Geochemical evolution of a fractured zone in the cap rock of an underground carbon storage site

AGU Fall Meeting 2013

Poster V41A-2743

Stéphanie Vialle[a], Jennifer Druhan[a] and Katharine Maher[a]

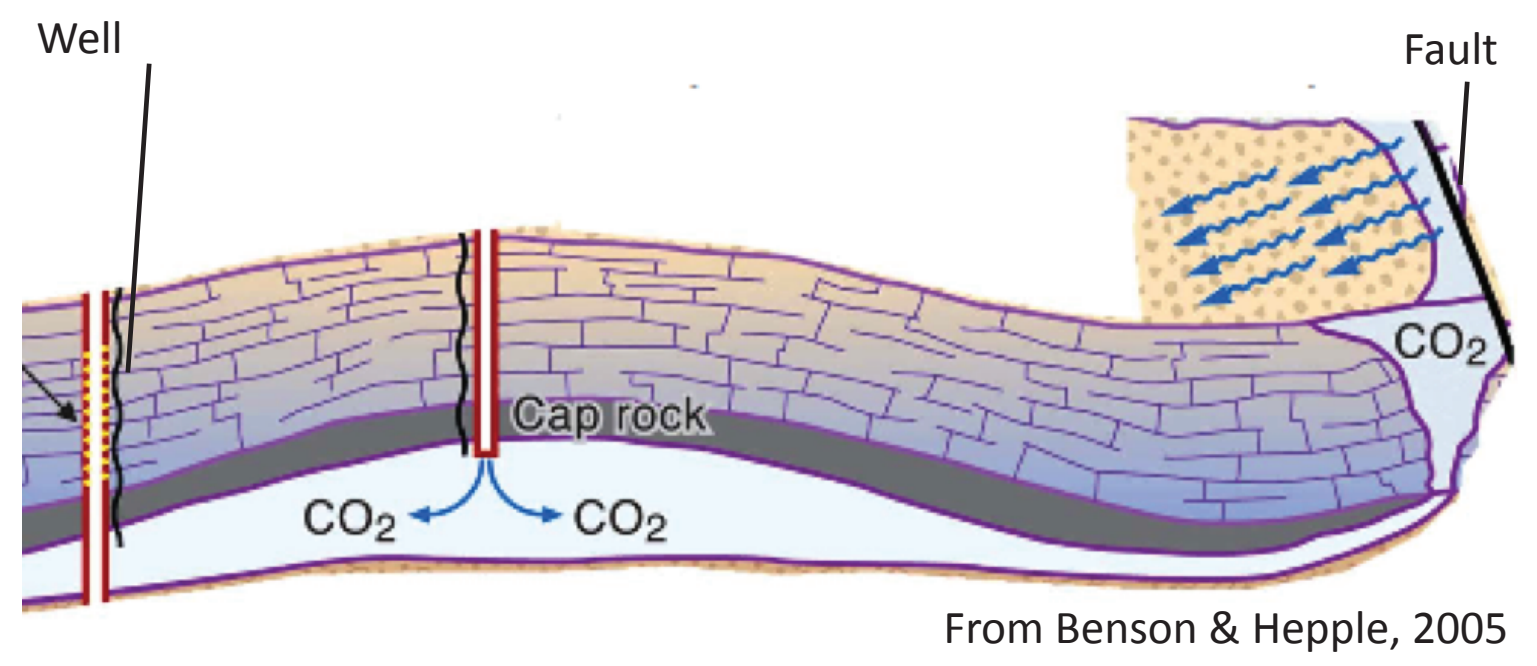
[a] Geological & Environmental Sciences Department, Stanford University, USA. svialle@stanford.edu; jdruhan@stanford.edu; maher@stanford.edu

INTRODUCTION

- Some large-scale projects of carbon capture and sequestration have already been implemented worldwide, coupled in some cases with enhanced oil recovery (EOR) or enhanced coalbed methane recovery.

Because of the relatively few CO2 projects operating at scale and the limited lifespan of pilot and demonstration projects, case studies of unexpected **CO2 or brine migration requiring detection and intervention** are rare. For both the commercial development of this method and the public acceptance and confidence in the oil and gas industry to safely and effectively operate projects at large scale, it is essential to integrate ***'what if' scenarios*** to the state-of-the-art site characterization, risk assessment, and monitoring systems in project risk registers. This is the role of the *Carbon Capture Project 3* or CO2 Storage Contingencies Project.

- The major sources of leaks are:
  - poorly maintained or undocumented wells;
  - fault reactivation;
  - creation of fractures in the caprock due to CO2 overpressure in the underlying storage reservoir;
  - **undetected fractures in the caprock that are below the seismic resolution (this study).**



From Benson & Hepple, 2005

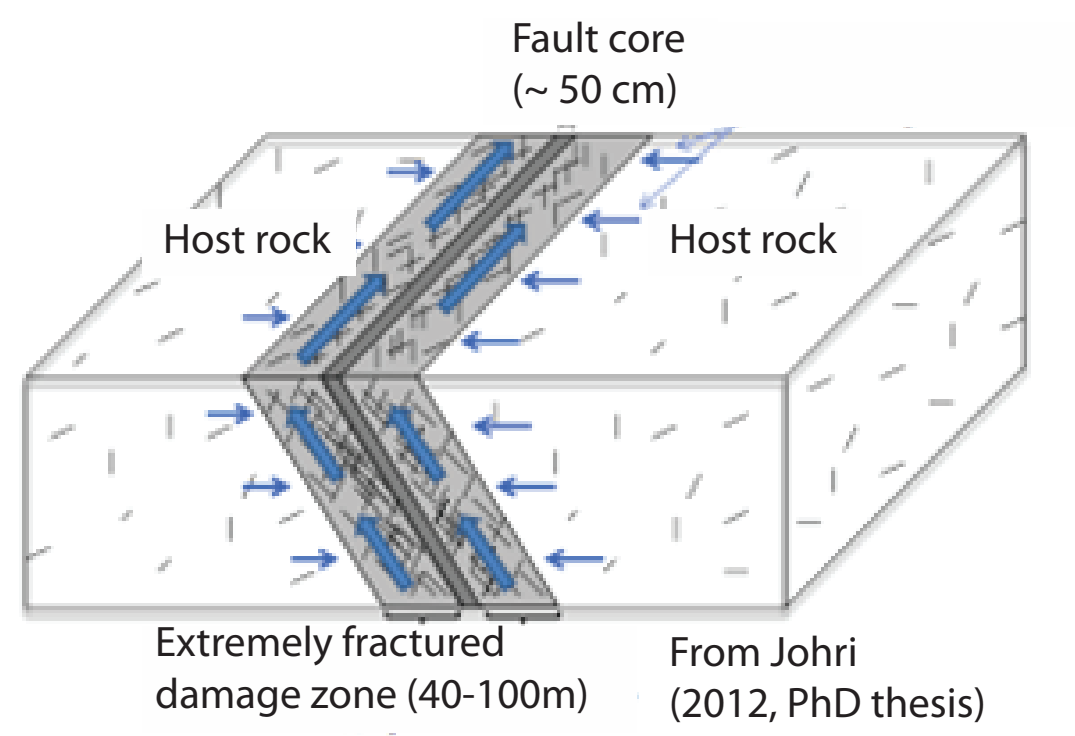
OBJECTIVES

The objective of this study is to evaluate coupled geochemical-hydrologic processes associated with CO2 leakage in fractured systems using reactive transport simulations:

- Evolution of the mineralogy and hydrologic properties of a fault/damage zone in the caprock (e.g., "self sealing", leak migration, etc.);
- Effectiveness of mitigation strategies of controlled permeability reduction at different locations in the fractured cap rock.

FAULT/DAMAGE ZONE SYSTEMS

Faults and fractures are complex systems but, for a low-prosity, low clay-content rock, a typical representation of a fault/damage zone can be given as sketched in the figure below:



From Johri (2012, PhD thesis)

The main components are:

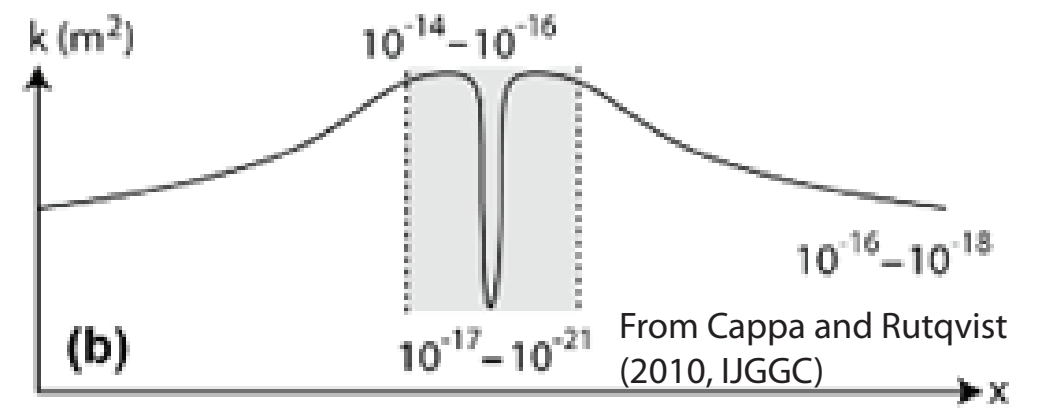
- a fault core, filled with high strain products;
- a damage zone, highly fractured;
- the host rock or protolith.

The fracture density *F* decreases with distance from the fault core, generally as a power law.

$$F(x) = F_0 \cdot (x/x_0)^{-n}$$

F_0: fracture density, at 1 m from the fault (fault constant)
n: fracture density decay

Resulting permeability field



From Cappa and Rutqvist (2010, IJGGC)

As a consequence, compared to the host rock, the permeability is decreased in the fault core and increased along the fault plane.

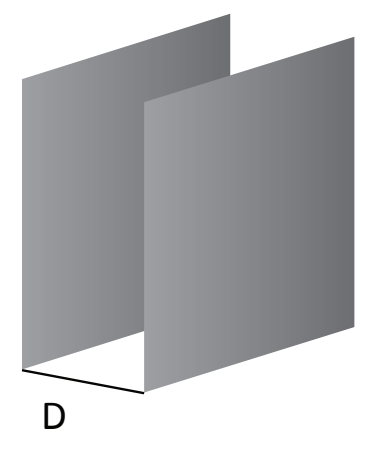
To model the heterogeneous permeability field in the damage zone, we use an upscaling relationship that relates permeability to fractures density and fracture hydraulic aperture:

Set of vertical, parallel fractures, with spacing *D*

$$k_{eff} = k_m + k_f = k_m + \frac{\phi_f \cdot h^2}{12}\cos^2\alpha = k_m + \frac{h^3}{12}\cdot F_0 \cdot \left(\frac{x}{x_0}\right)^{-n}$$

Fracture porosity

$$\phi_f = \frac{h}{D} = h \cdot F$$



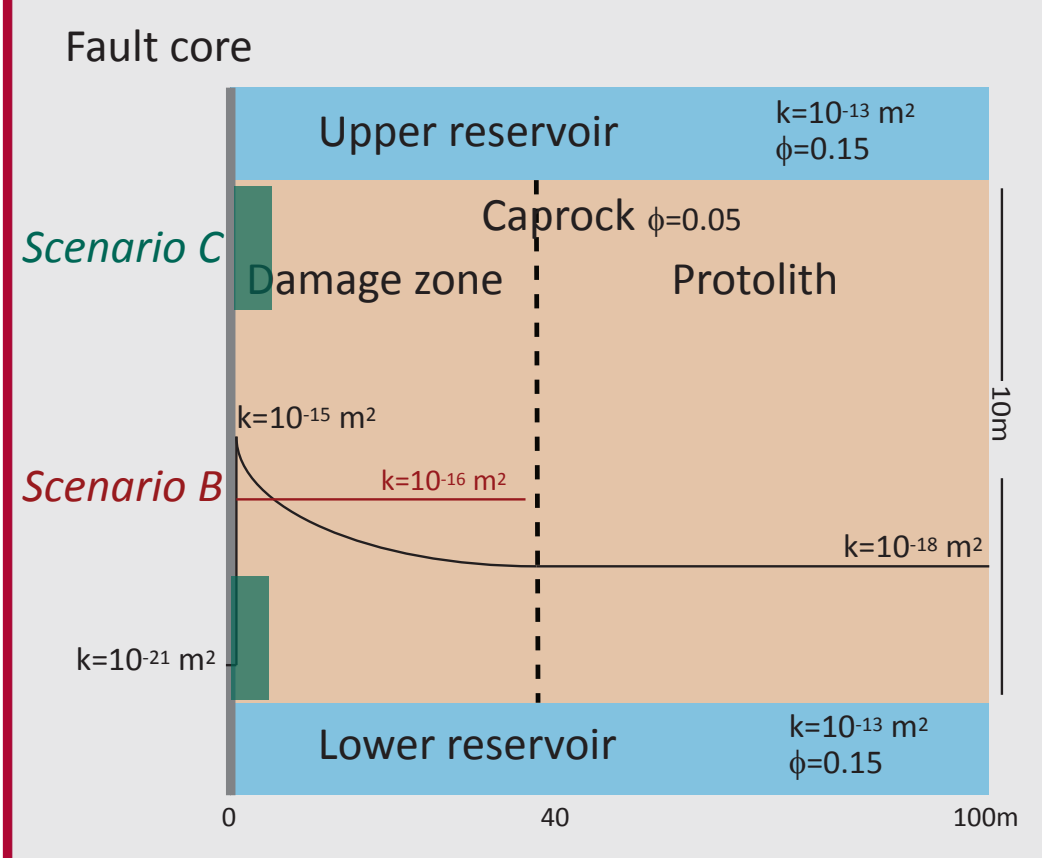
k_m: matrix permeability
h: effective hydraulic aperture
ϕ_f: fracture porosity
α: angle between the fracture plane and the pressure gradient vector (0° here)
x: distance from the fault plane
F_0: fracture density at 1m

This work was sponsored by the Carbon Capture Project Phase 3.

Special thanks to Scott Imbus, Chevron, for his support and feedback, to Elin Skurtveit, NGI, and Pål Saevik, Bergen University, for fruitful discussions on fractured systems, and to Sally Benson and Anshul Agarwal, Stanford University, for their encuraging feeback.

MODELING OF CO2 LEAKAGE THROUGH THE CAPROCK

Model setup



Temperature: isothermal 55°C

Pressure: hydrostatic gradient 17 MPa at the bottom of the caprock

The caprock is initially filled with brine of salinity 0.15% in weight.

Van Genuchten equations are used for relative permeabilities and capillary pressures, with characteristic parameters of a reservoir and a caprock.

After hydrostatic equilibration of the model, the brine in the lower reservoir is replaced by CO2 (supercritical here, from 'dry' to a saturation of 60%) and the pressure increased from 17 MPa to 20 MPa to initiate the leak.

The simulations are performed with the numerical **flow simulator TOUGH2**, coupled with the fluid property module ECO2N for modeling the thermodynamic and thermophysical properties of the mixture H2O-NaCl-CO2.

Three different simulations:

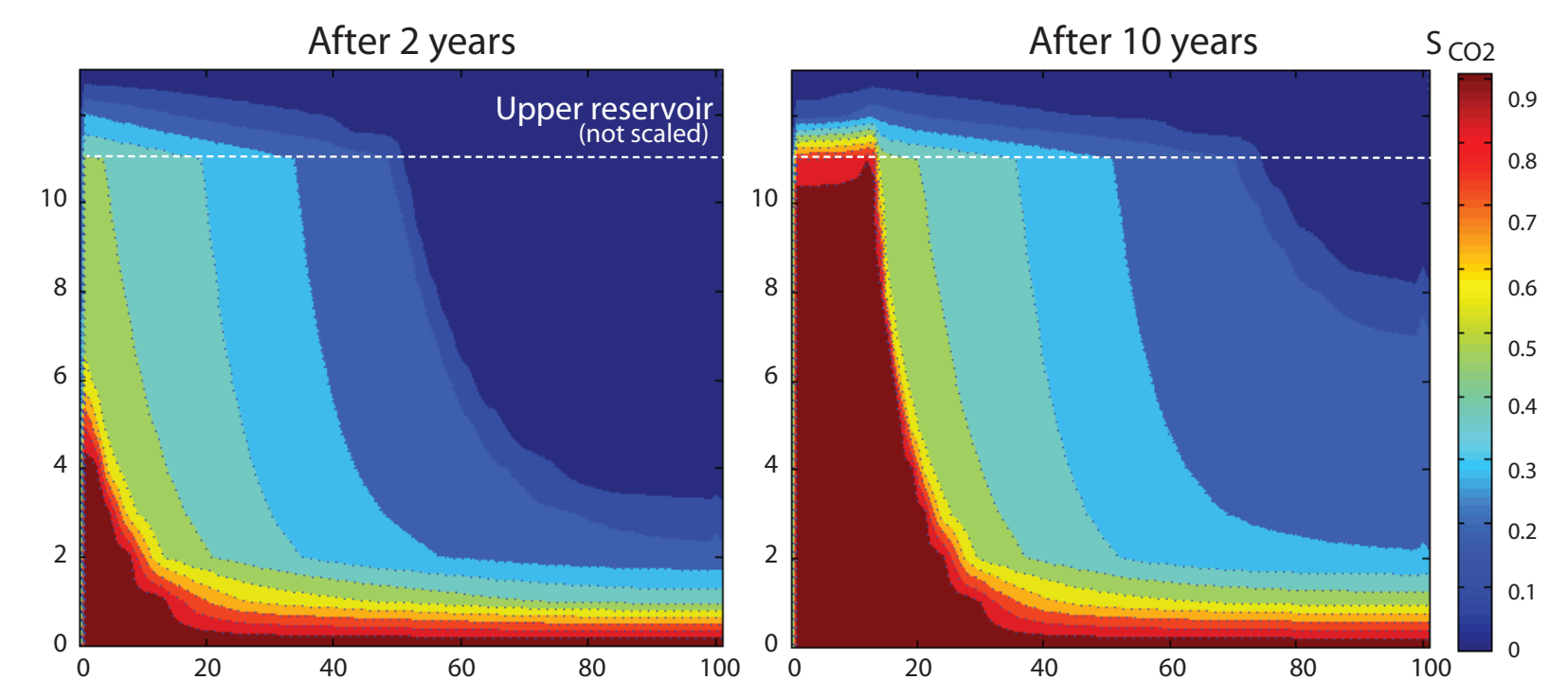
Scenario A: heterogeneous permeability field in the damage zone.

Scenario B: homogeneous permeability field in the damage zone.

Scenario C: mitigation strategies of controlled permeability reduction

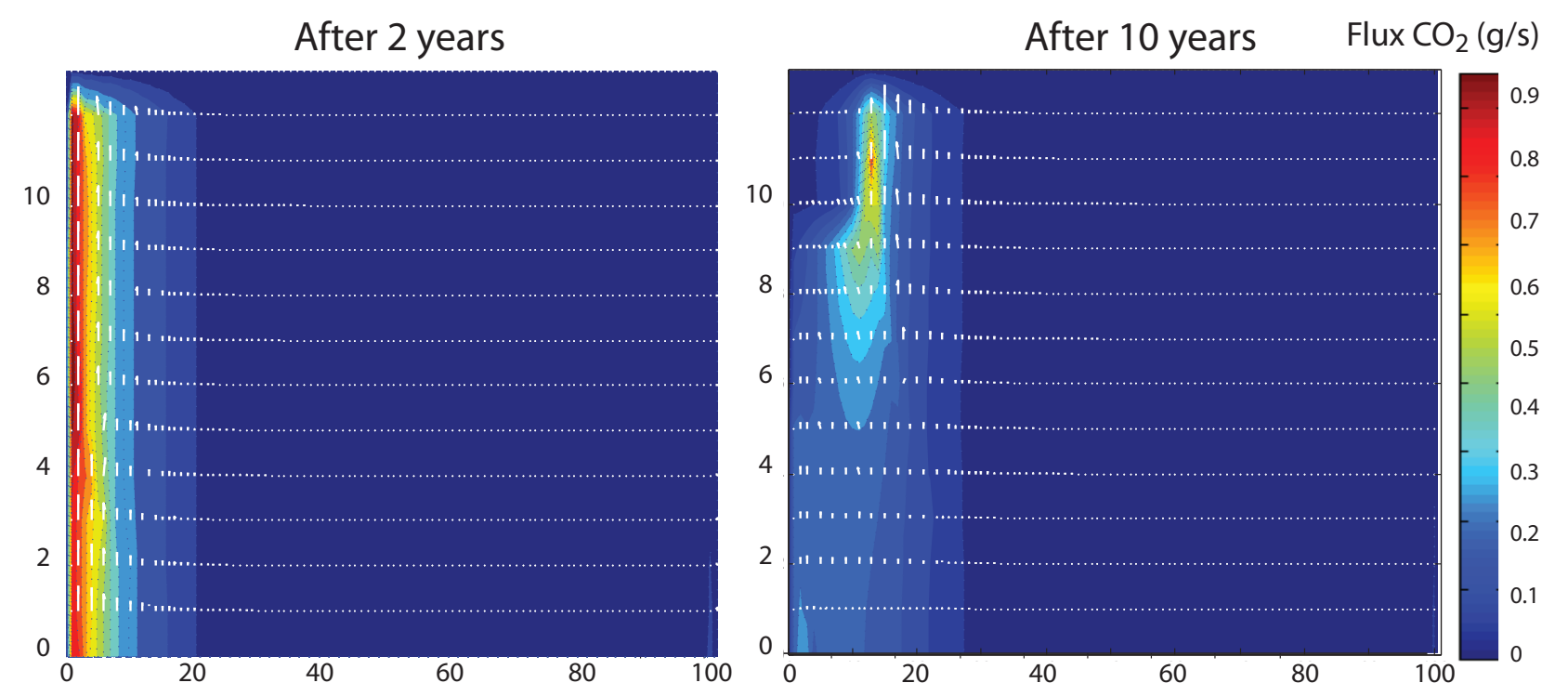
SCENARIO A: HETEROGENEOUS PERMEABILITY FIELD

CO2 saturations



CO2 is migrating preferentially along the fault plane, where permeability is higher.

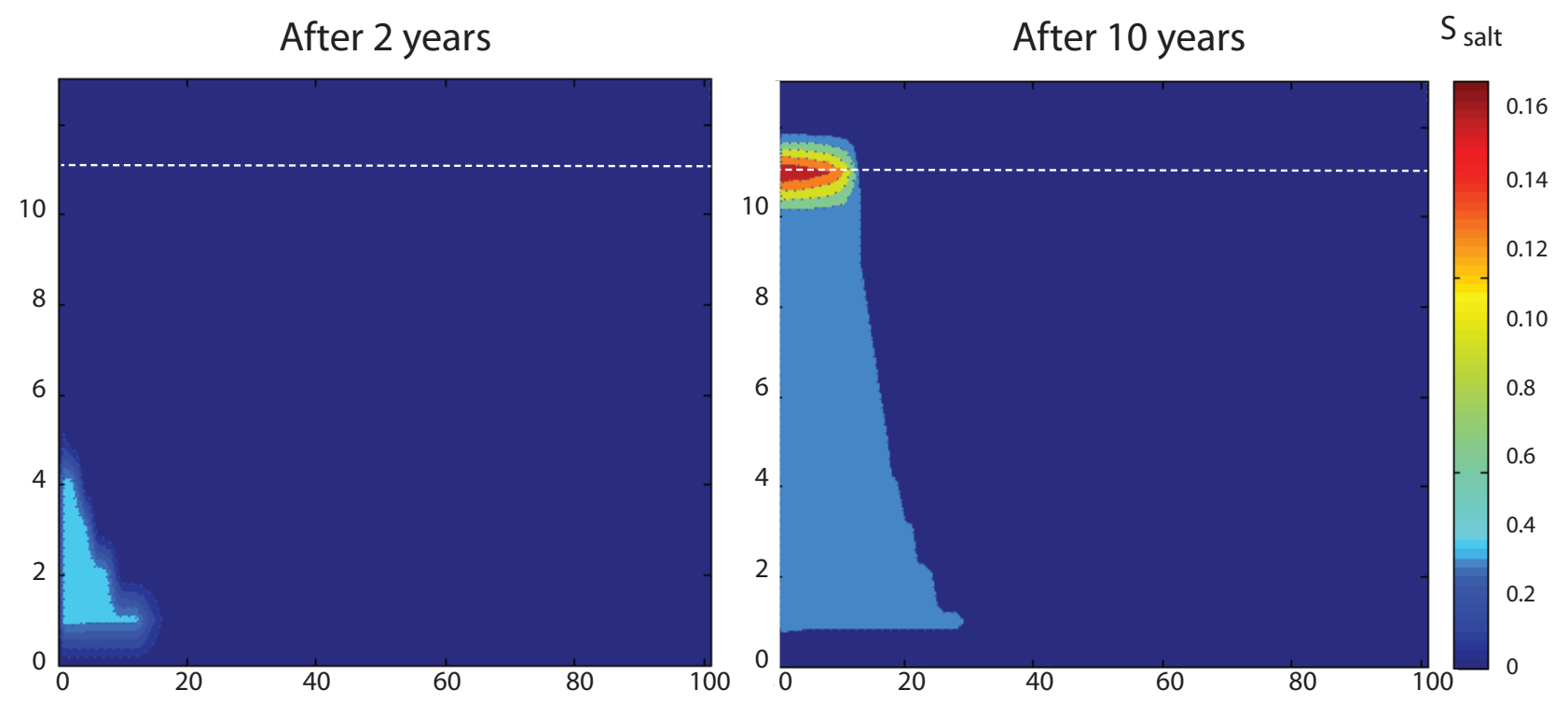
CO2 fluxes



Some CO2 is leaking in the fault core

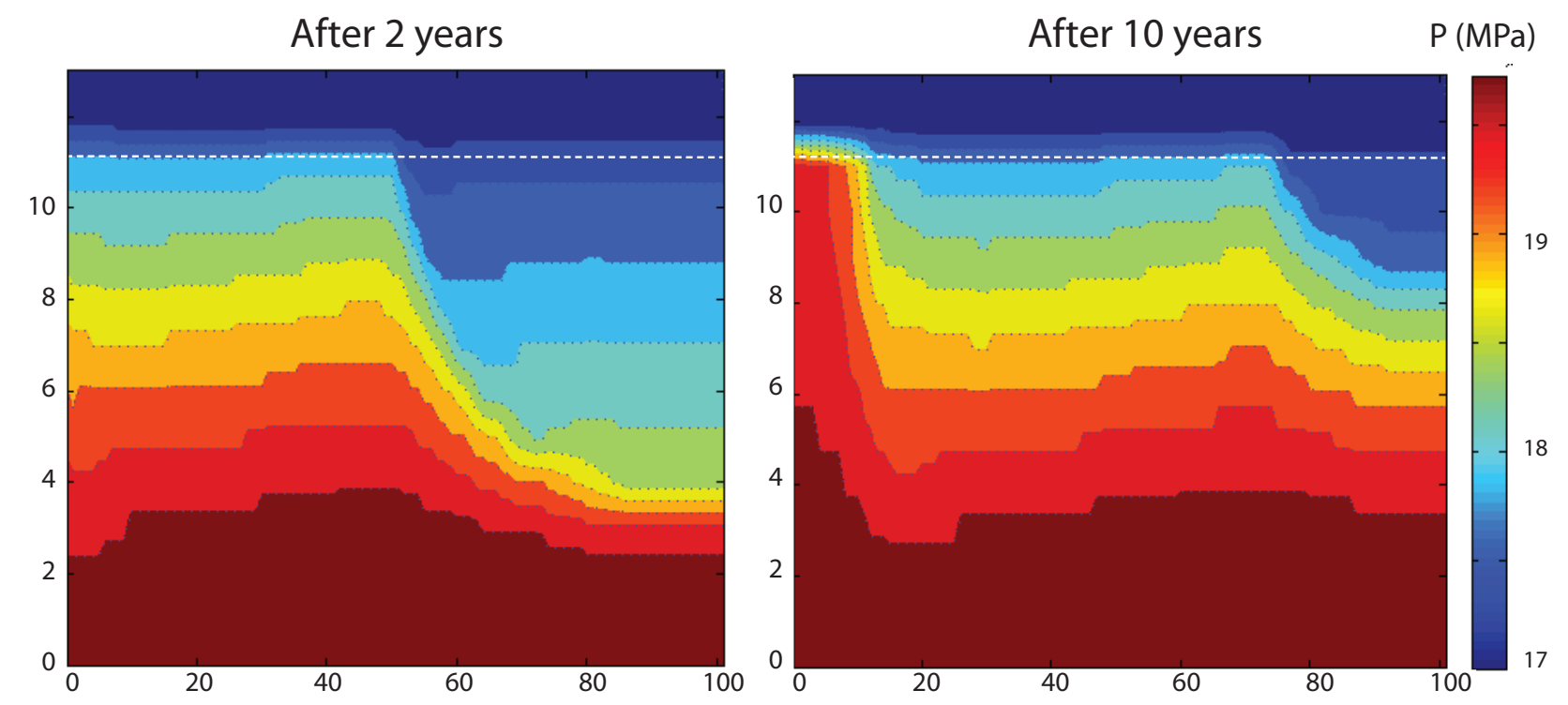
The leak is migrating away from the fault.

Salt saturation



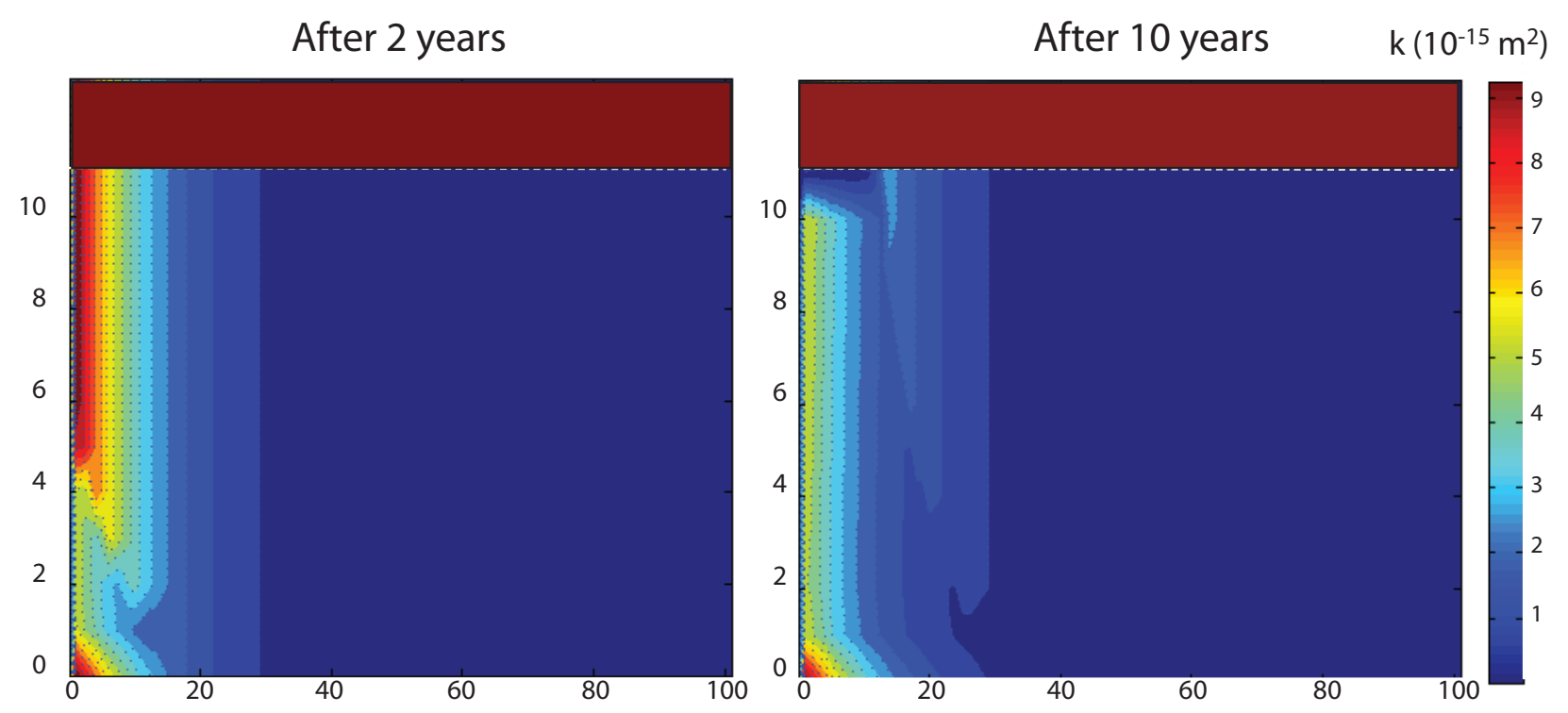
The partitioning of CO2 and H2O between the 'gas' and liquid phases leads to precipitation of salt.

Pore pressures



Pore pressure increases along the fault because of the salt precipitation.

Permeability field

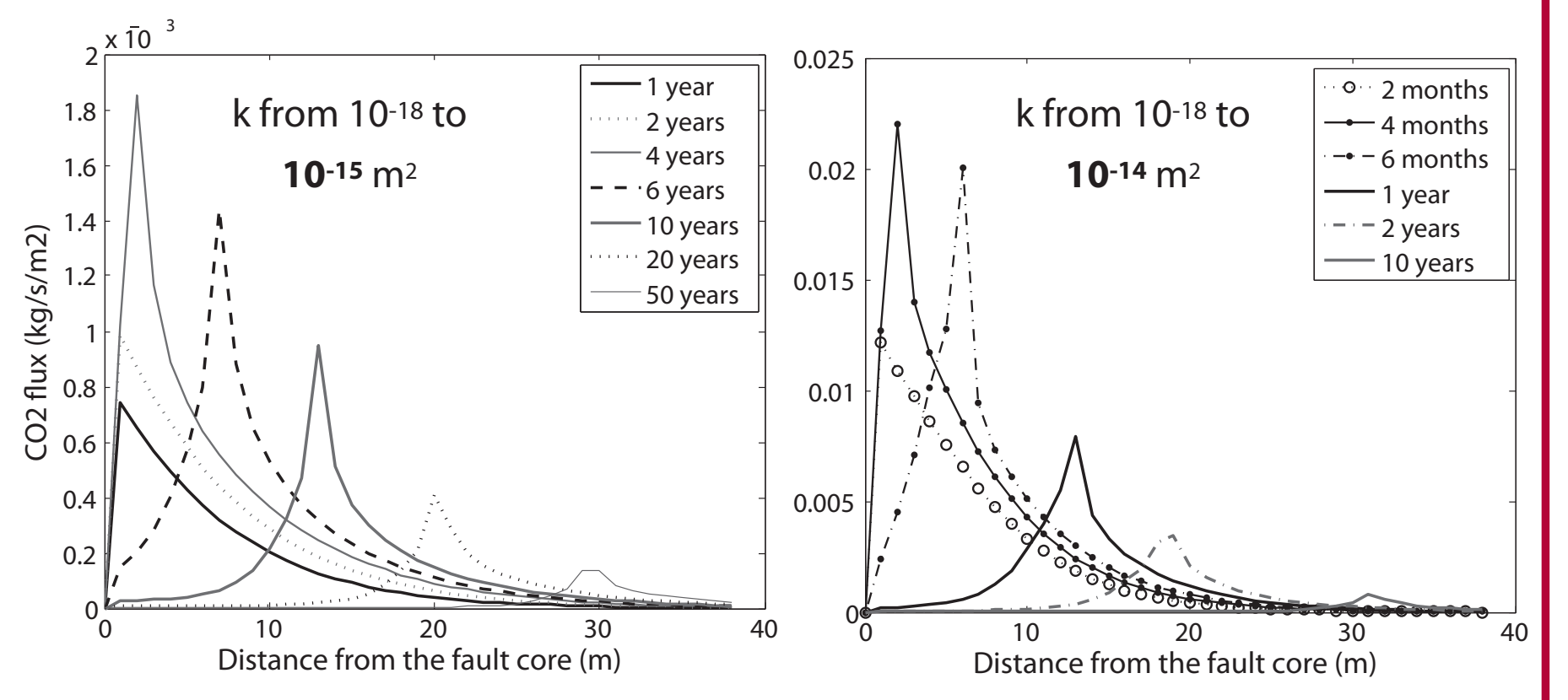


The functional dependence of relative change in permeability on relative change in active flow porosity is captured with Verma and Pruess equation (1995)

$$\frac{k}{k_0} = \theta^n \frac{1-\Gamma+\Gamma/w^n}{1-\Gamma+\Gamma\left(\theta/(\theta+w-1)\right)^n} \qquad w = \frac{1+1/\Gamma}{1/\phi_r - 1} \qquad \theta = \frac{1-S_{Salt}-\phi_r}{1-\phi_r}$$

The changes in the permeability field indicate self-healing of the damage zone.

Leakage rates



The CO2 leak is a source point leak that is laterally migrating away from the fault core and decreasing over time.

A wider range of permeability leads to shorter response times of the system.

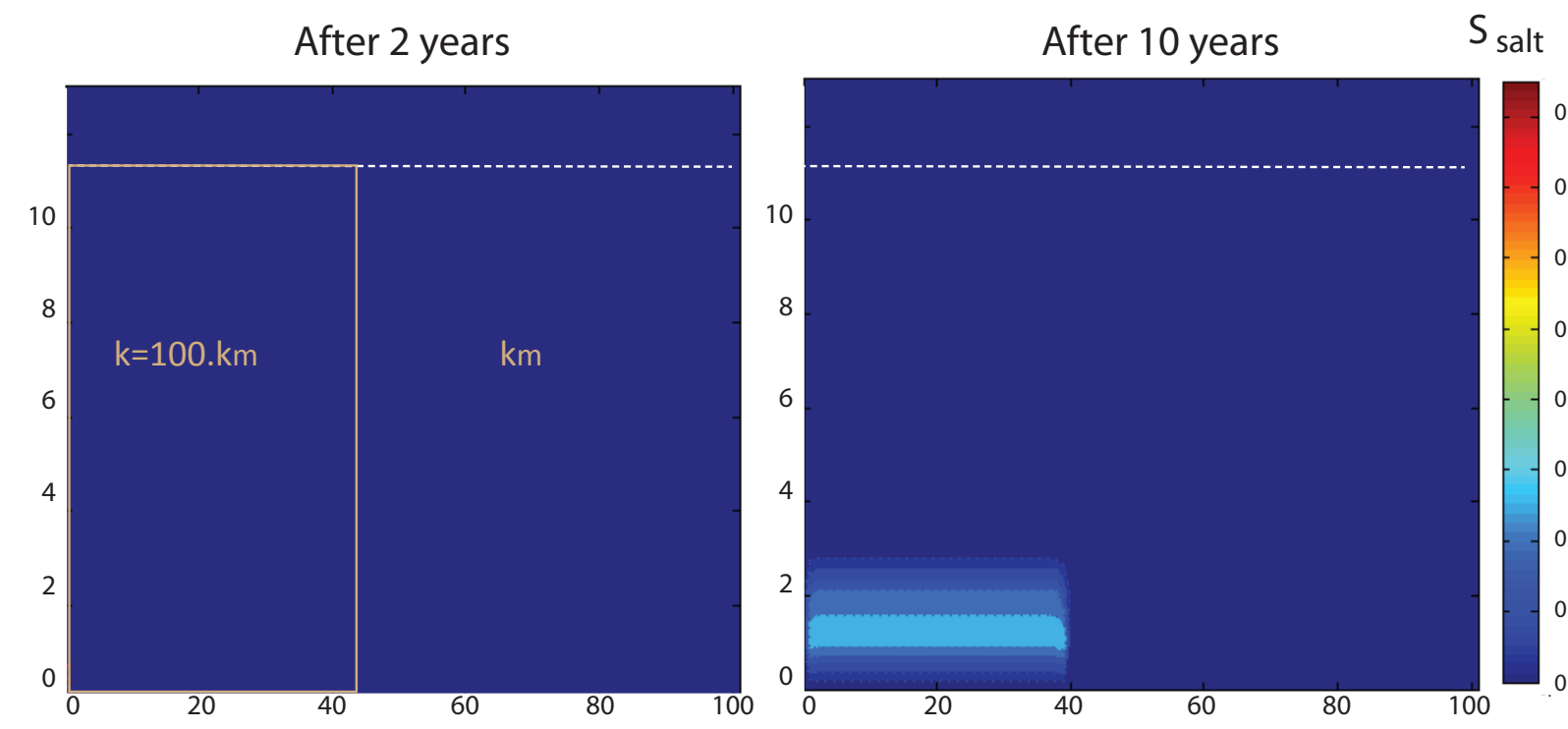
'Dry' CO2 is unlikely to be found beyong a few meters from the injection well.

This self-healing scenario can be seen as an analog of a mitigation strategy for which the sealant acquires its sealant properties while reacting with CO2 (e.g. CO2-SPI gels currently tested for EOR).

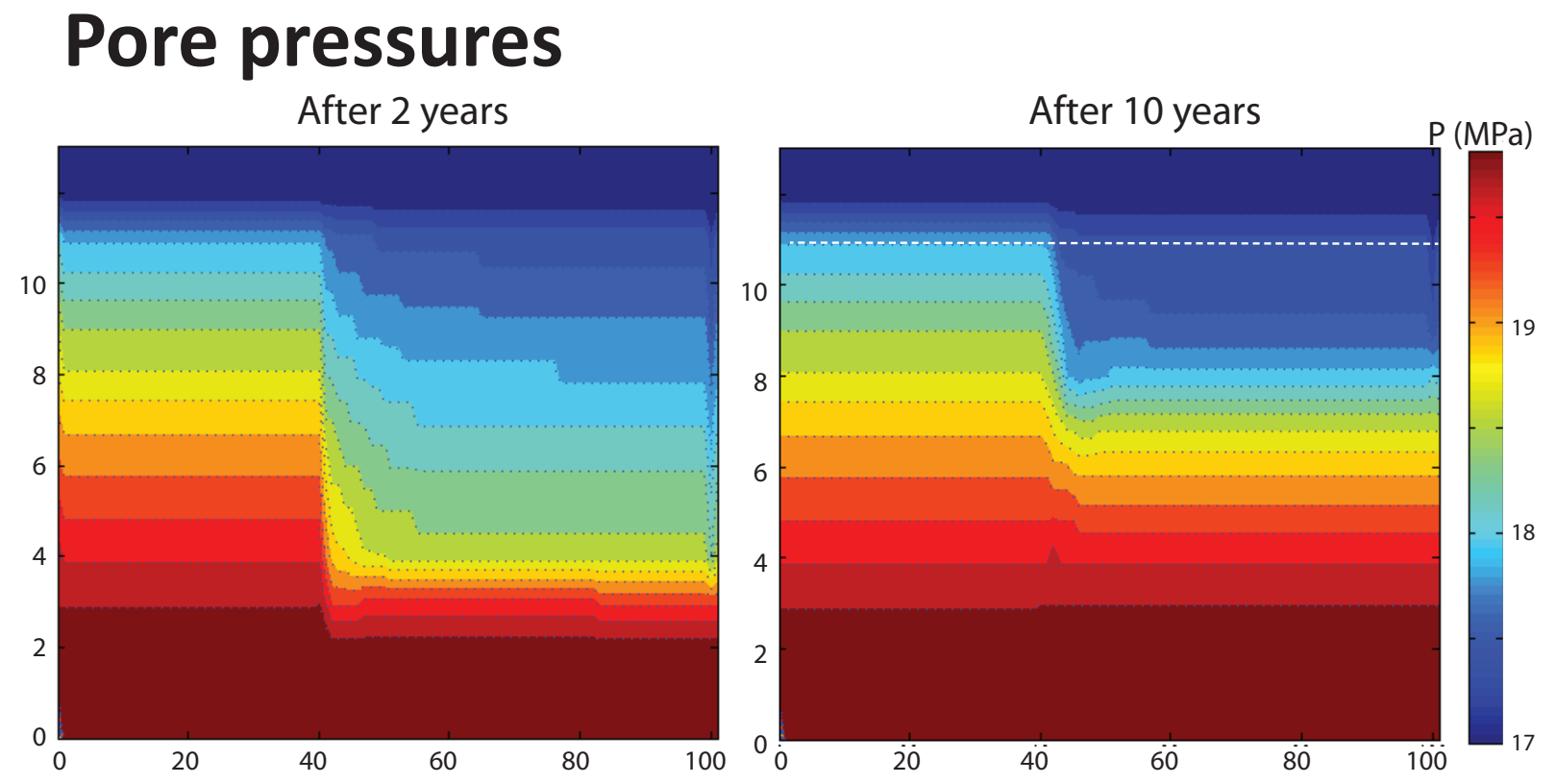
A lateral migration of CO2 seepage has also been observed at the CO2 natural analog site of Crystal Geyser, Utah (Burnside et al., 2013).

SCENARIO B: HOMOGENEOUS PERMEABILITY FIELD

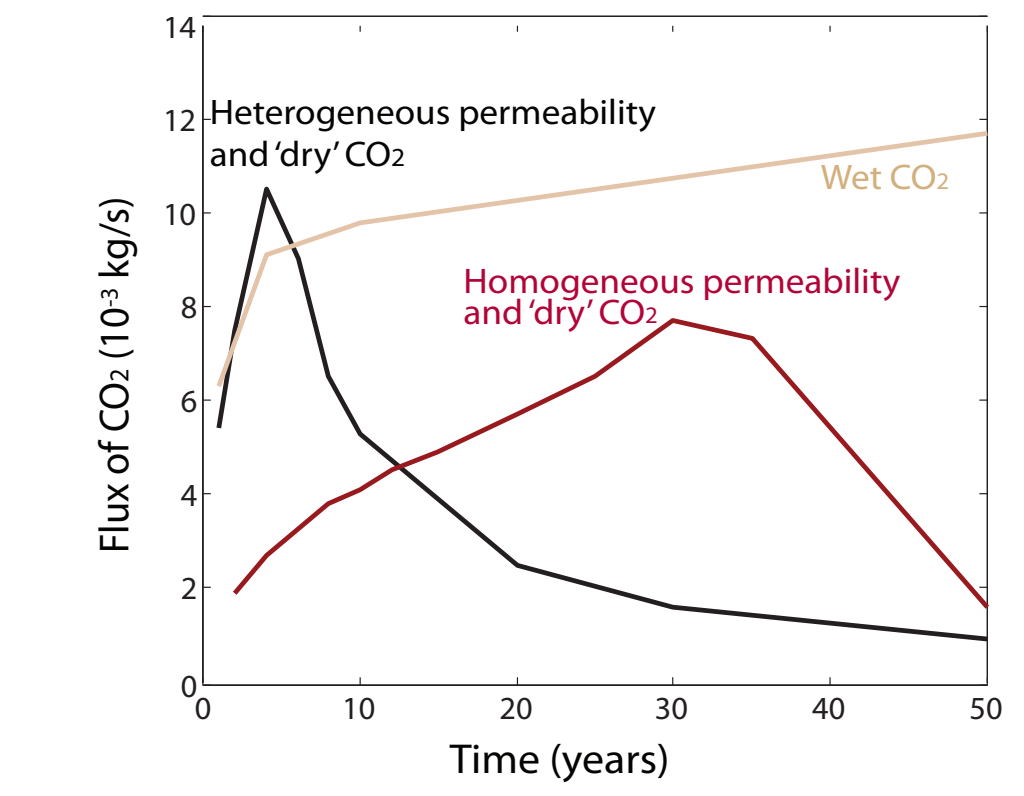
Salt saturations



Pore pressures



Leakage rates



Comparison of total leakage rate of CO2 in the overlying aquifer, for different scenarios.

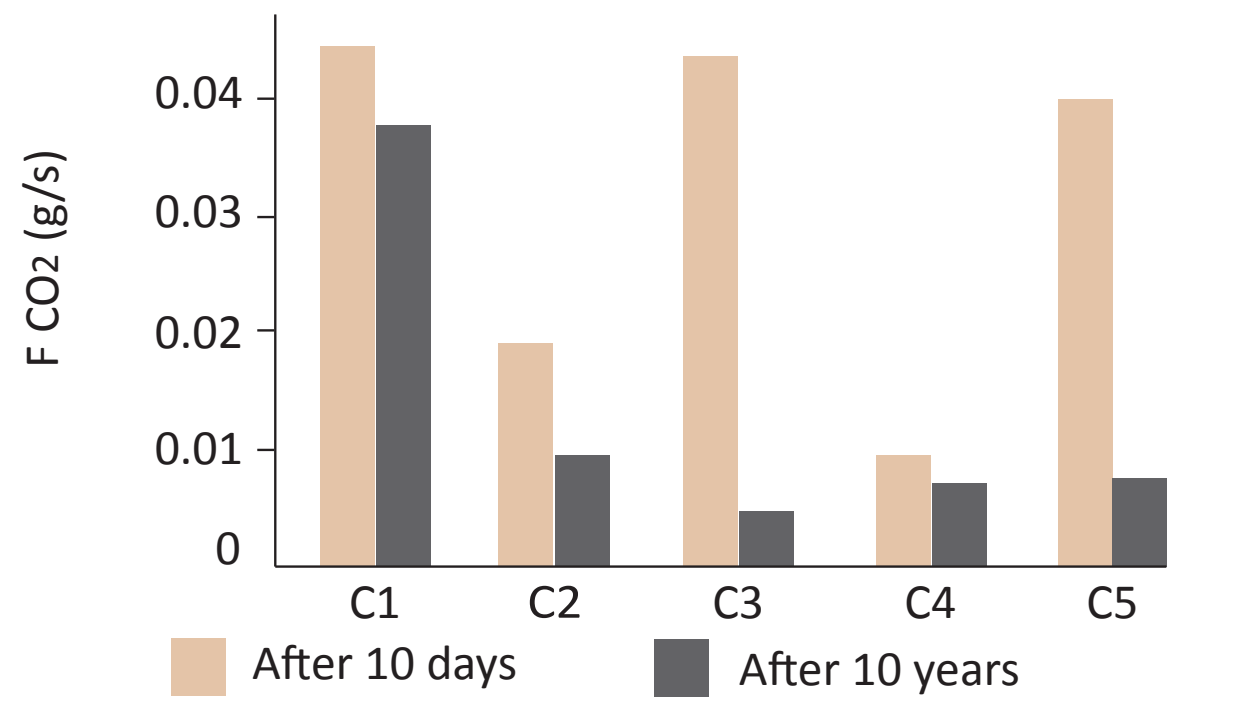
The localization of salt precipitation is different, both in time and in space, from the case where the permeability field is heterogeneous.

It is thus important to provide an appropriate physical representation of the fluid flow through the system, since geochemical reactions will strongly depend upon the local hydrodynamics of the CO2 leak.

Dynamics of the flow in fractured damaged zones is still poorly understood and current and future laboratory experiments and field tests will allow a better representation and understanding of such systems.

SCENARIO C: CONTROLLED PERMEABILITY REDUCTION

We have investigated the effectiveness of various strategies of controlled permeability reduction at different locations within the fractured damage zone. These mitigation strategies are placed 2 years after the leak starts, time at which the leakage rate is 23 g/s.



Different scenarios :
C1 – The permeability is reduced by 2 orders of magnitude in an area 3m x 3m along the fault plane, at the top of the caprock
C2 – The permeability is reduced by 3 orders of magnitude in an area 3m x 3m along the fault plane, at the top of the caprock
C3 – The permeability is reduced by 2 orders of magnitude in an area 3m x 3m along the fault plane, at the bottom of the caprock
C4 – As C1, but the pressure is first decreased down to 17.5 MPa and the CO2 saturation down to 10 % in the lower reservoir
C5 – No permeability reduction - The pressure is decreased down to 17.5 MPa and the CO2 saturation down to 10 % in the lower reservoir

All the strategies investigated lead to a significant reduction of the leak.
Placing the sealant at the bottom of the caprock, and in conjunction with CO2 pressure and saturation reduction in the underlying reservoir, is the most effective mitigation intervention.

CONCLUSIONS

- In the caprock, permeability changes in the damage zone of a fault from precipitation reactions can result in **lateral migration of leakage** over time as well as a **progessive self-healing** of the fractured system.
- On-going work that includes fluid-rock interactions (module TOUGHREACT) in the damage zone, the fault core and the protolith of the caprock, will give a more comprehensive picture of the possible scenarios of the geochemical evolution of a CO_2 leak through a fractured system.
- Understanding the hydrodynamics of the CO_2 leak through the caprock allows to better design mitigation strategies.
- A sealant strategically placed in the main CO_2 flow paths in the caprock will significantly decrease the leak.

References and suggested reading

Burnside, N.M., Shipton Z.K., 2, Dockrill B., and Ellam R.M., 2013. Man-made versus natural CO2 leakage: A 400 k.y. history of an analogue for engineered geological storage of CO2. Geology 41(4), 471-474, doi:10.1130/G33738.1.

Cappa F. and Rutqvist J., 2011, Modeling of coupled deformation and permeability evolution during fault reactivation induced by deep underground injection of CO2,International Journal of Greenhouse Gas Control 5(2), 336--346.

Johri M., 2012, Fault Damage Zones - Observations, Dynamic Modeling, and Implications on Fluid Flow, PhD dissertation, Stanford University.

Benson et al., 2013, Assessment of Leakage Detection and Intervention Scenarios for CO2 Sequestration CCP3 contingency Planning: White Paper on Existing Literature. Stanford Center for Carbon Storage, Stanford University.

Druhan J., Vialle S., Maher K., Benson S., and Agarwal A., Reactive transport modeling for geochemical detection and mitigation of CO2 leaking into a confined aquifer. *In preparation*

Vialle S., Druhan J., and Maher K., Geochemical evolution of a fractured system in the context of underground carbon storage, using reactive transport modeling. *In preparation*