (model 1) prevent the fluid diffusion and favor CO_2 accumulation in the most permeable layers. Inversely, the lack of damage zone layering (model 2) favors the fluids diffusion along the fault zone and fluid overpressures in the host rock. At the end of the injection, the fluid pressures increased of 2.5×10^5 Pa in the damage zone in model 1, whereas the pressure increased of to 1.2×10^5 Pa in model 2 (Fig. 3). In this saturated reservoir, the

overpressures occur in high permeability and storativity layers because these layers still have the ability to store more fluids.

5. Conclusion

We have shown that small fault zones can strongly influence fluids circulations and storage within a reservoir. Their architectures are related to the initial stratigraphic series properties in the host rock and to their differential alteration in the damage zone. This results in the alternation of more or less permeable layers leading the appearance of levels acting as drains while others act as barriers to fluid flow. The deformations are not enough evolve to be considered as a continuous thick layer like the mature fault zone.

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