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The Impact of Hydrodynamics on CO_2 Migration and Sealing Capacity of Faults

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Introduction

Research on the hydraulic properties of faults has attracted a renewed interest recently because faults were identified as potential risks to the containment of injected carbon dioxide in the case of geological storage of greenhouse gases. In petroleum exploration, fault complexes are often targeted because they can provide a structural trap, whereas when locating potential carbon storage sites some researchers recommend avoiding faulted successions because of the potential leakage risk. This apparent contradiction can be explained by the complex nature of faults, which may form either barriers or conduits to fluid flow depending on their hydraulic properties, geometry and the prevailing stress regime. The impact of hydrodynamics on fault seal capacity has been largely neglected in the scientific literature but is the main focus of this study.

Underschultz (2007) has demonstrated, in theory, that pressure differences of formation water between the two sides of a fault have an impact on the total membrane (capillary) seal capacity for the fault. In fact, the high-pressure side of the fault, independent from the location of the hydrocarbon accumulation, determines the height of the hydrocarbon column that can be supported by the fault seal. In other words, the side with the lower pressure can hold more hydrocarbons because, in addition to the capillary entry pressure of the fault rock, migrating hydrocarbons also have to overcome the increasing pore pressure gradient through the fault zone. While in the static case, the seal capacity depends only on the capillary entry pressure. When considering hydrodynamic effects, the ability of sustaining a pressure gradient across the fault zone depends on seal thickness and permeability.

Modelling Case Study

Two-phase numerical flow modelling of carbon dioxide migration under hydrodynamic conditions was performed using the Tough2 code. The intent of these simulations was to focus on the relationship between the height of the CO_2 column that can be sustained by a fault seal and the hydraulic gradient across the fault zone. Lateral migration (viscous coupling forces) and temperature effects are not investigated. The model domain has the dimensions 10 m x 10 m x 200 m Figure 1, with fixed pressure and concentrations at its lower boundary and no-flow boundaries along the remaining borders. Consequently, mainly vertical migration of CO_2 results in fast accumulation times below the top seal and against the fault, reducing simulation times compared to a gently dipping reservoir layer. A large thickness was chosen to allow the accumulation of a sufficiently high CO_2 column to breach fault and top seals that may have a varying range of permeabilities. The fault zone is 2 m thick, but only the outer 25 cm on either side represent slip surfaces. This was based on outcrop characterization of actual fault seals. The vertical length of the fault seals is 5 m on the left and 20 m on the right, below which a 0.001 mD barrier restricts fluid flow across the fault zone. Three cases were modelled for this permeability configuration: a) no initial formation water flow, b) across-fault hydraulic gradient with higher pressure on the right side of the fault, and c) across-fault hydraulic gradient with lower pressure on the right side of the fault (Figure 2). The respective hydraulic gradients are induced by injecting or producing water from a well at 100 m depth on the right side of the fault. The carbon dioxide is introduced through a 100 m long source with fixed CO_2 saturation (0.6) along the left boundary of the model for 300 days, after which it is turned off. The pressure is fixed at 16,000 kPa along the lower model boundary, which is approximately equivalent to pressure conditions at 1650 m depth. The temperature is assumed to be at constant 50 degC, which results in a range of CO_2 density between 680 and 700 kg/m^3 in the upper 100 m of the model.

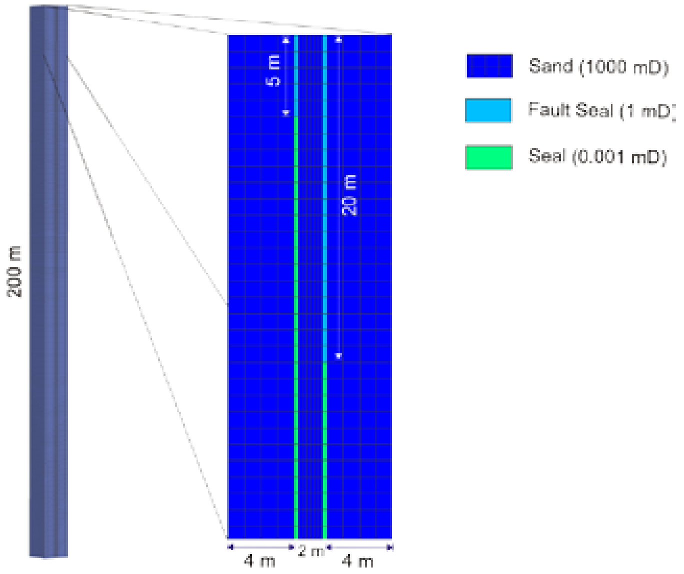


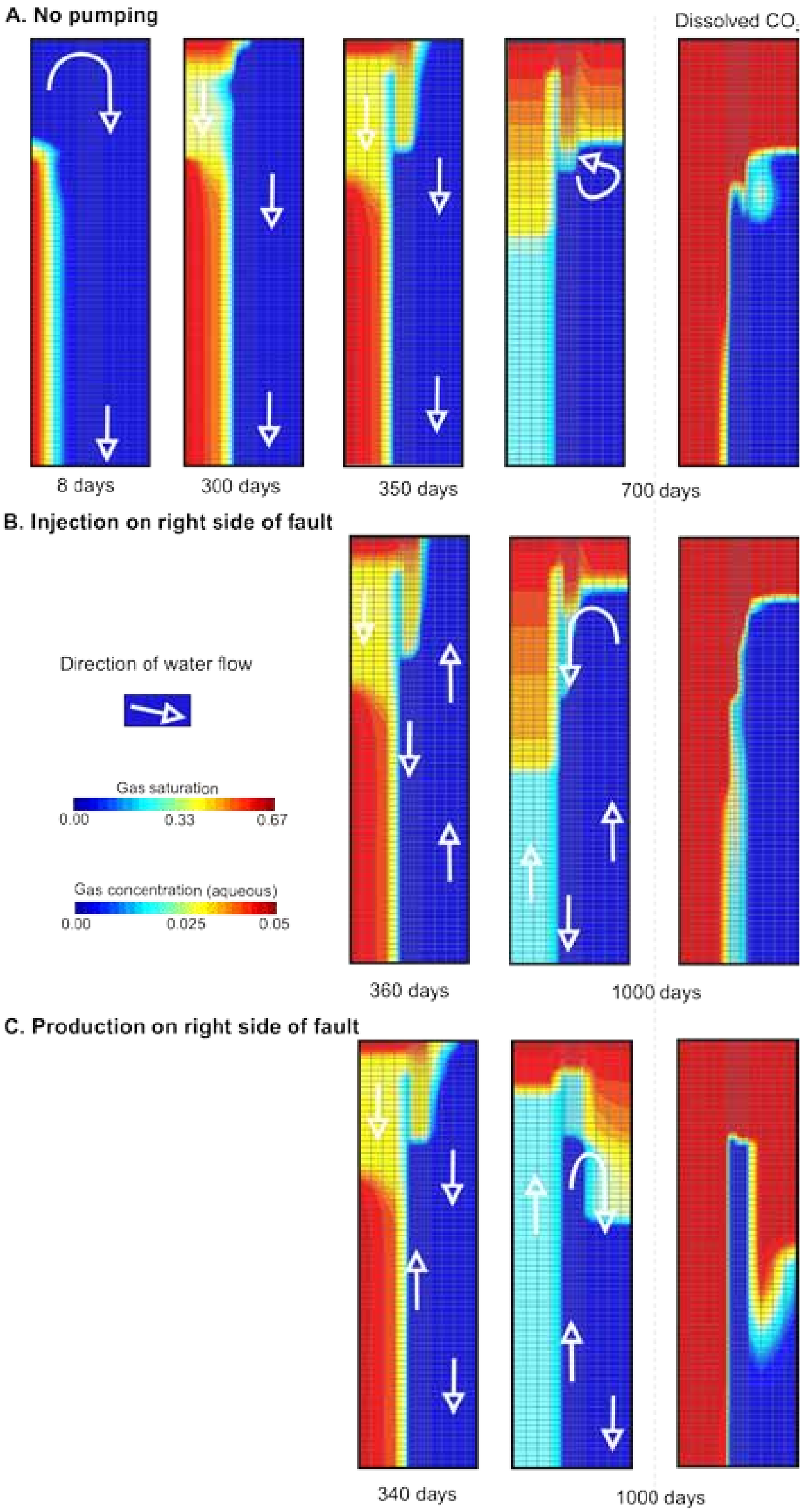
Figure 1. Model domain and permeability distribution.

A. No pumping

Initially, CO_2 migrates to the top of the model, where it accumulates and after approximately 300 days breaches the fault seal on the left. As a result of the CO_2 migration, formation water is displaced downwards where it leaves the model domain through the fixed pressure boundary at the bottom. After 300 days no more CO_2 is added into the model column. Carbon dioxide continues to build against the top seal in the compartment between the two fault seals, until the CO_2 column reaches sufficient height (~20 m) and capillary pressure to breach the fault seal on the right at approximately 350 days. The CO_2 fills the right side of the reservoir until the column on the left side of the fault can not provide sufficient buoyancy drive to overcome the fault seal entry pressure after approximately 700 days. During this period, formation water re-imbibes the left side of the reservoir through the fixed head boundary below and only residual saturation of CO_2 remains. At this point in time, all reservoir rock that has been contacted by the CO_2 plume contains formation water fully saturated with CO_2. On the right side, the dissolution of CO_2 results in a downward moving finger of dense formation water at the bottom of the CO_2 column.

B. Injection

The same initial conditions are used in this case and CO_2 is allowed to accumulate for 300 days. Subsequently, injecting water at a rate of 0.1 kg/s in the lower part of the column on the right hand side of the fault results in an upward and, more importantly across-fault hydraulic gradient with approximately 10 m difference in hydraulic head. Breach of the right fault seal occurs slightly later as in Case A and the respective threshold pressure is larger (Figure 2). The maximum CO_2 column in the middle reservoir unit reaches 25 m as indicated by the residual saturation (light blue), 5 m more than in the “non-pumping” case. There are two reasons why this maximum column cannot be sustained. Firstly, although the threshold pressure is overcome and the fault is breached, additional CO_2 can accumulate as long as the migration rate into the middle reservoir is larger than the leakage rate across the fault. Secondly, and maybe more importantly, the increased circulation of formation water due to the pumping enhances dissolution of CO_2 at the base of the CO_2 column and subsequent downward migration of the denser, CO_2 saturated water (Figure 2B, third diagram).



A. No pumping

B. Injection on right side of fault

C. Production on right side of fault

Figure 2. Modelling results showing CO_2 saturation and dissolved CO_2 concentration for cases of A) no pumping, B) injection, and C) pumping.

C. Production

The same initial conditions are used in this case and CO_2 is allowed to accumulate for 300 days. Subsequently, continuous production of water at a rate of 0.1 kg/s in the lower part of the column on the right hand side of the fault results in a downward and, across-fault hydraulic gradient with approximately 10 m decrease in hydraulic head from right to left. In this case, breach of the right fault seal occurs slightly earlier than in the previous cases and the respective threshold pressure is lower. The maximum CO_2 column after 1000 day in-between the two faults reached approximately 17 m, which is 5 m less than in the "non-pumping" case. Similar to Case B, the increased circulation of formation water enhances dissolution of CO_2, however, in this case on the right side of the fault. The denser, CO_2 saturated water migrates downwards, ahead of the separate-phase CO_2 plume (Figure 2C, third diagram).

Summary and Conclusions

Initial modelling results confirm the theoretical findings that across-fault hydrodynamic gradients enhance or reduce fault seal capacity depending on the direction of flow. However, the enhancement of fault seal capacity can only increase up to that point where the hydrodynamic drive becomes sufficiently high to sweep the hydrocarbons or carbon dioxide out of the trap. Obviously, the across-fault flux of water declines with decreasing fault zone permeability for a given hydraulic gradient. At the same time, lower fault zone permeability results in a higher threshold pressure and higher sustainable hydrocarbon column. As a result, fault seal enhancement (without sweeping) due to across-fault hydraulic difference (Δh) is limited to a range of permeabilities, fluid densities and hydraulic gradients according to:

$$\frac{(\rho_w - \rho_b)}{\rho_w} \cdot D \leq \Delta h \leq \frac{k_r}{k_f} \cdot \frac{(\rho_w - \rho_b)}{\rho_w} \cdot D \cdot \nabla E$$

for $\Delta h = h_{nr} - h_r > 0$

where ρ_w = water density (kg/m^3), ρ_b = density of buoyant fluid (kg/m^3), D = fault thickness (m), k_r = aquifer permeability (m^2), k_f = fault permeability (m^2), ∇E = aquifer slope, h_r = hydraulic head on reservoir side of the fault (m), h_{nr} = hydraulic head on non-reservoir side of the fault (m).

Generally, the mere existence of faults should not automatically prohibit geological storage of carbon dioxide. In the contrary, faulted structures that successfully trap hydrocarbons should also form suitable storage sites for carbon dioxide. Still, when looking for suitable sites for the geological storage of carbon dioxide, the containment of the injected fluid in the subsurface is a major concern and it is essential to ensure that existing faults in the vicinity of the storage reservoirs do not provide a leakage pathway to shallower formations or the ground surface. In this case, across-fault leakage is of secondary concern, but still plays an important role in the assessment of storage capacity and placement of injection wells.

References:

Underschultz, J.R. (2007). Hydrodynamics and membrane seal capacity: *Geofluids Journal* 7, pp. 148-158.