Workshops on Carbon Capture and Storage
Instituto de Ingeniería, UNAM

Modeling of the CO_2 Plume

Ramon Carbonell

CSIC

The Compostilla Project OXYCFB300

GOBIERNO DE ESPAÑA

ciudad de la energía

European Energy Programme for Recovery

MUSTANG CO_2

March 2012

CIUDEN: Spanish government foundation to promote, among other things, Carbon Capture and Storage

MUSTANG: EU 7th FP project: “A MUltiple Space and Time scale Approach for the quaNtification of deep saline formations for CO2 storaGe” (2009-2013)

Hontomin is the Tech Demonstration Plant of the Compostilla OXYCFB300 EEPR project, run by ENDESA, in collaboration with CIUDEN and FOSTER-WHEE
LER

EEPR “European Energy Programme for Recovery” facilitates investments on infrastructure and technology projects in the energy sector; helps improve the security of supply of the Member States and, promotes implementation of the 20/20/20 objectives for 2020.

CSIC is the “Spanish Agency for Scientific Research”, a network of research institutes.

The Players

The Research Team:

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The Journalist: R. Carbonell[1,4]

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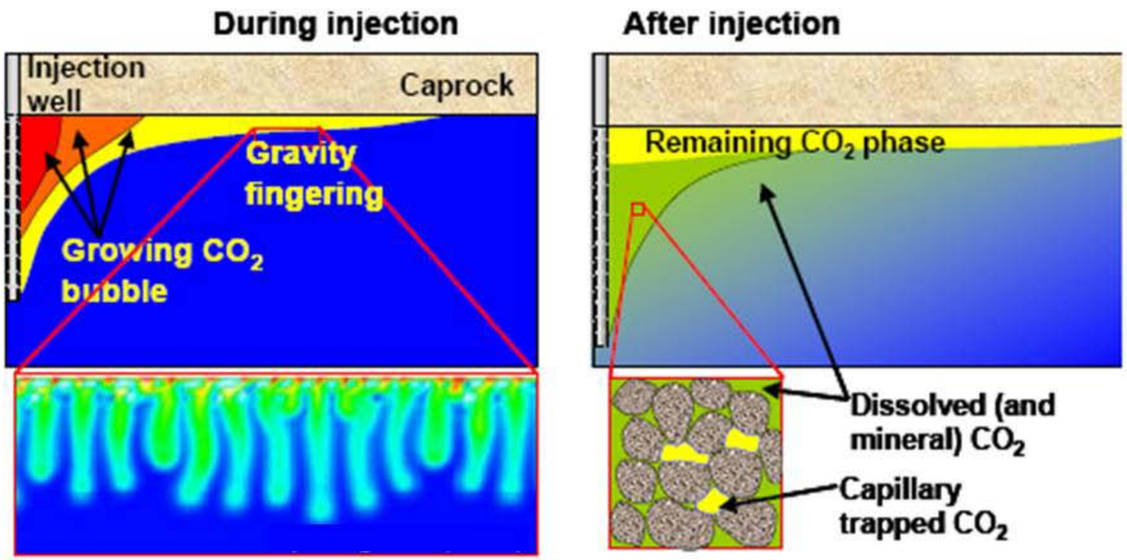
Main issues



- Movement of the CO_2-rich phase within the geological formations (long-term sequestration).
- Understanding of different mechanisms of trapping: structural, capillary, solute and mineral.
- CO_2 dissolution into the aqueous phase (brine) (solute trapping: ideally as bicarbonate, but also carbonic acid).
- Interaction between these solutes and minerals, and the ability of the geological formation to neutralize the solution and mineralize the CO_2.
- Coupled hydro-mechanical effects (porosity and permeability changes) caused by the evolution of fluid pressures during and after CO_2 injection.
- Management of CO_2 at surface and injection strategies.

Objectives

- Development of numerical, analytical and semi-analytical tools.

- Design and planning of characterization tests (hydro-thermo-chemical-mechanical) and CO_2 injection tests that will be undertaken at the Technological Demonstration Plant (TDP) of Hontomín.

- Interpretation of characterization tests:
  - Knowledge of chemical and structural composition, heterogeneity of the geological formations.
  - To know the porosity changes.
  - To determine the hydraulic connectivity between reservoir and caprock.
  - To know the dynamics of CO_2 migration within the reservoir.
  - Hydro-mechanical response of the system: evolution of pressures in the reservoir as CO_2 is injected; mechanical resistance of caprock; risks of leakages.
  - To know if the CO_2 will be effectively trapped.

- Modeling also can contribute to the development of CCS integration models (capture-transport-storage), and new technologies (e.g., injection strategies to improve the efficiency in the short term and the effectiveness in the long term.

Methodology (tools)

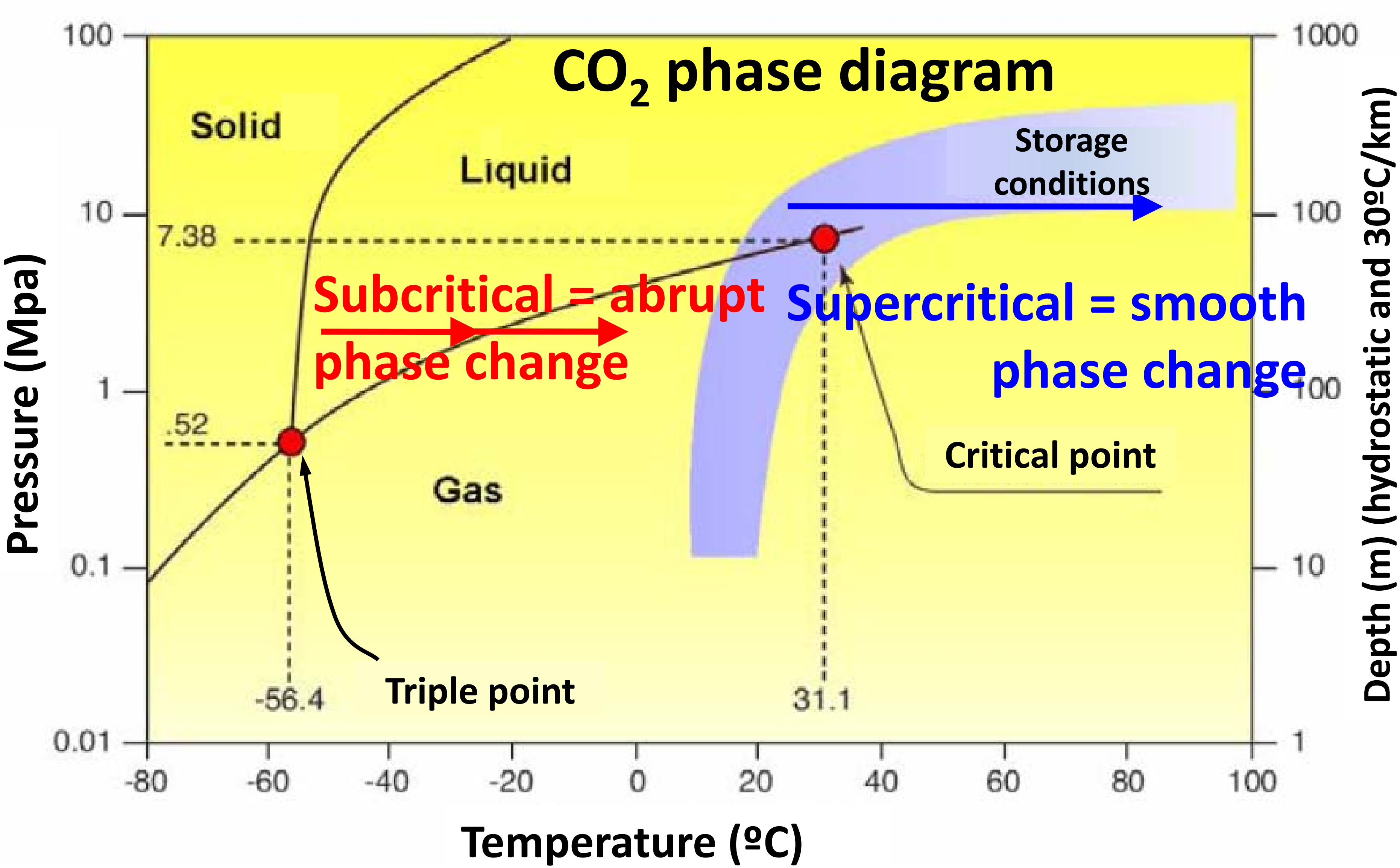
Modeling of multi-phase flow and multi-component reactive transport

- Thermodynamics of CO_2 (gas, liquid and supercritical states) and brine.
- Thermodynamics of multi-component gaseous mixtures (EoS, fugacity coefficients, equilibrium constants).
- Analytical solutions and non-local formulations (both in time and space), upscaling: MRMT, R-MRMT.
- Use of existing codes
  - INVERT
  - TRANSIN
  - CODE_BRIGHT
  - RETRASO
  - COGERE
  - KRINET
- Code development: object oriented programming (PROOST, CHEPROO): FORTRAN, C++, MatLab.

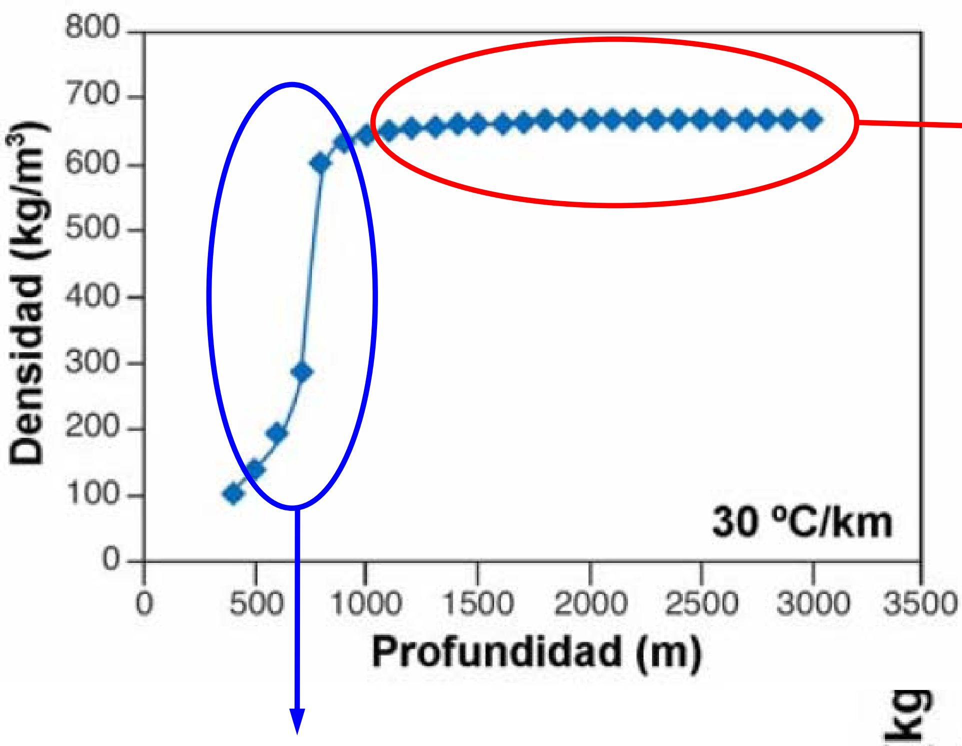
Key issues

- Fluid mechanics (hydraulic) issues
  - Basic description
  - Scoping calculations for: Pressure impact (magnitude and extent) and CO2 bubble
  - Hydraulic characterization. Preferential flow paths
- Geo Chemical issues (coupled to hydraulic)
  - CO2 Dissolution and fingering
  - Mineral dissolution (and precipitation?)
- Mechanical issues
  - Stability
  - Microsesmic activity
- Hontomin

CO2 supercritical?



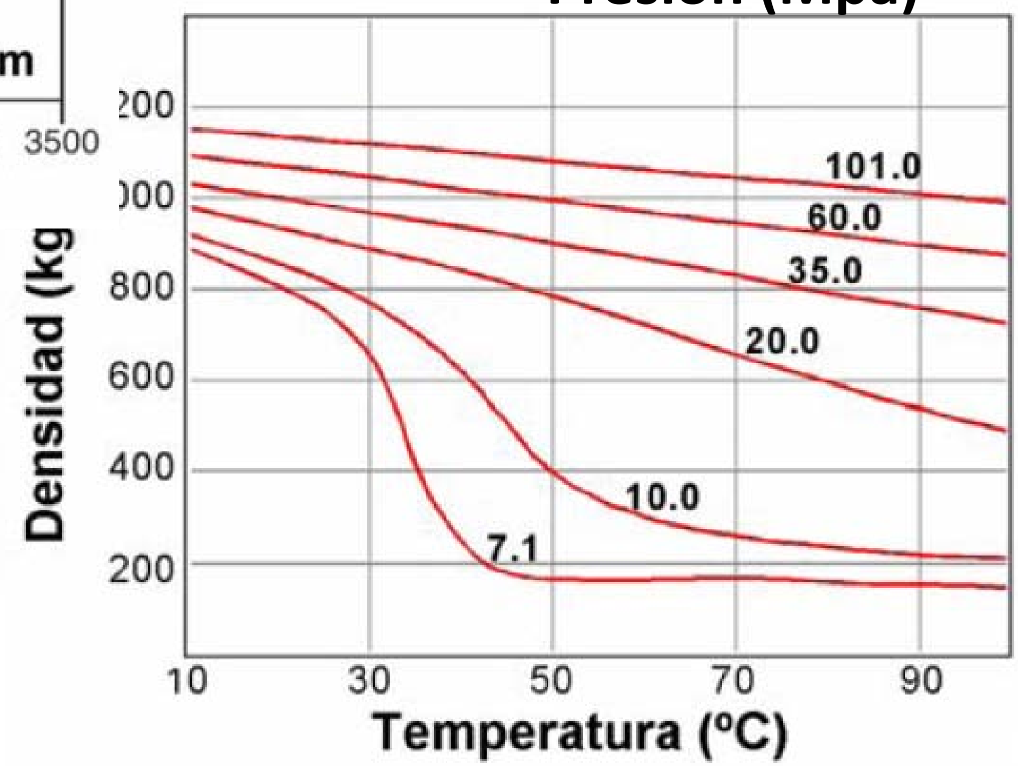
CO2 supercritical?



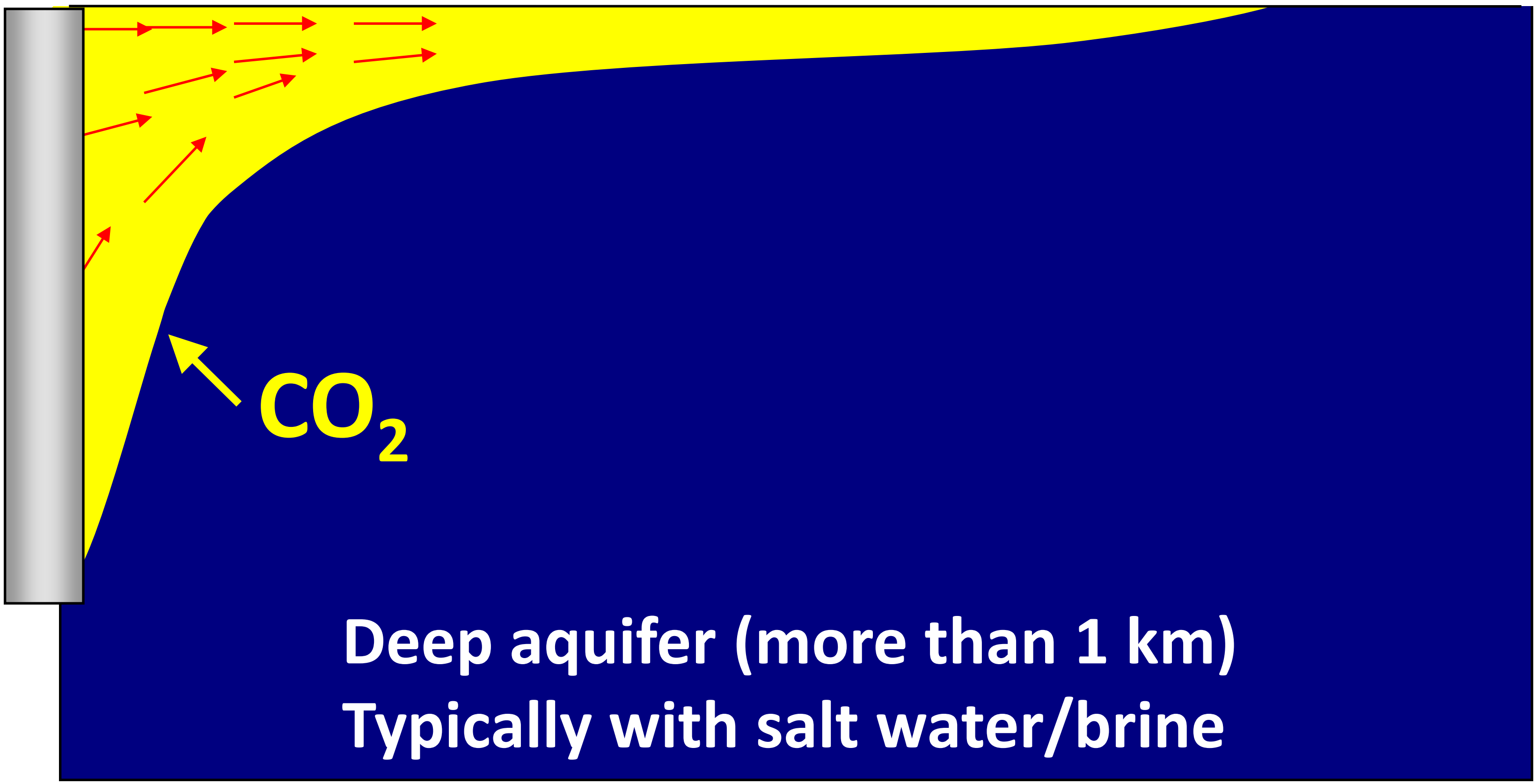
For high P, high density low compressibility (like a liquid)

For low P & T, low density & high compressibility (like a gas)

Presión (Mpa)

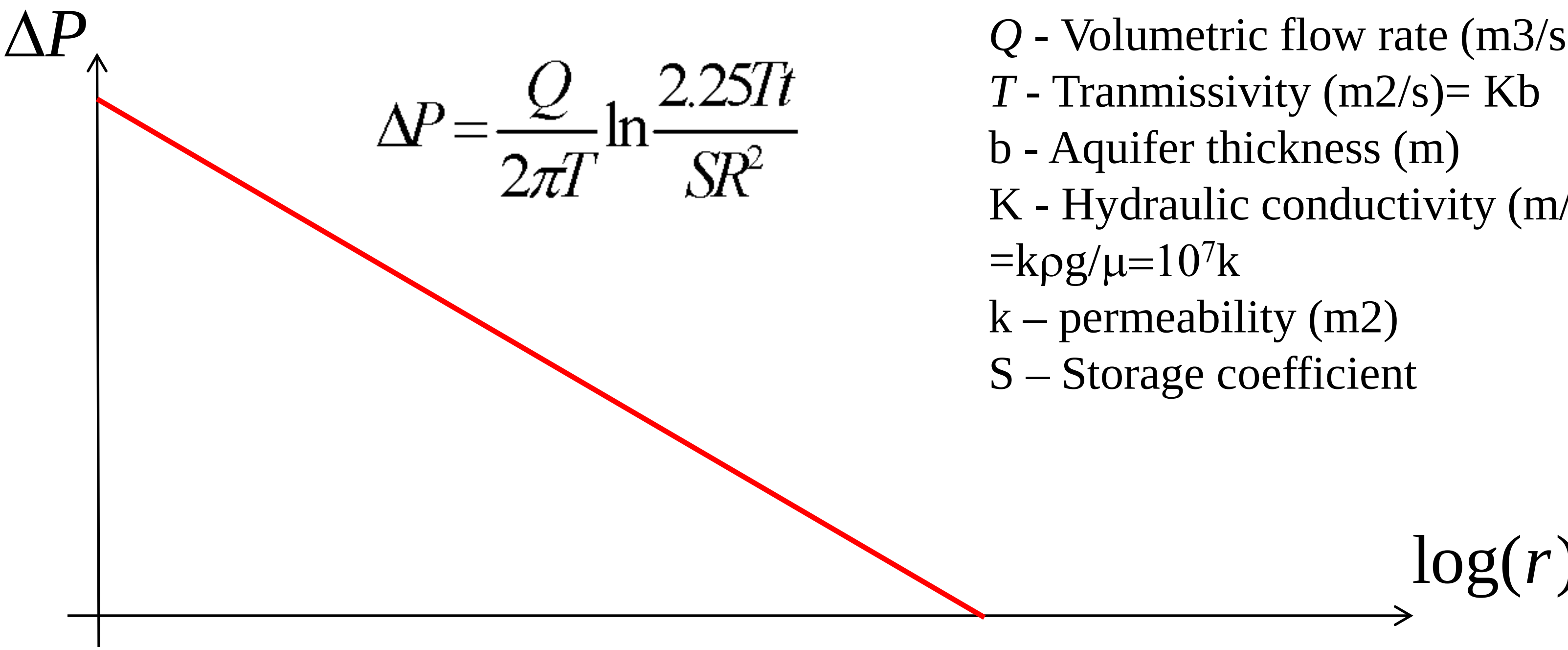


Buoyancy and flow



Scoping calculations: Regional pressure buildup

Most of the pressure build-up is associated to the resistance of water to be displaced



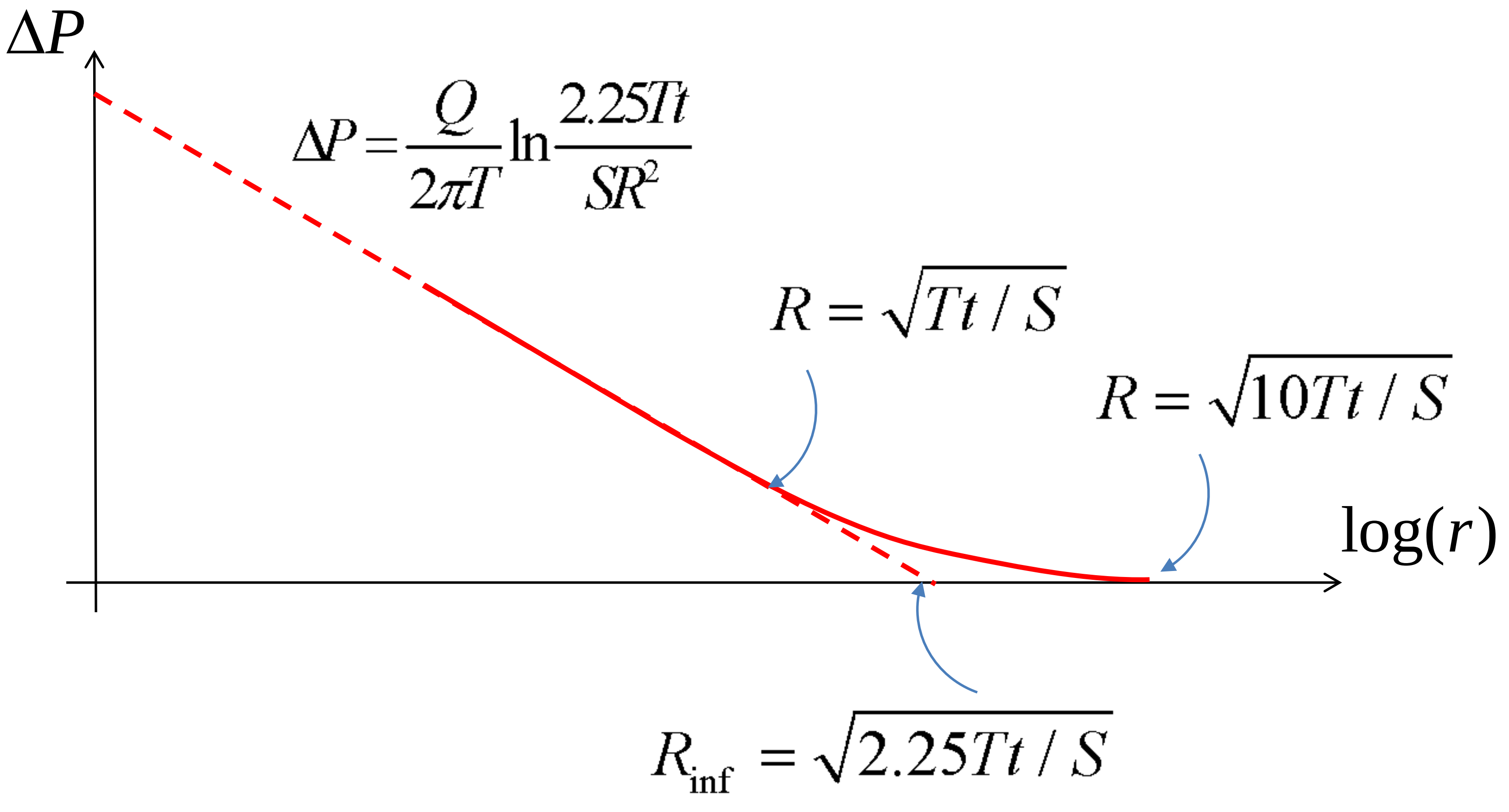
$$\Delta P = \frac{Q}{2\pi T} \ln \frac{2.25Tt}{SR^2}$$

Q - Volumetric flow rate (m3/s)
T - Tranmissivity (m2/s)= Kb
b - Aquifer thickness (m)
K - Hydraulic conductivity (m/s) $=k\rho g/\mu=10^7 k$
k – permeability (m2)
S – Storage coefficient

$$R_{\text{inf}} = \sqrt{2.25Tt / S}$$

Scoping calculations: Regional pressure buildup

Most of the pressure build-up is associated to the resistance of water to be displaced



Scoping calculations (regional): the bad news
Pressure buildup and Radius of influence

Assume a 1Mt/year injection rate

If compressible and permeable formation ($k=10^{-12}\ m^2$, $Ss=10^{-5}\ m^{-1}$)

t (days)	10 days	30 years
Rinf (km)	1.39	46.1
ΔP (bar) (r=100m)	1.69	3.94

Large region affected
Risk brine migration

If low compressibility and permeability formation ($k=10^{-14}\ m^2$, $Ss=10^{-6}\ m^{-1}$)

t (days)	10 days	30 years
Rinf (km)	0.44	14.6
ΔP (bar) (r=100m)	95.2	320

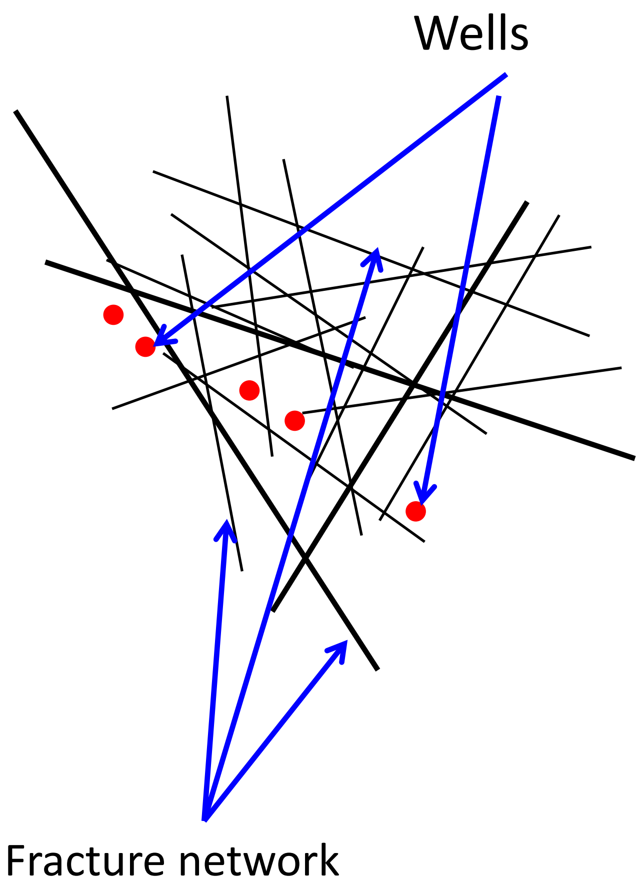
Unbearable pressure

Observations:

1) Characterization (geologic and hydraulic) needed
2) Very likely, brine pressure control will be needed

But, do not go away yet!

Cause (and solution) of scale effects



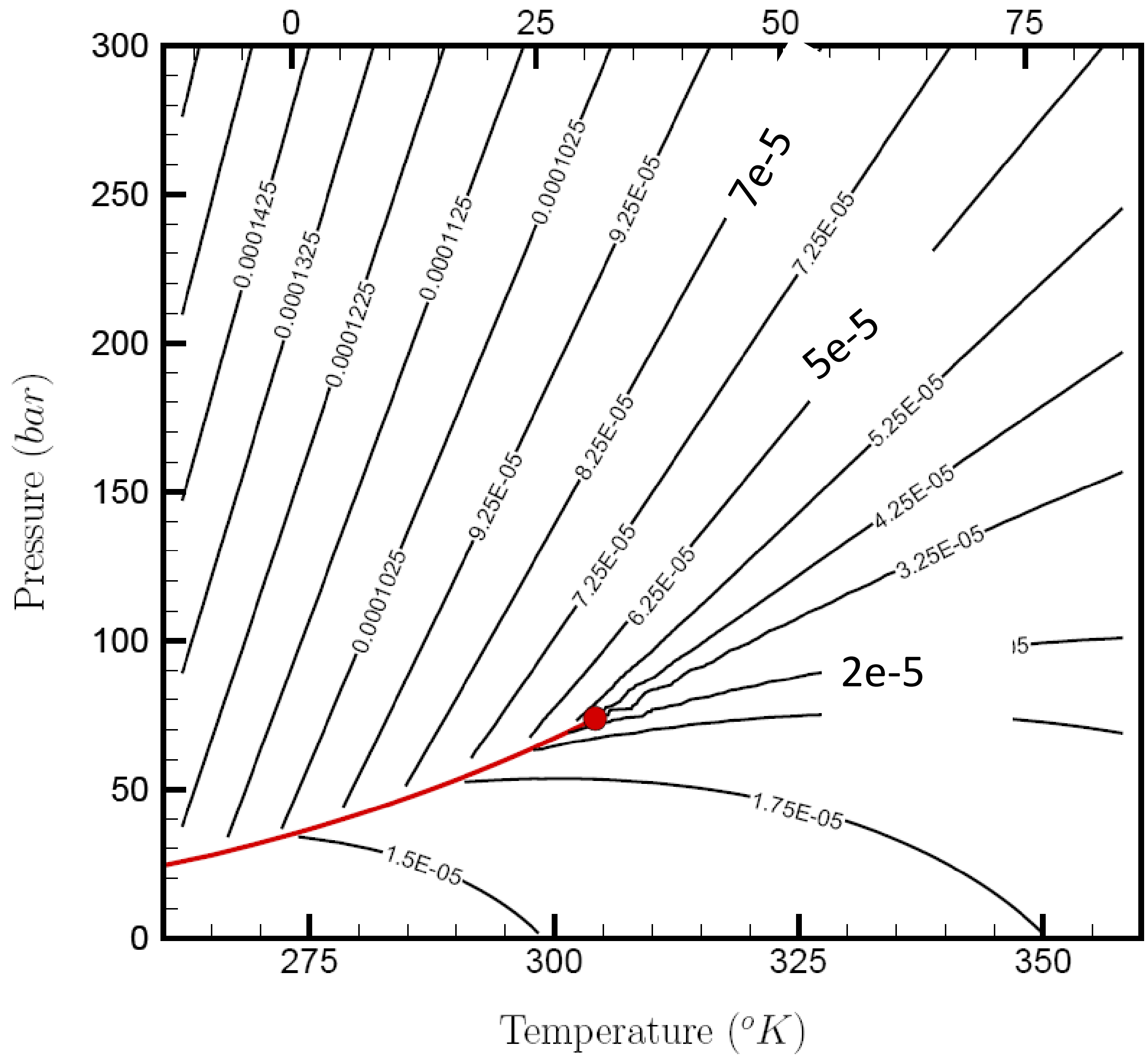
Large scale permeability, which is derived from hydraulic tests, is controlled by large fractures

The effective permeability of every well depends on whether or not a conducting fracture is intersected. Chances of hitting a subvertical fracture are low.

Wells act as if they were poorly built

Solution: Long horizontal wells

Low viscosity

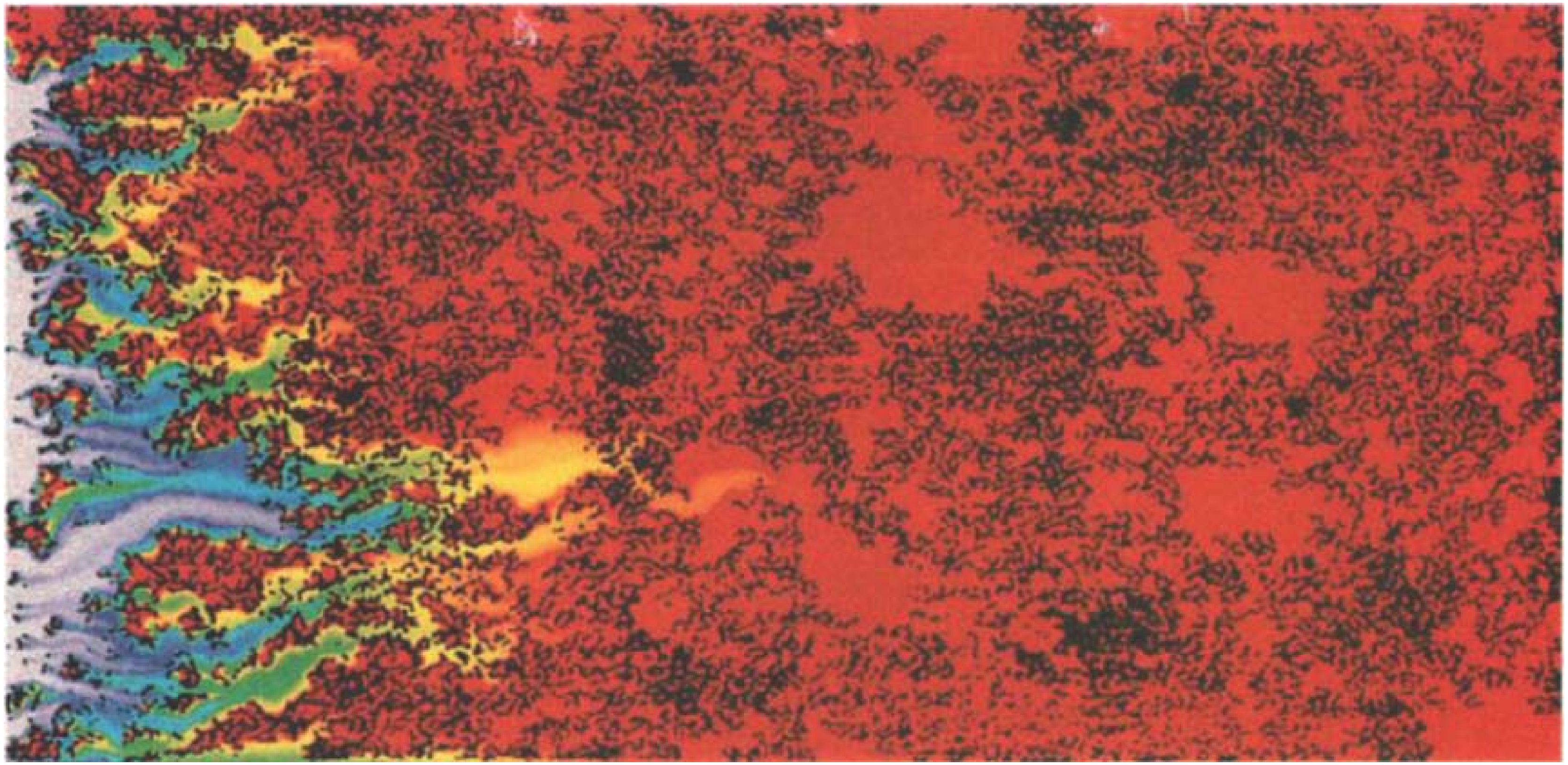


Pure CO_2 viscosity (Pa·s)

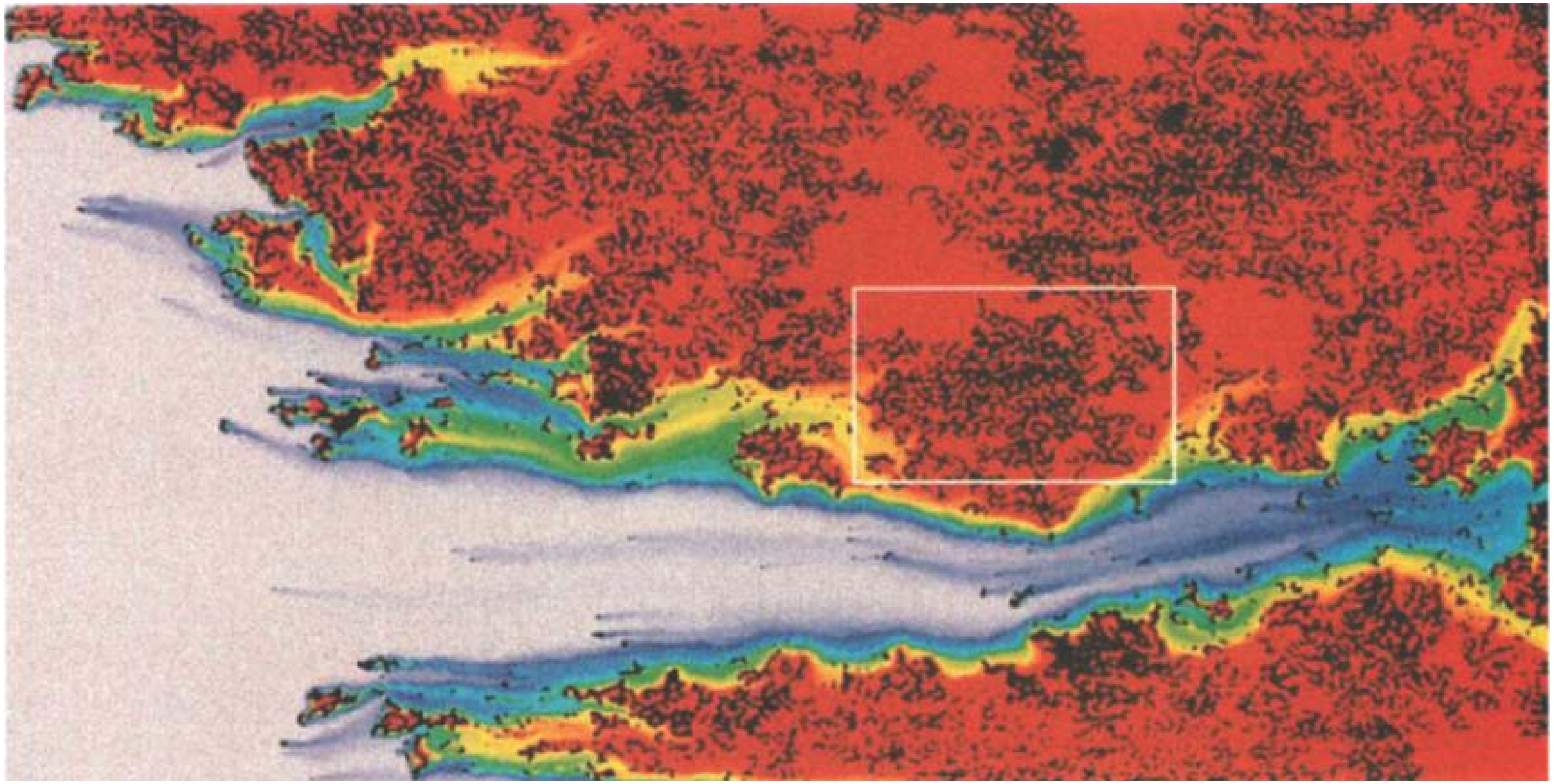
CO_2 viscosity is some 10-20 times smaller than water

Water viscosity 0.001 Pa·s

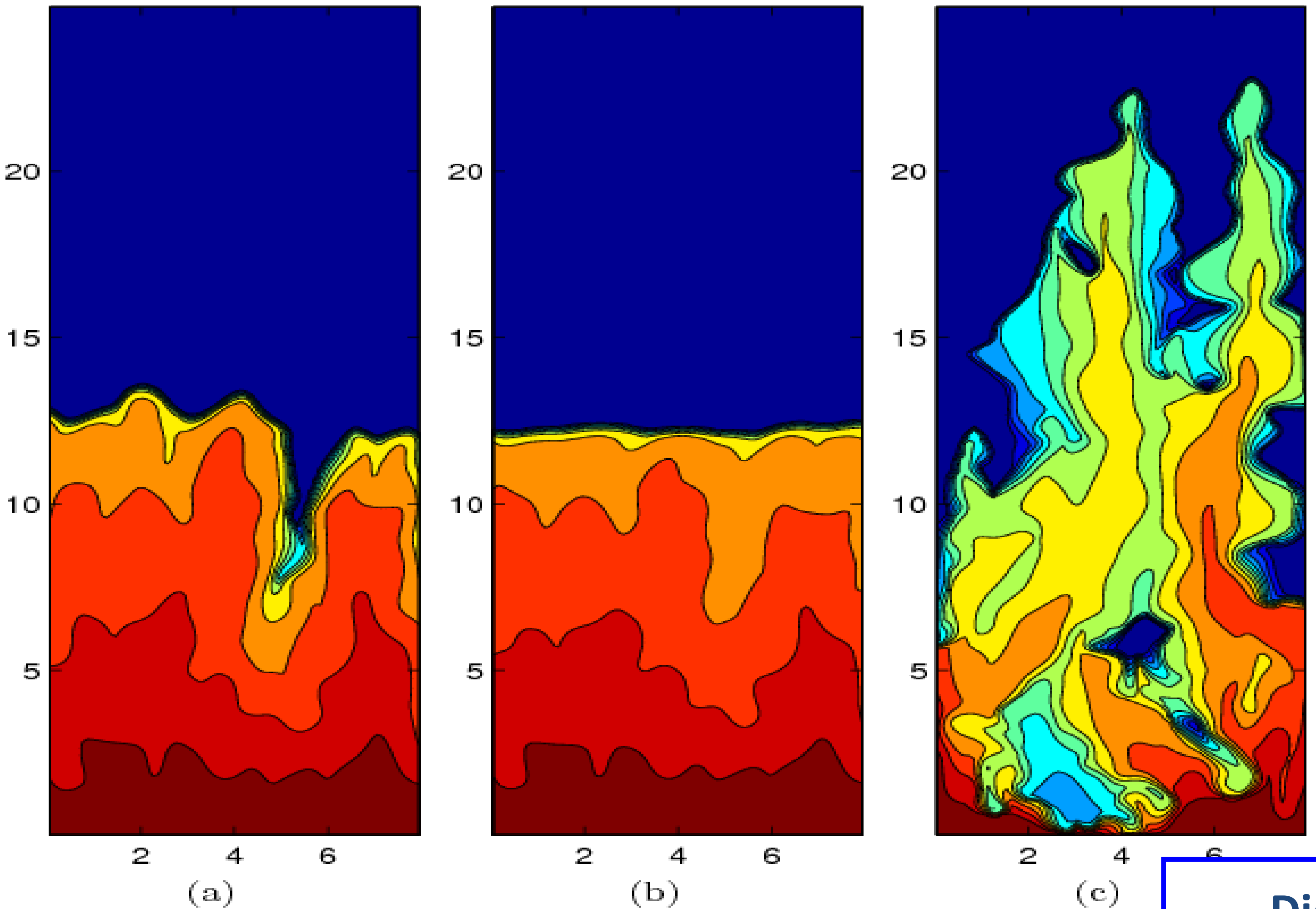
Viscous fingering



Viscous fingering



Fingering increases by superposition of buoyancy and viscosity effects

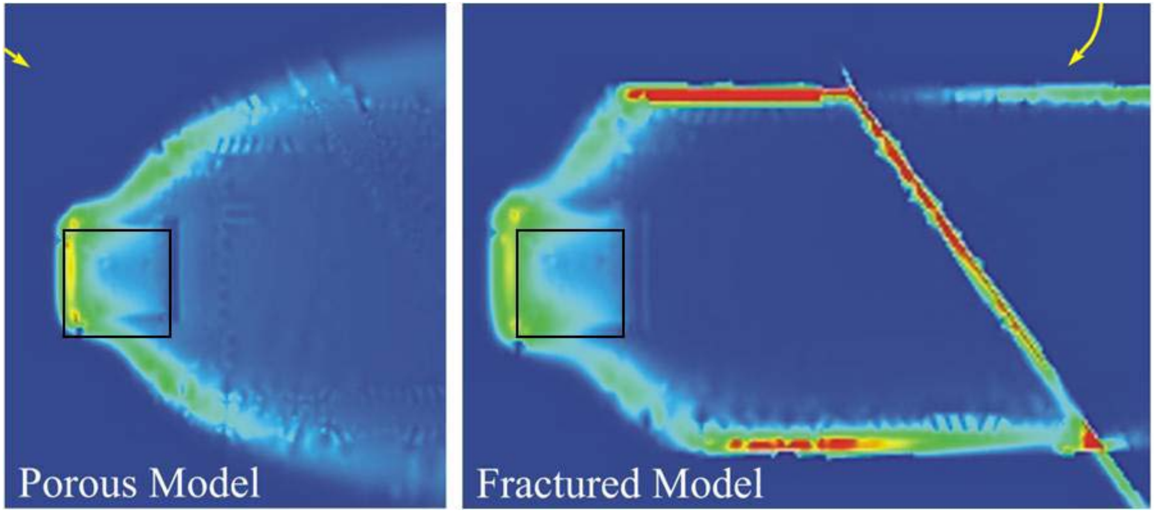


Diogo

R-MRMT and MRMT-R

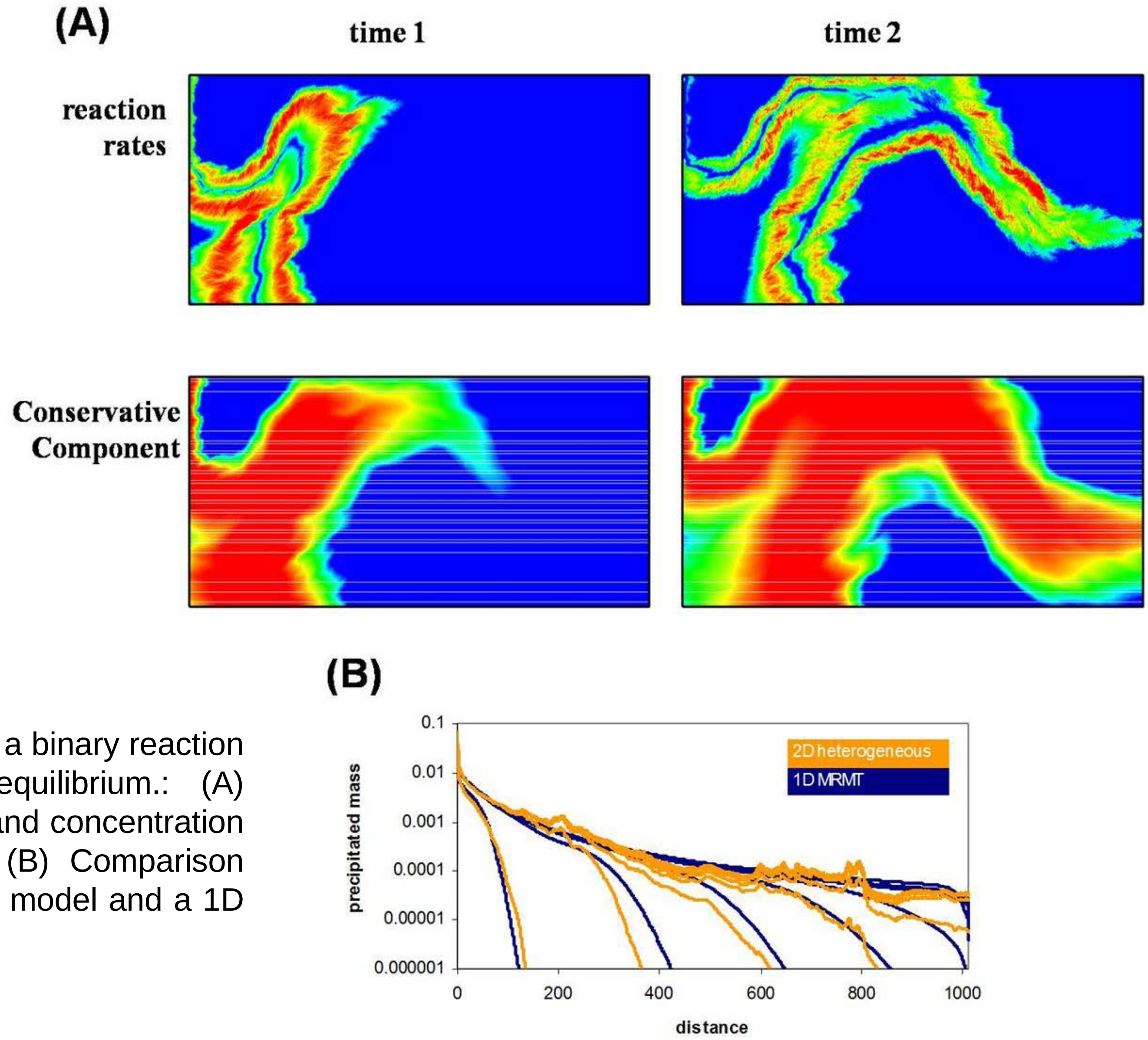
1. Mixing induces reaction

2. The presence of mobile and immobile zones induces mixing



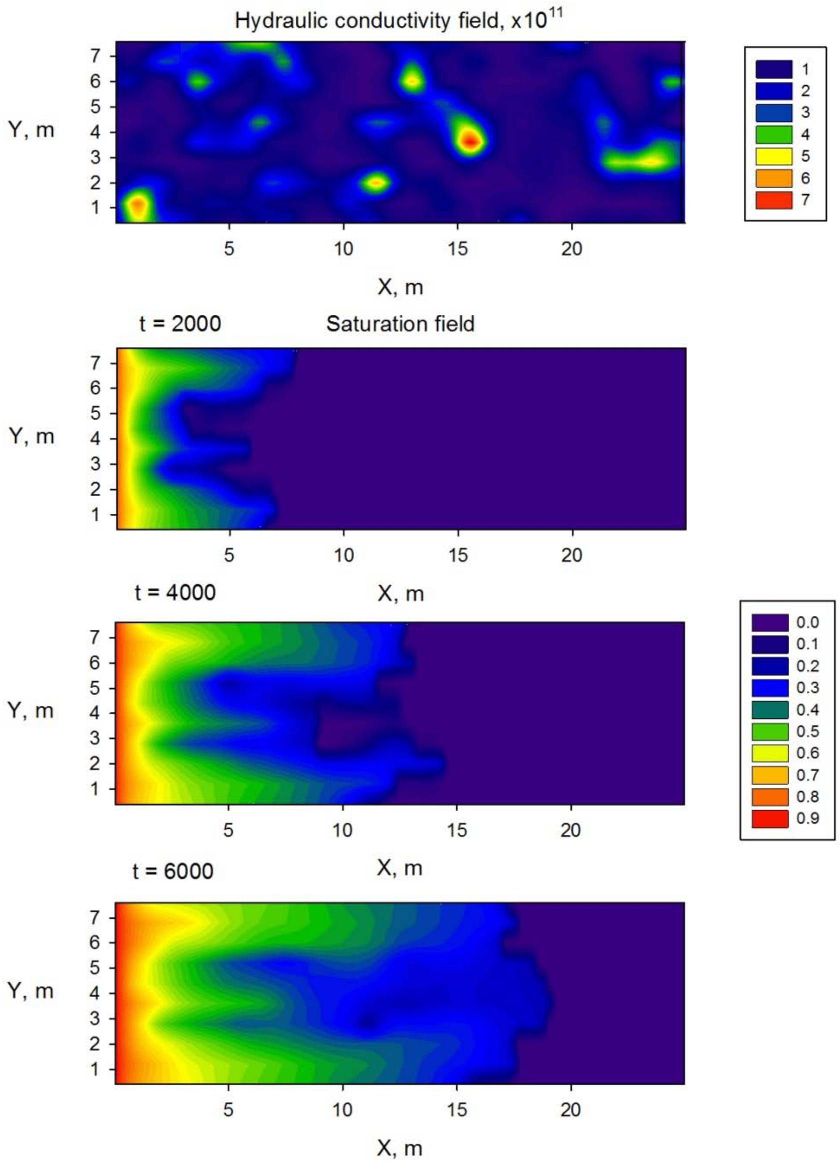
3. To take into account reaction induced by mixing: R-MRMT (<u>Reactive</u> Multi Rate Mass Transfer)

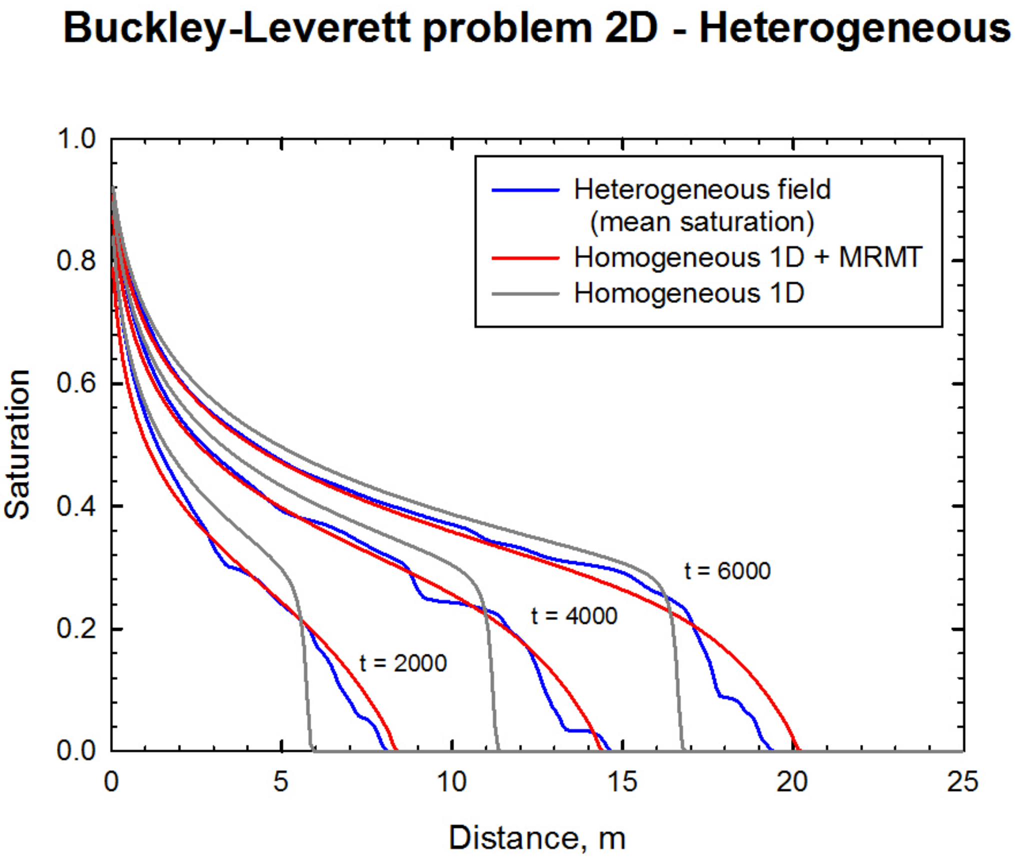
Application: Upscaling of reactive transport processes in heterogeneous media



Scale effects in a system with a binary reaction of dissolution-precipitation equilibrium.: (A) Distribution of reaction rates and concentration of conservative component. (B) Comparison between a 2D heterogeneous model and a 1D effective model of MRMT-R.

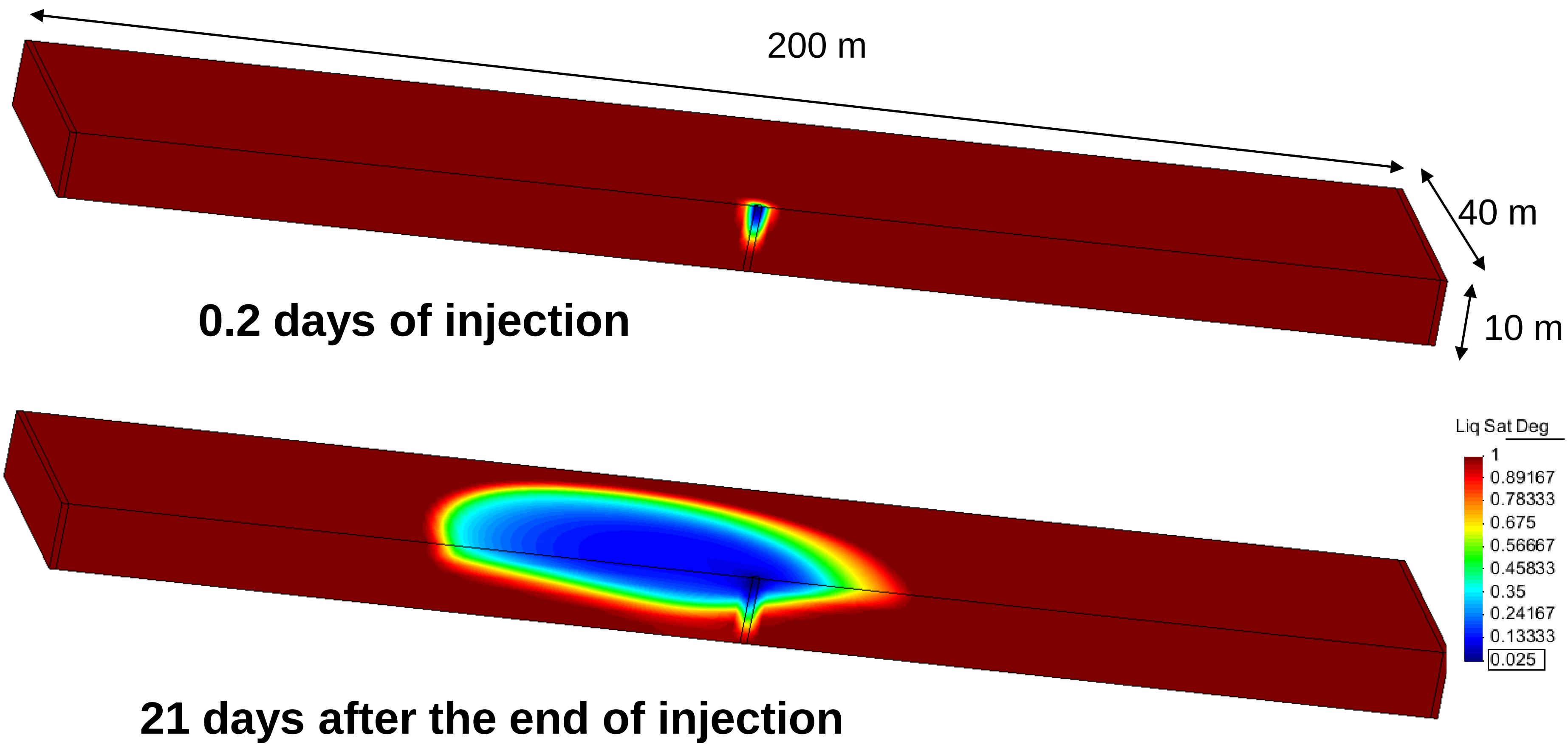
Application: Upscaling of multi-phase flow in heterogeneous media





CO_2 injection into anticline aquifers

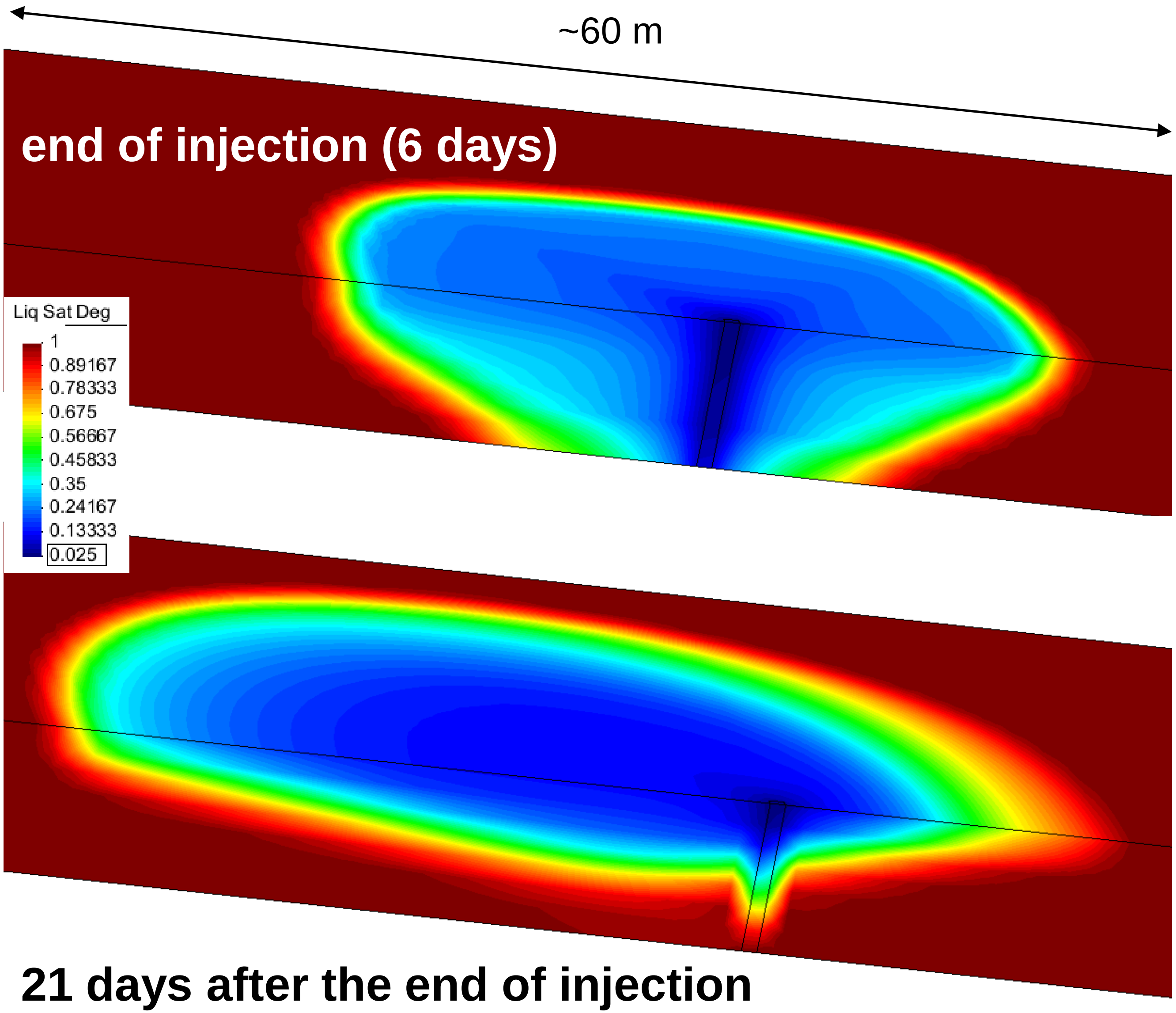
CODE_BRIGHT: 3D simulation of CO_2 injection at 1 kg/s into an aquifer with a slope of 5º (injection during 6 days)



CO_2 injection into anticline aquifers

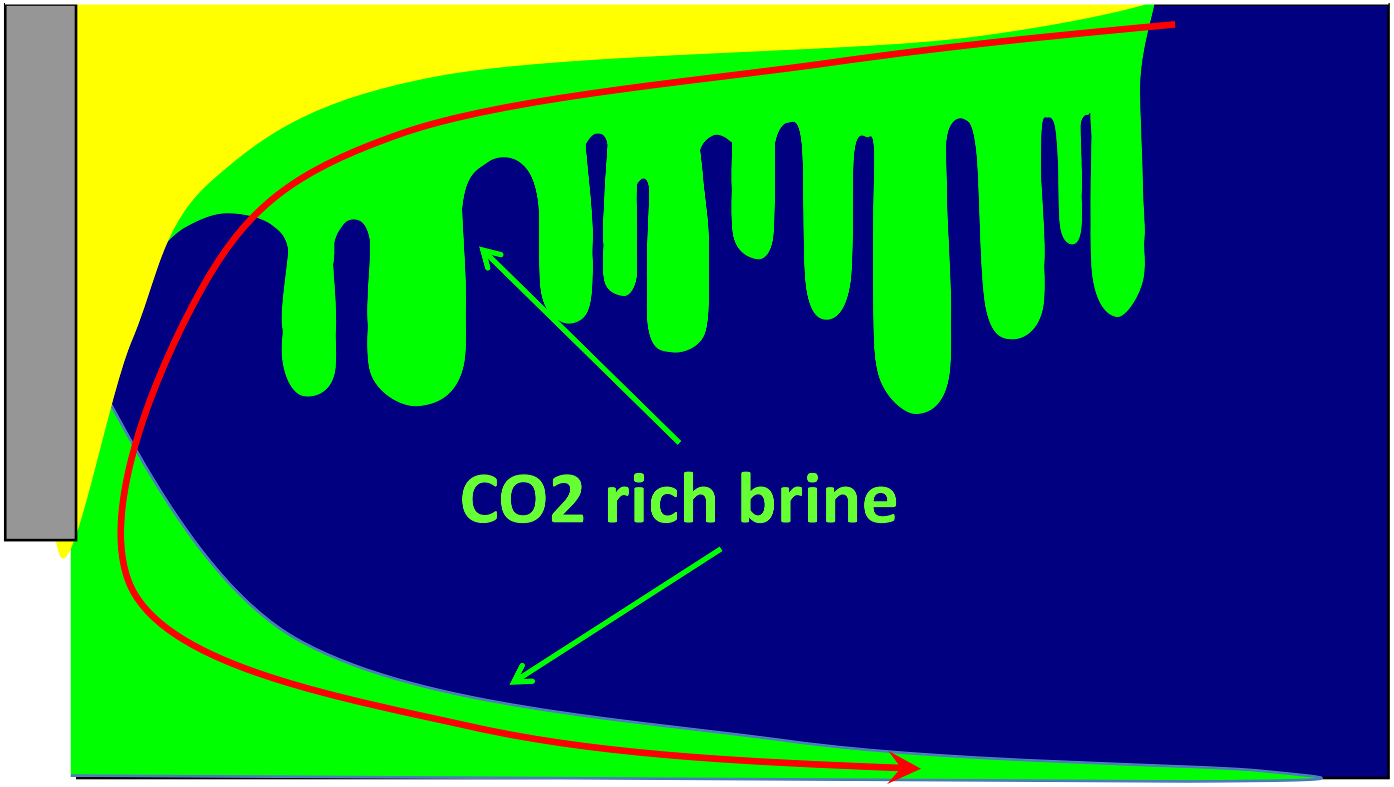
CO_2 buoyancy effect causes a migration of the CO_2 bubble upwards, specially after injection stop.

Gravitational forces dominate over viscous forces.

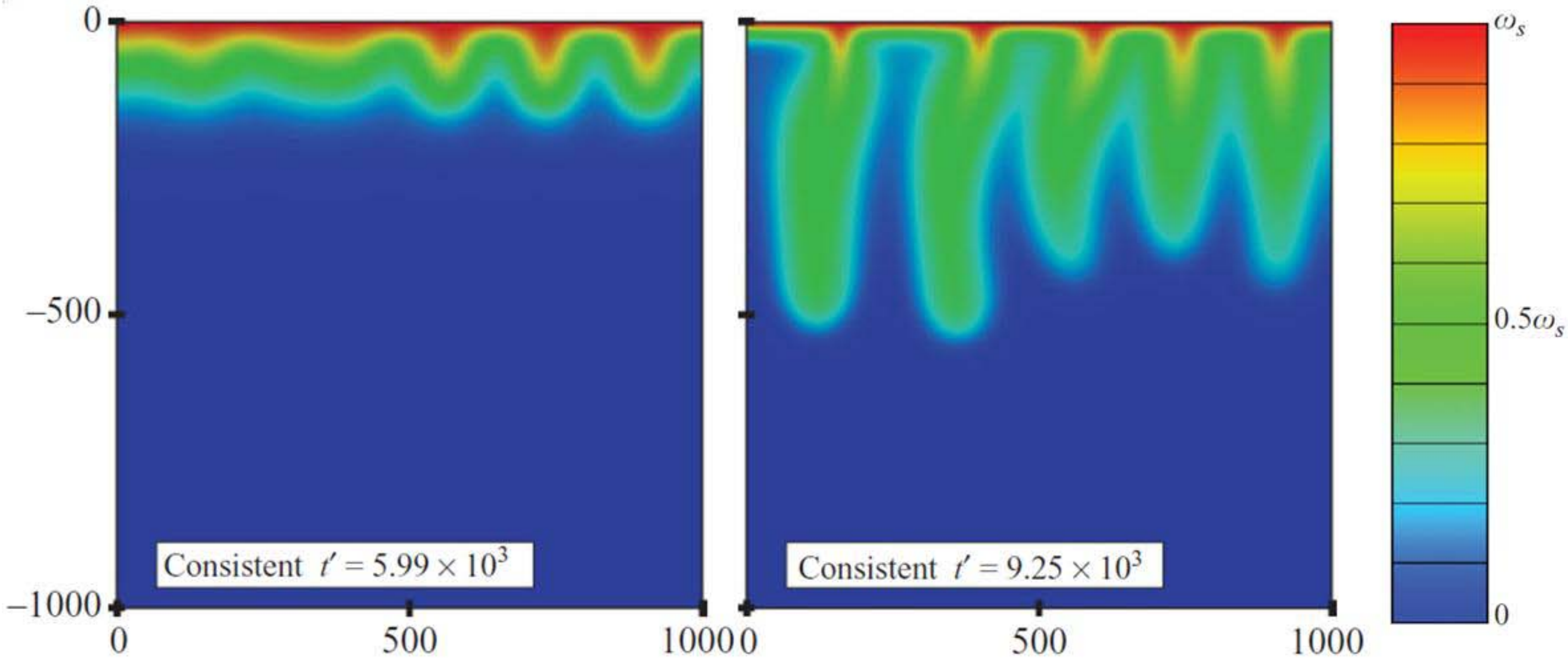


CO2 rich brine fingering

(CO_2 rich brine is denser and sinks in native brine)



Scoping calculations on dissolution rate



Scoping calculations on dissolution rate and onset of advection

$$m_s \approx 35 u_b \Delta\rho \omega_s$$

$$u_b = k \Delta\rho g / \mu$$

$$t' = \frac{u_b}{\phi L_s} t$$

$$b_L = \frac{\alpha_L}{L_s}$$

$$L_s = \frac{\theta D_m + \alpha_L u_b}{u_b}$$

μ	5,00E-04	Pa·s
Δρ	25	kg/m3
k	1,00E-12	m2
ub	4,90E-07	m/s
ωs	2,50E-02	
ms	1,07E-05	kg/m2/s
	0.34	**Mt/km2/yr**
α	10	m
Ls	10	
ϕ	0,1	
t_{onset}	**6,58**	**yrs**

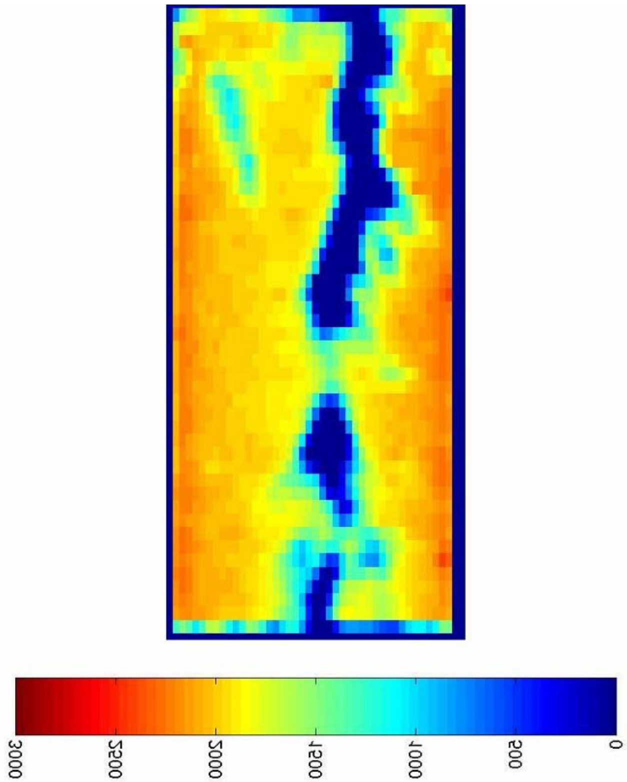
Dissolution can be very significant after a few years (which prevents further pressure buildup)

Challenge: reduce the time for the onset of advection (increase dispersion: viscous and capillary fingering, fluctuating injection)

Chemical interactions

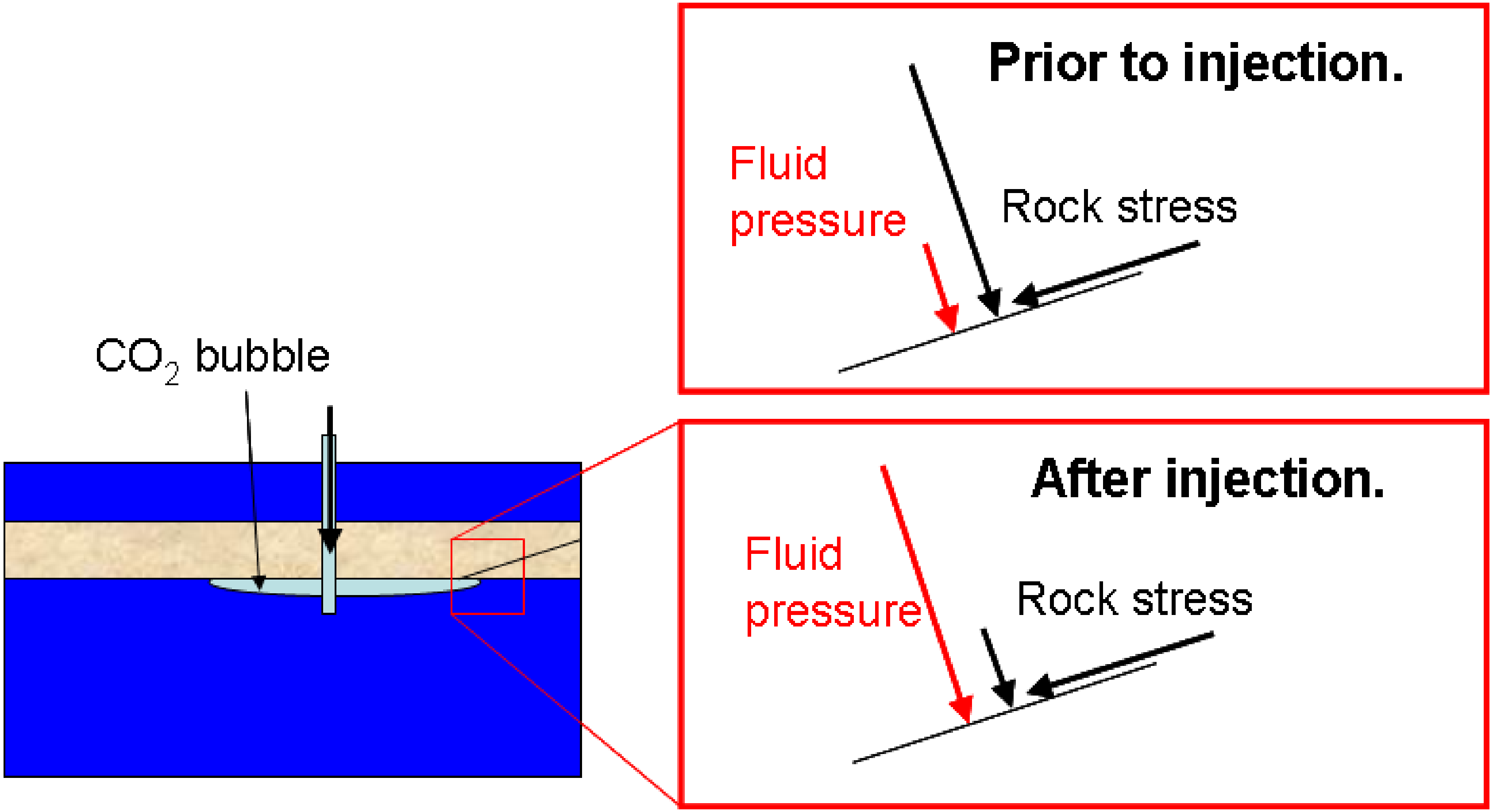
- CO2 saturated brine will be very aggressive (pH around 3)
- This will cause:
  - Mineral dissolution
  - Partial neutralization of acidity (further solubility of CO2)
  - Depending on mineralogy of the rock and chemistry of the brine, other minerals may precipitate (e.g., if brine is rich in sulphate and rock rich in cacite, anhidrite will precipitate)
- Mineral dissolution increases the permeability of the rock

Chemical coupling



Core photos prior to and (left) and after (center) injecting a CO2 rich solution and tomographic image (right). (Wormholes)

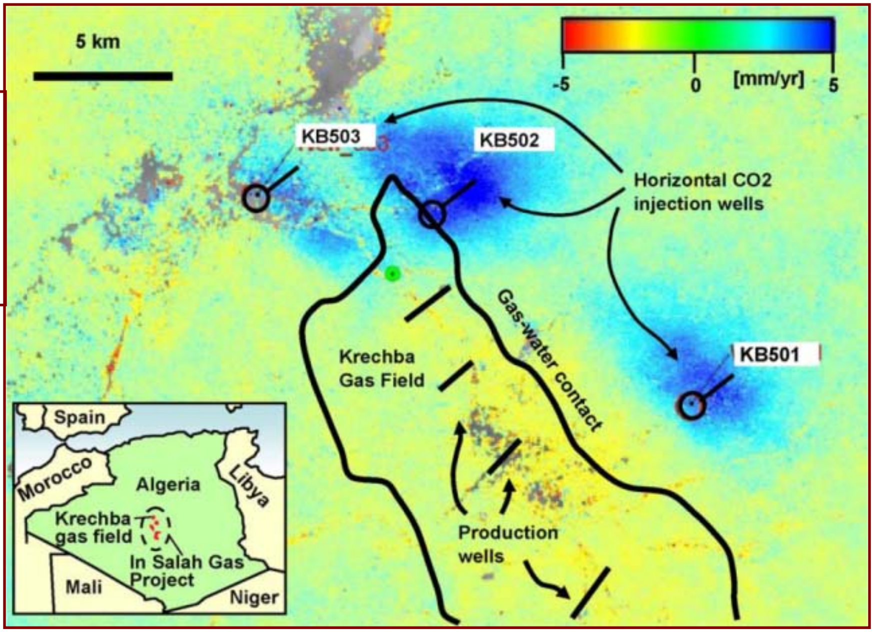
Mechanical coupling_ seal stability

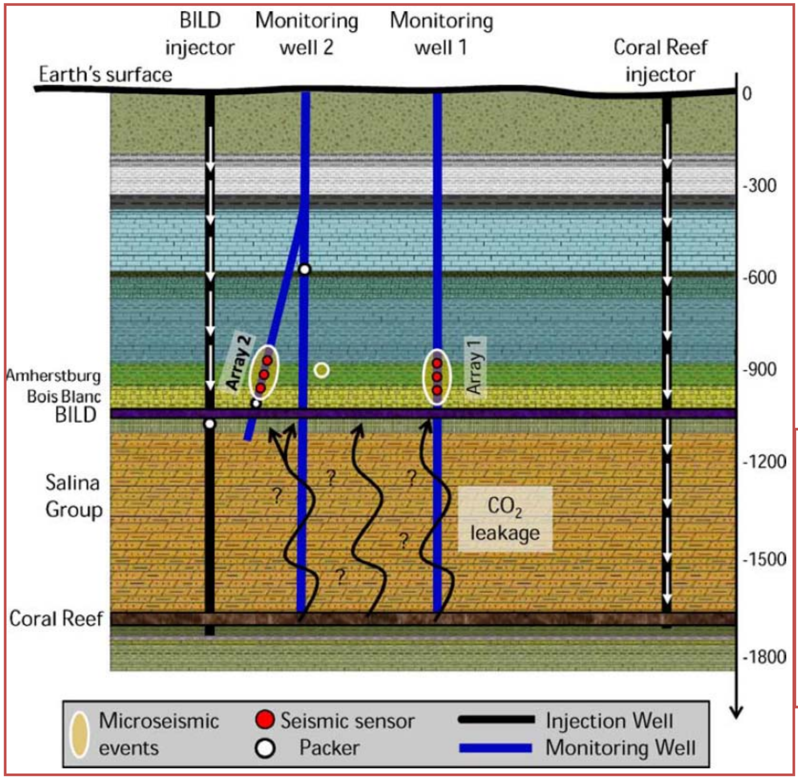


Pressure build up in the CO2 bubble and surrounding brine may compromise mechanical stability of the cap rock and its isolating properties.

HYDROMECHANICAL EFFECTS

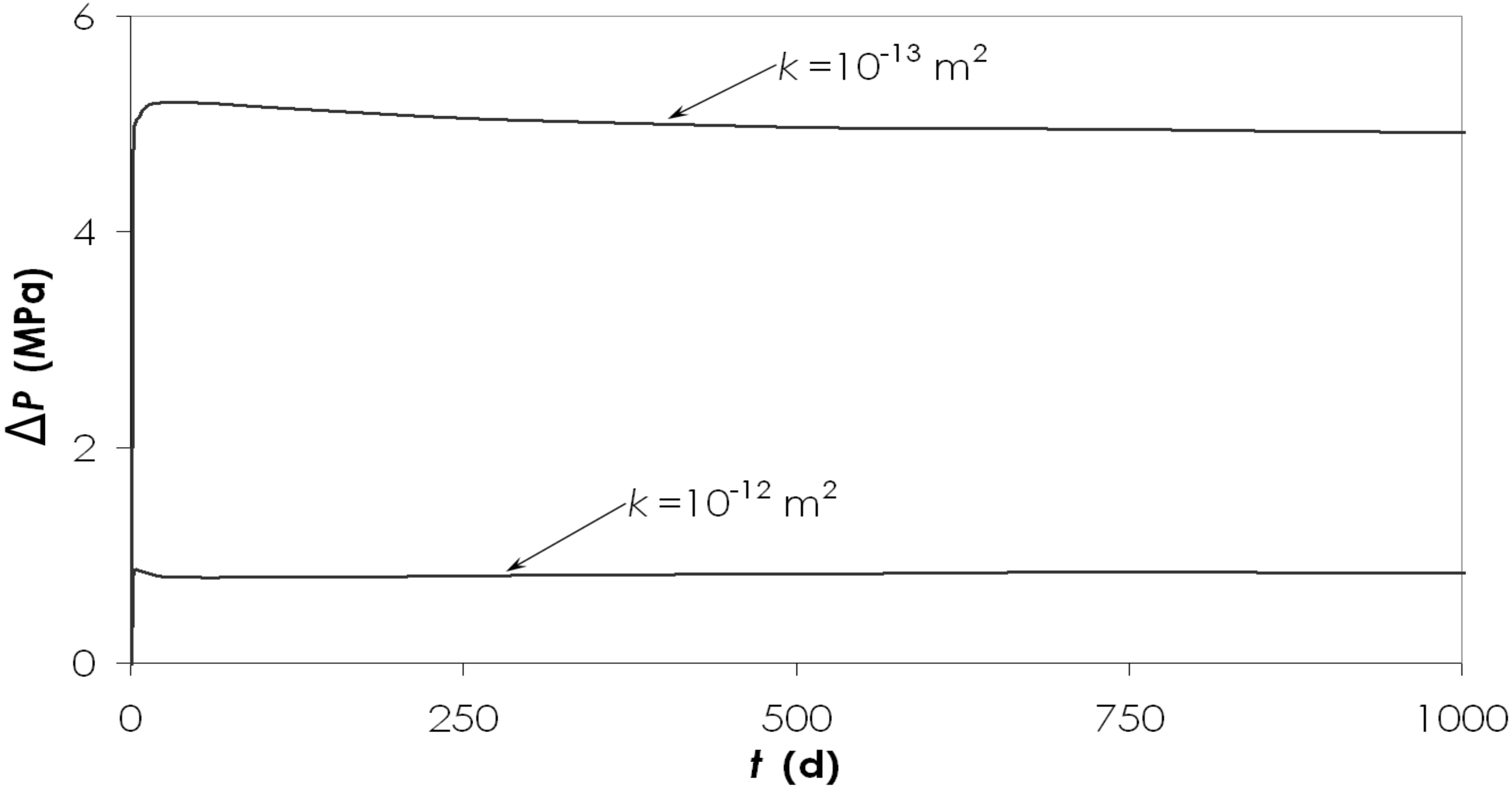
Uplift of 5 mm/yr in In Salah (Rutqvist *et al*., 2010, IJGGC)





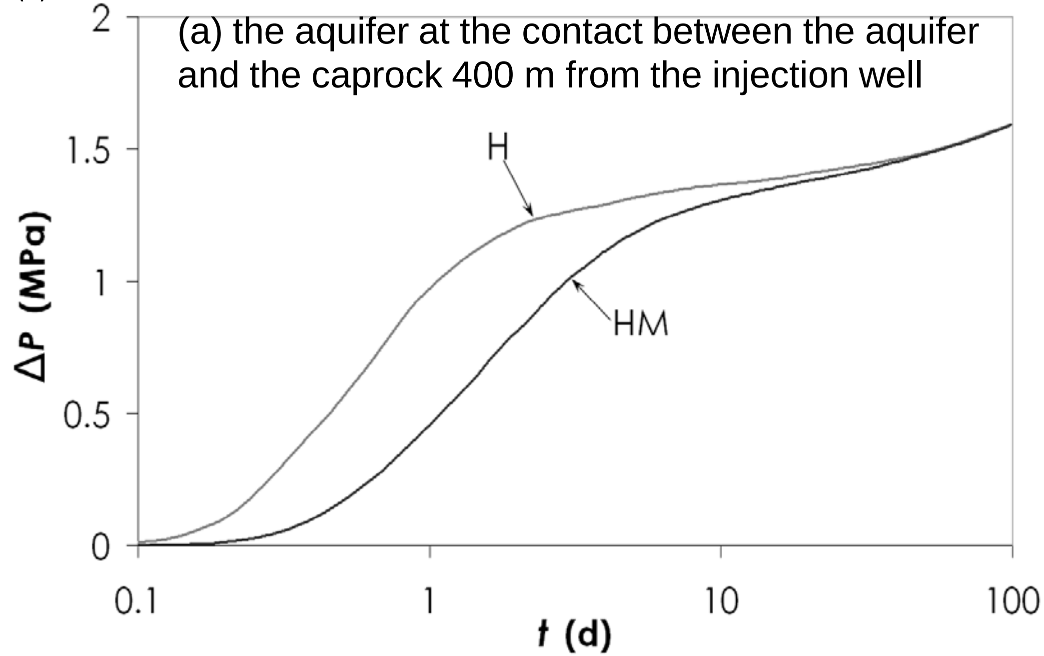
Microseismicity due to CO_2 leakage around wells in Otsego County, Michigan Basin, USA (Bohnhoff *et al*., 2010, IJGGC)

Pressure buildup

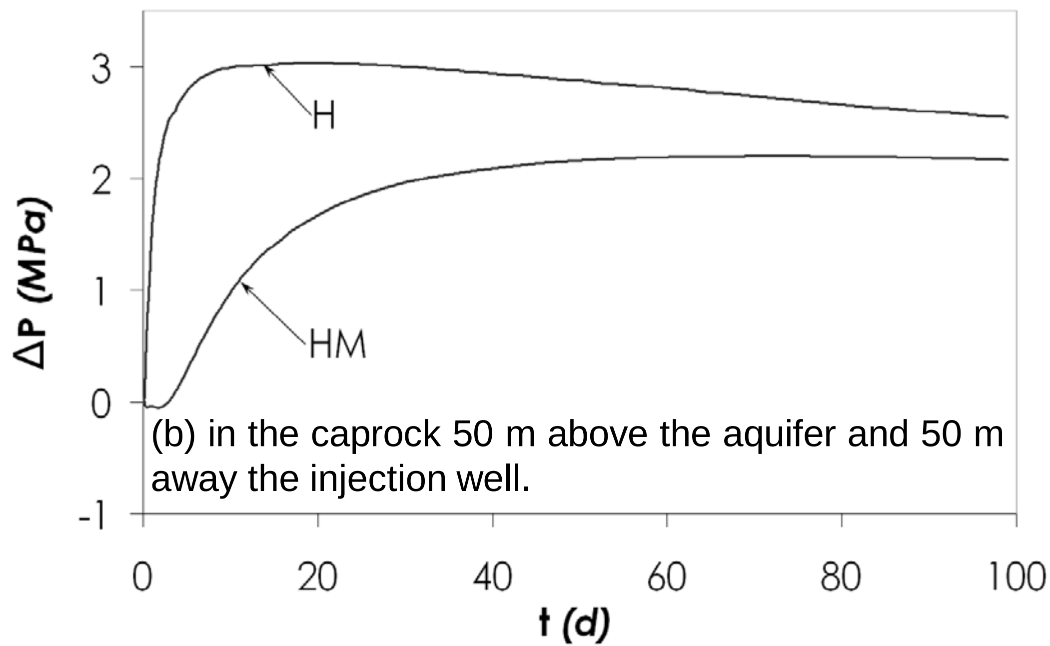


: Injection pressure at the top of the aquifer for a 1000 day injection period, for two intrinsic permeabilities of the aquifer. Injection pressure drops because of the lower CO_2 viscosity with respect to that of brine.

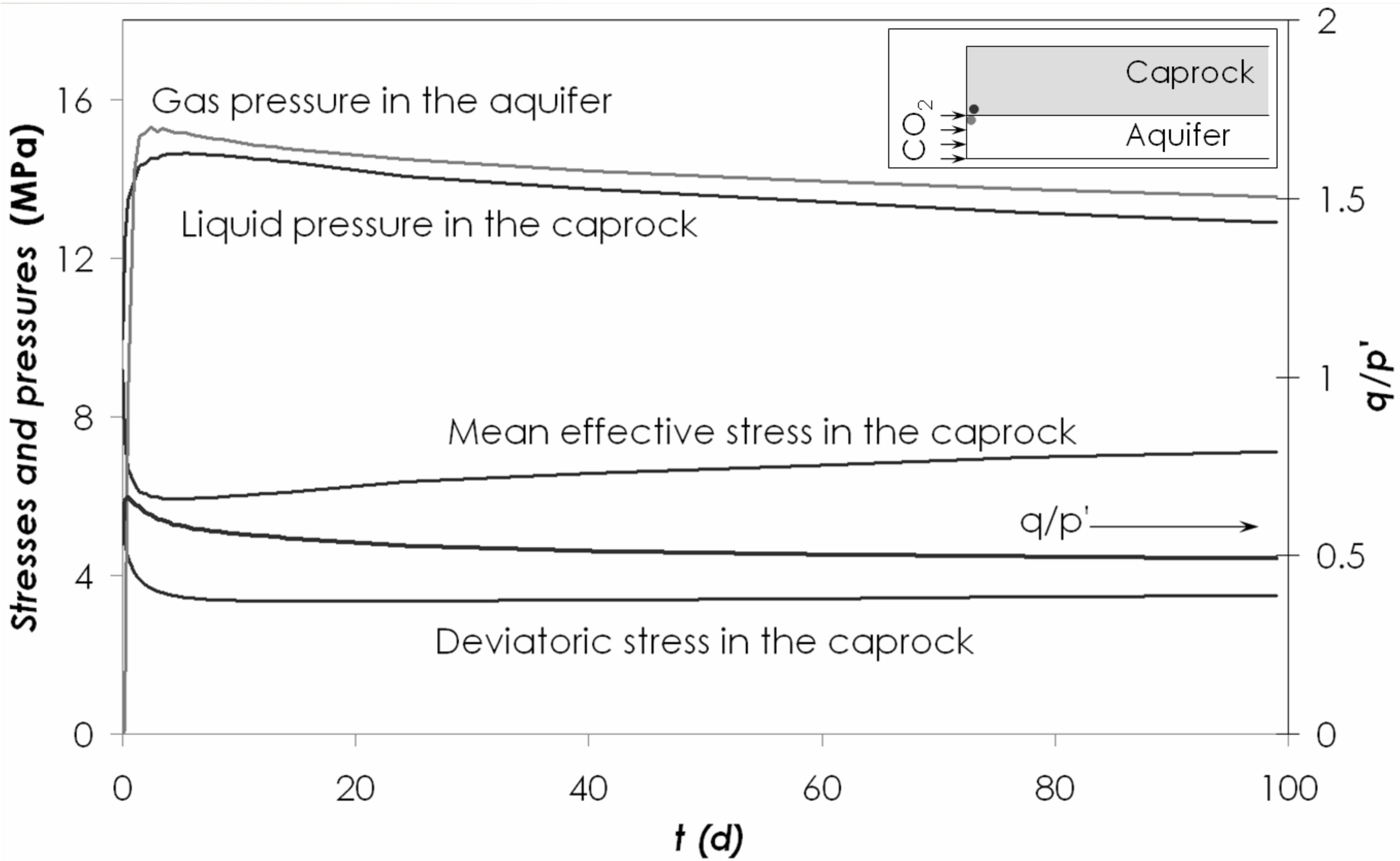
(a)



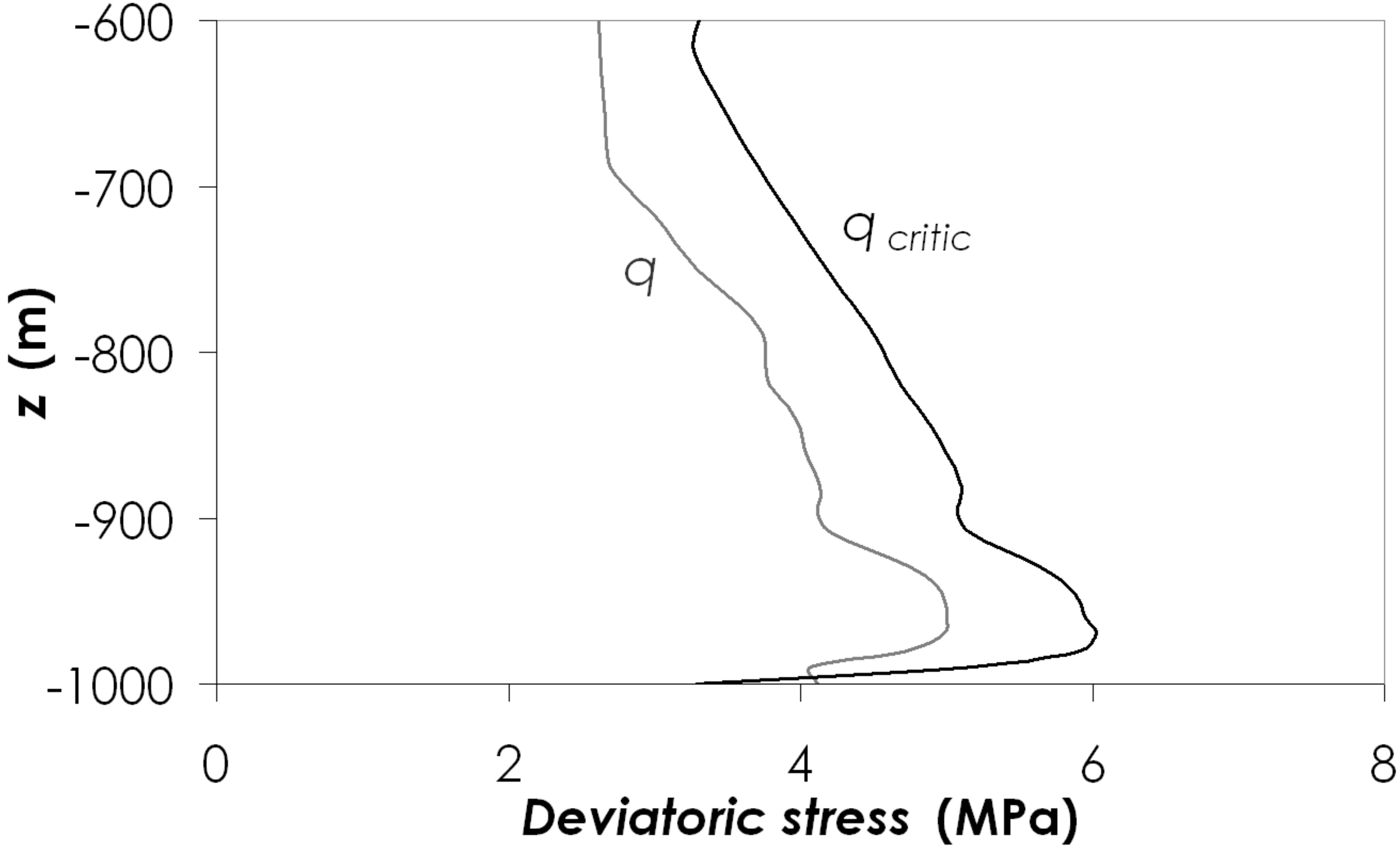
(b)



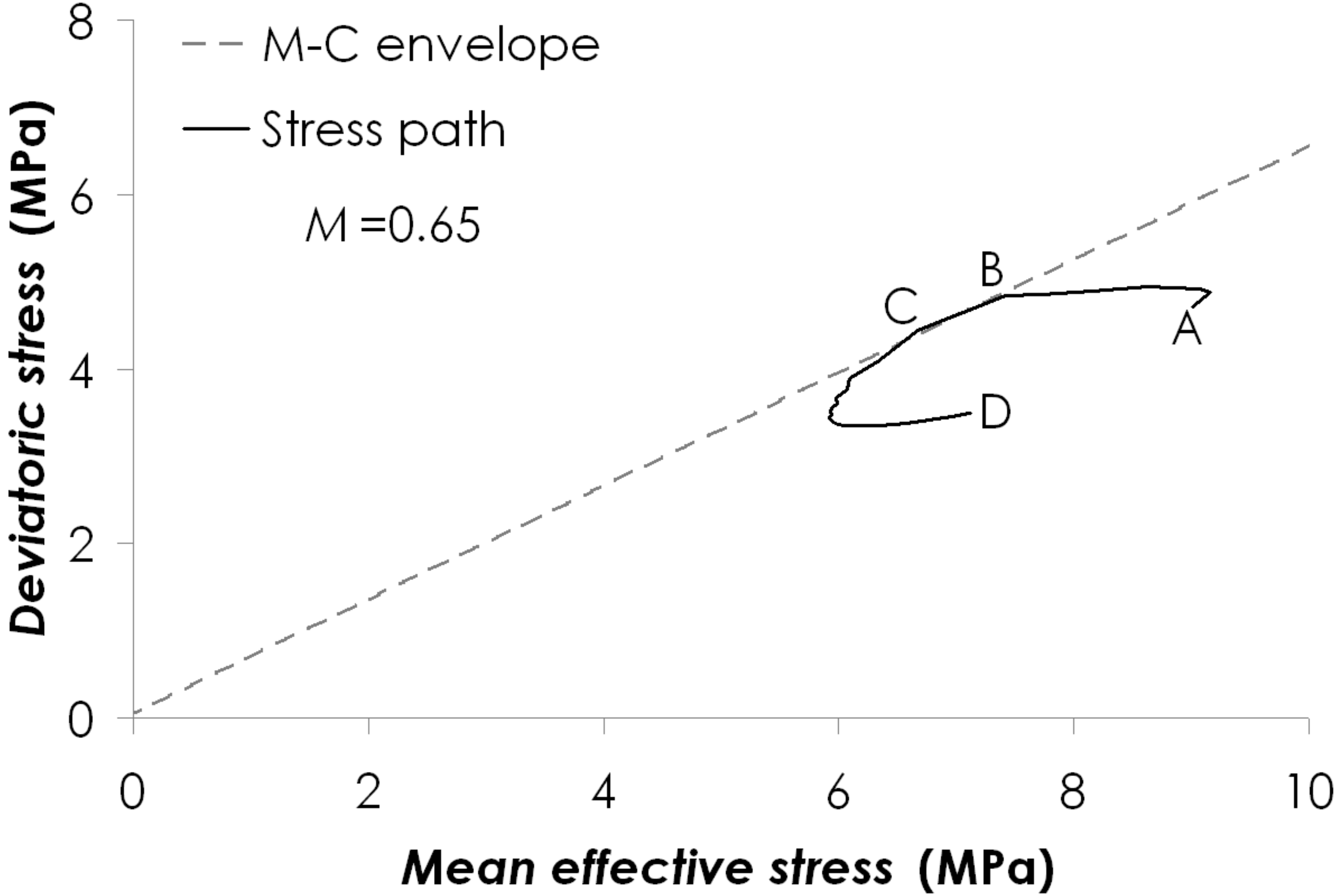
Fluid overpressure for a 100 days injection period, comparing pure hydraulic (H) with coupled hydromechanical (HM) simulation in and



Stress and pressure evolution with time at the beginning of CO_2 injection at the base of the caprock next to the injection well (see location in inset).



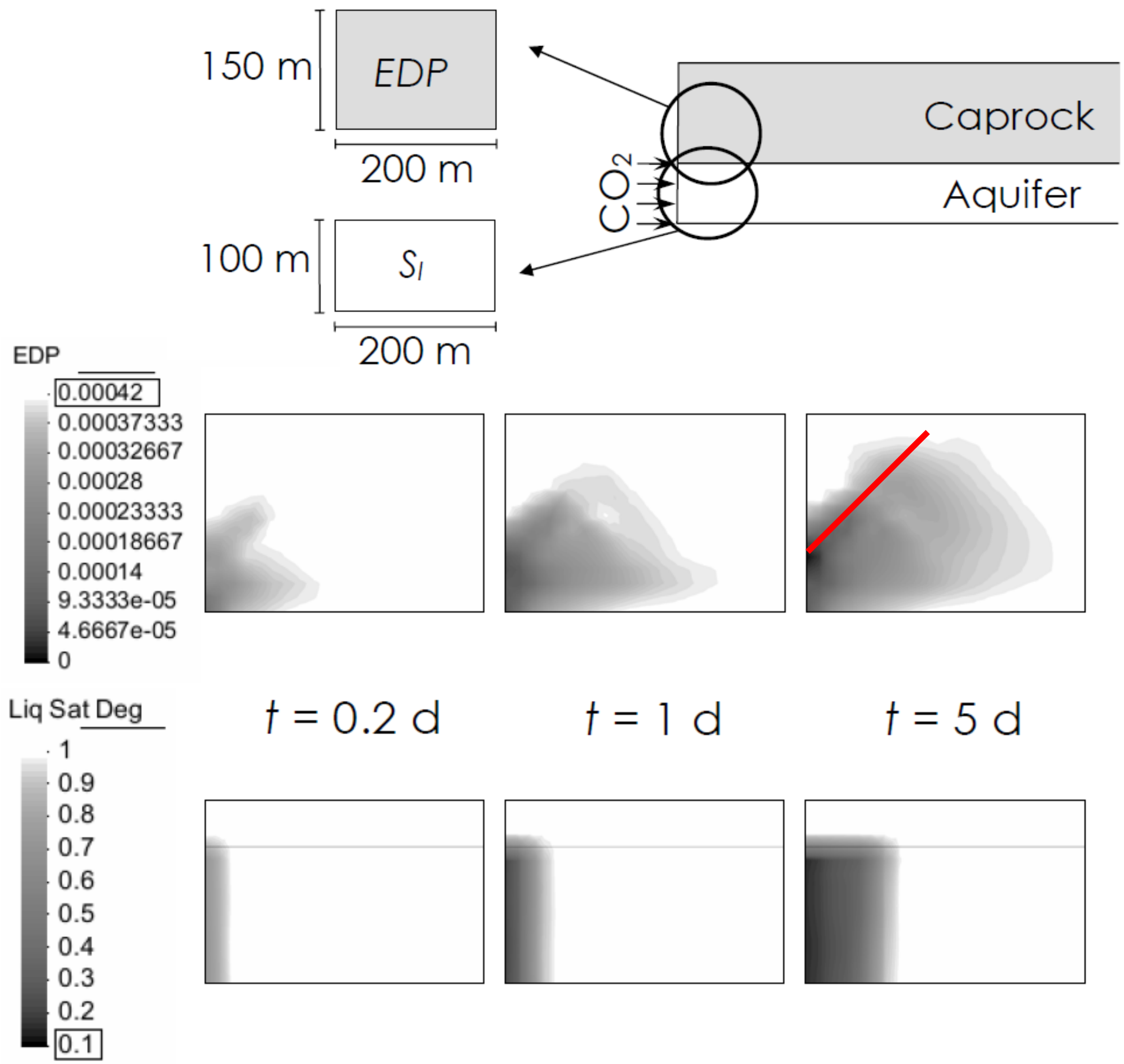
A vertical section of the caprock in the vicinity of the well, with the deviatoric stress, q, and critical the deviatoric stress, q_{critic}, after 4 days of injection. Note that q exceeds q_{critic} in the contact between the caprock and the aquifer, thus causing the caprock to plastify.



: (*q, p'*) trajectory for a 100 day injection. The initial and final states are represented by A and D, respectively. The onset of plasticity takes place during early times (B-C), but plastic behavior eventually stops.

Hydro-mechanical coupling

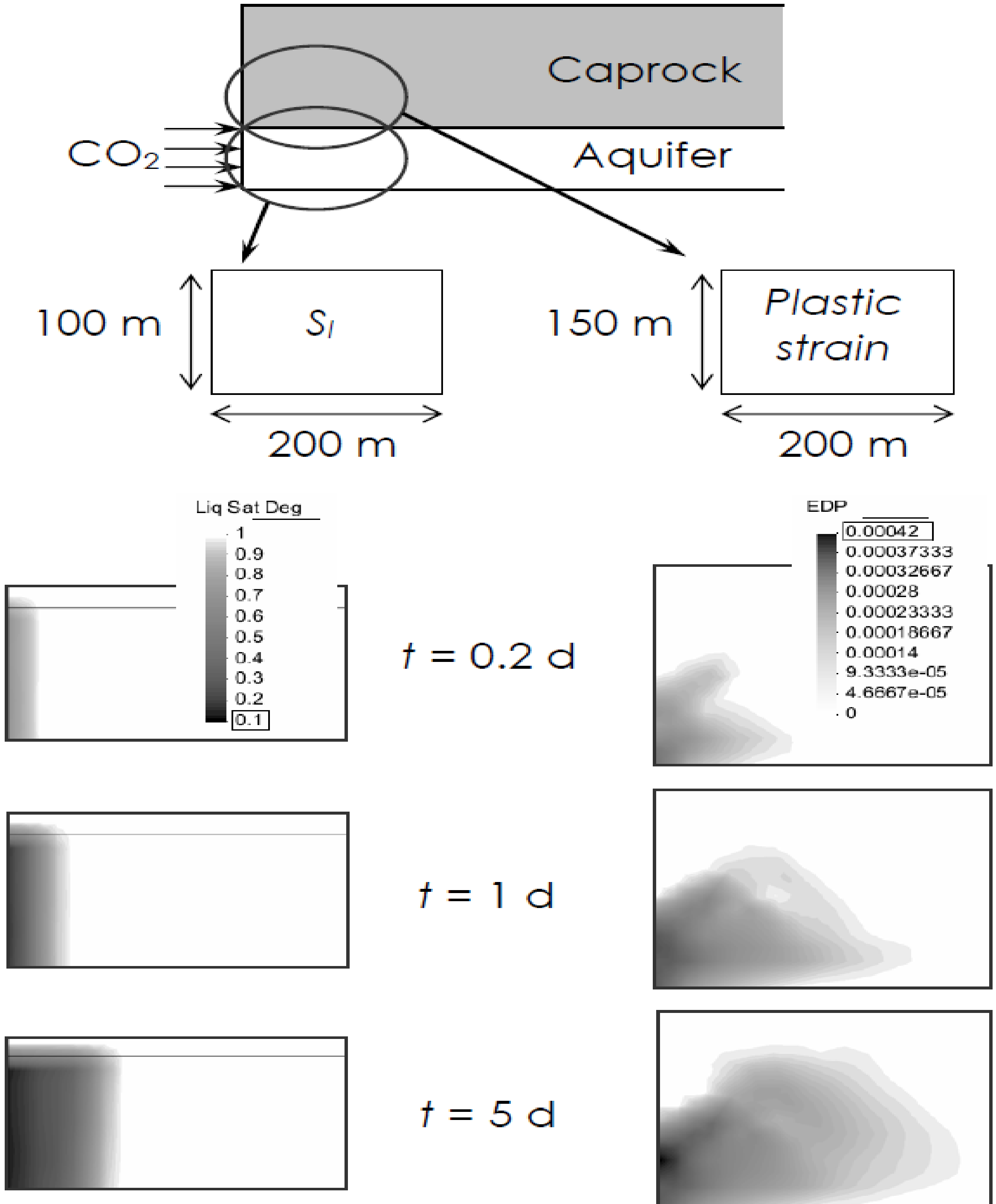
Evolution of deformations and CO_2 saturation



Caprock plasticize as the CO_2 migrates (for a caprock relatively weak)

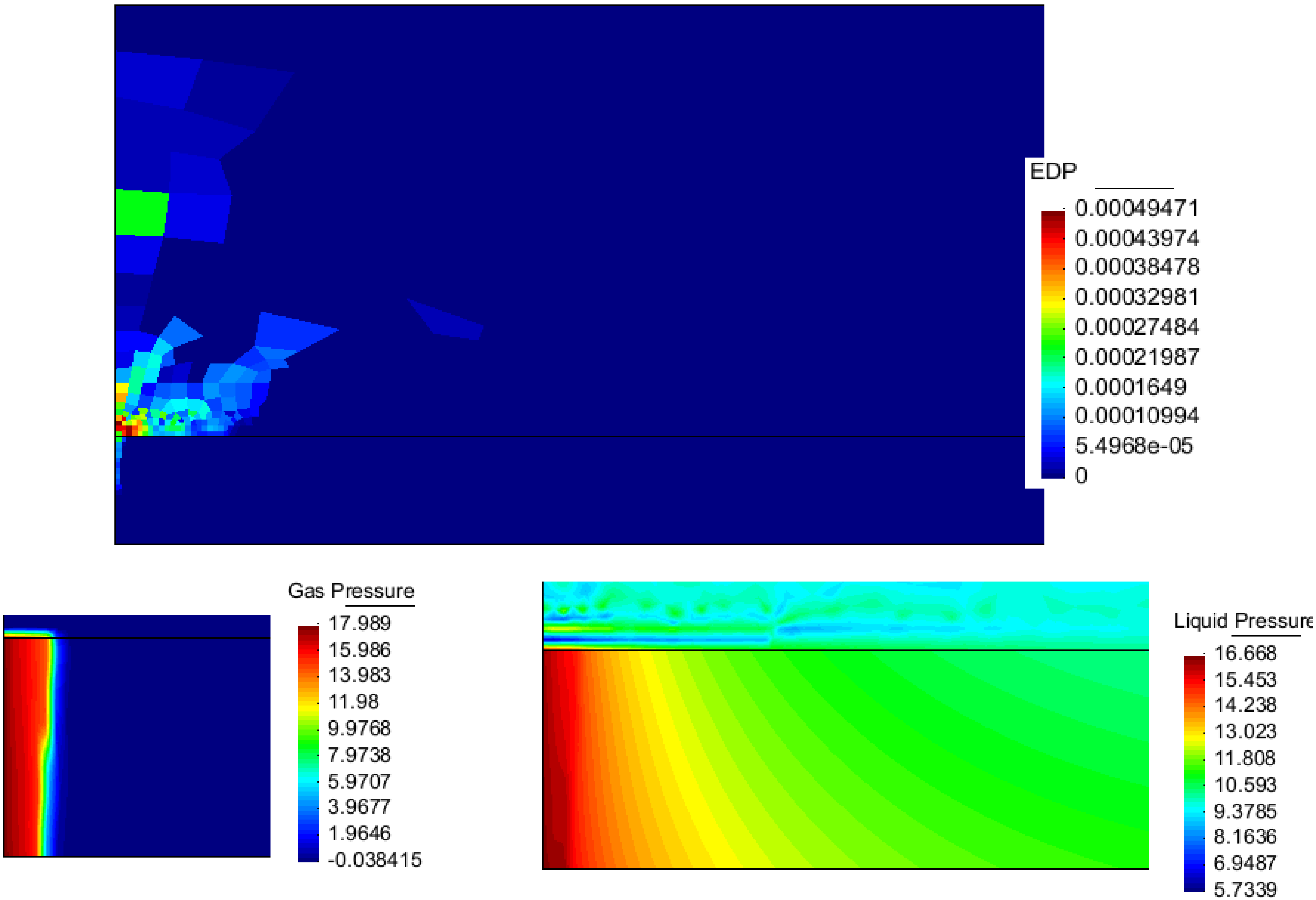
Plastic region propagates in a direction of 45º

Plastic deformations stabilize after 5 days of injection

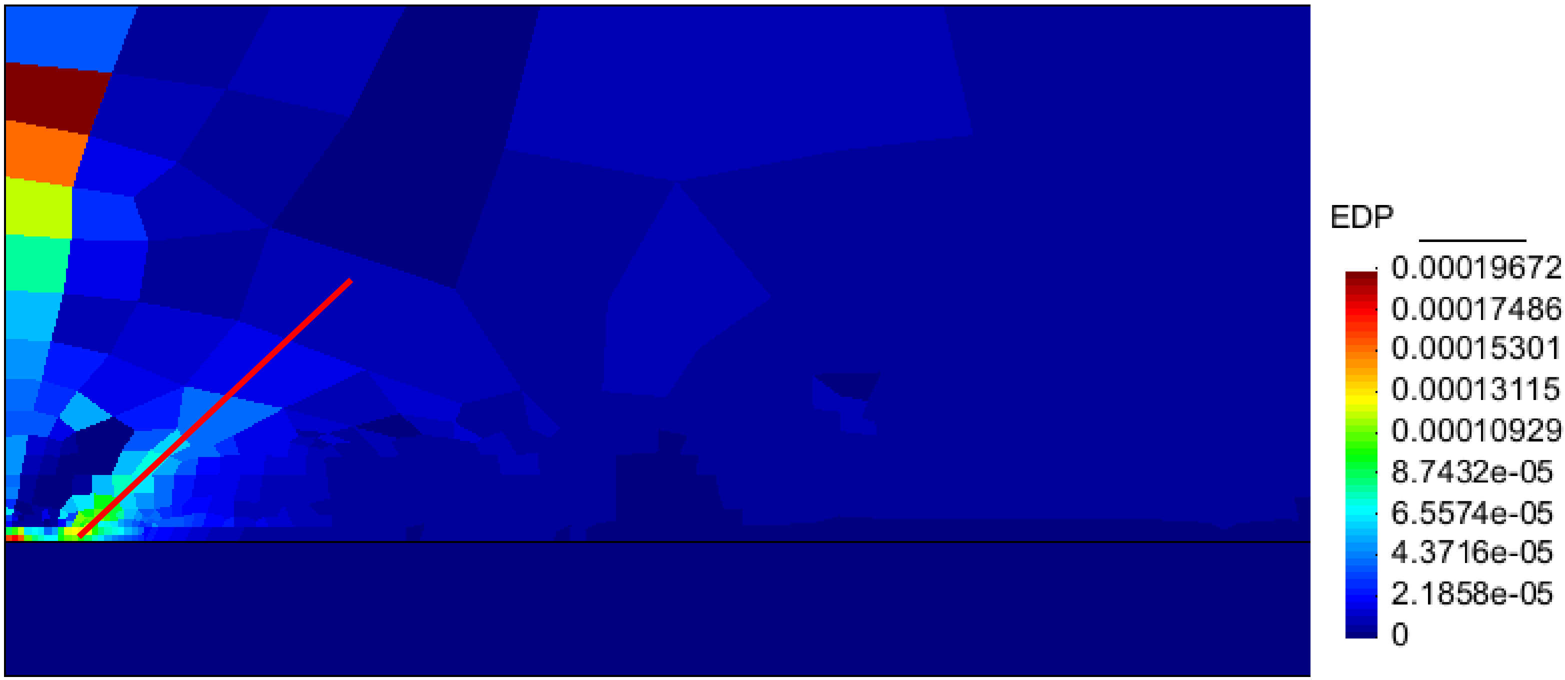


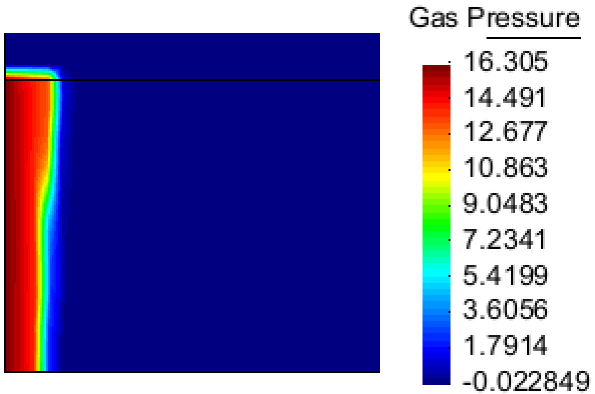
Plastic strain (*EDP*) in the caprock (left) and liquid saturation degree, S_l, in the aquifer (right) for different injection times. Plastic strain propagates as CO_2 advances at the beginning of injection.

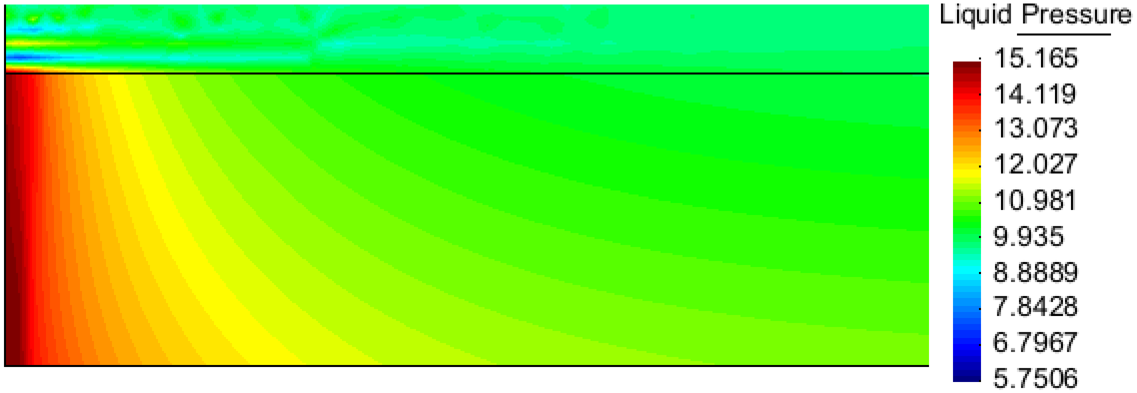
M=0.6 t=1.10703 d



M=0.4 t=1.09063 d







Summary hydromechanical coupling

- Pressure buildup bounded
- HM coupling needed
- Shear conditions worst at the beginning
- Partially monitorable by measuring pressures at cap rock.
- Work on-going

In summary

- Low density and viscosity
- High solubility
- Geochemistry
- Potential mechanical coupling
- Capillary effects
- Thermal effects
- Buoyancy
- Viscous fingering
- Gravity fingering
- Chemical fingering
- Seal Rock failure risk
- Migration of CO2 and/or brine
- and, CCS expensive

TheHontomin challenge:

¿Can we understand all this qualitatively?

¿Can we take advantage of these “problems” to reduce costs?

Key issues

Reduce costs

Reduce Energy:

Permeabilty how much?, how to increase it?

Increase storage capacity

How much, how to increase it?

Reduce requirements

Purity of CO_2?

Increase safety

Improve social acceptance

Tool: Increase understanding

Key parameters

Permeability: Controls

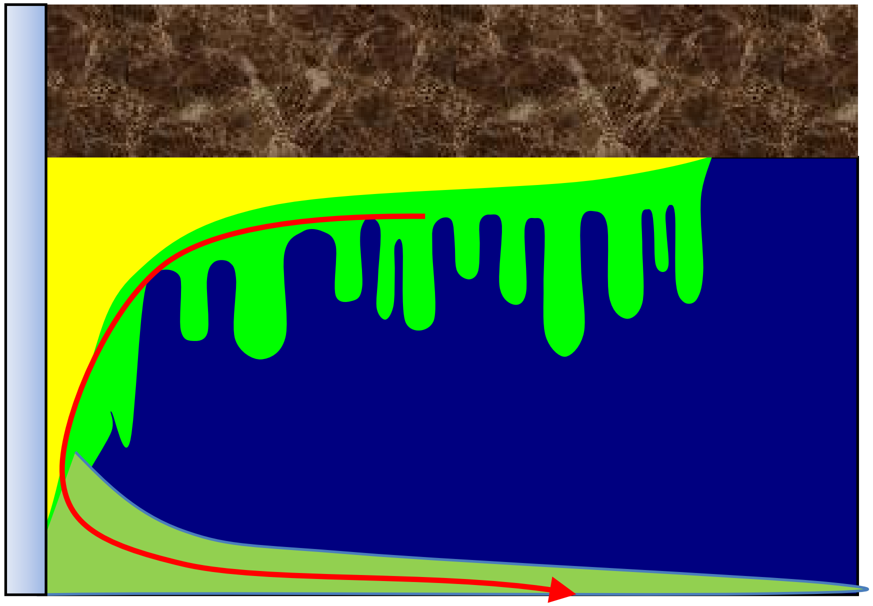
Effective: Buildup of injection pressure

Vertical: Rate of fingering (dissolution)

Connection: Migration of brine

Seal: vertical migration trough seal

(But also entry pressure)



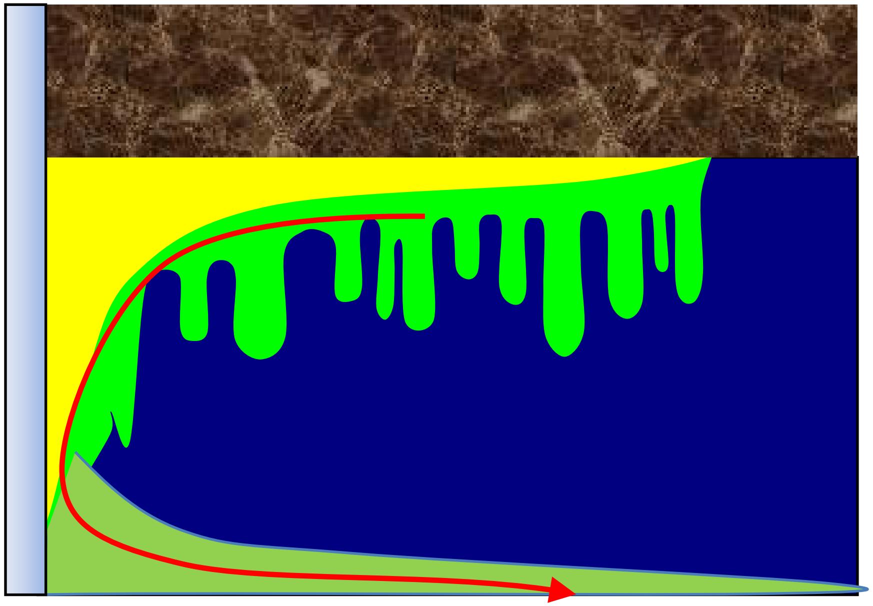
Key parameters

Porosity: Controls

Storage capacity

Porosity increase may increase permeability

But affect mechanical properties

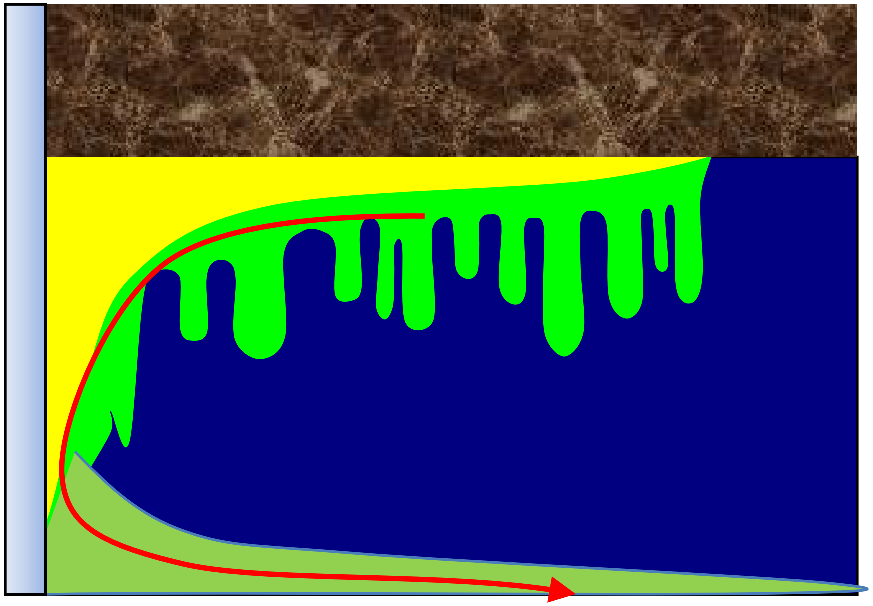


Key parameters

Reactivity: Controls

Porosity and permeability variations

State of CO_2



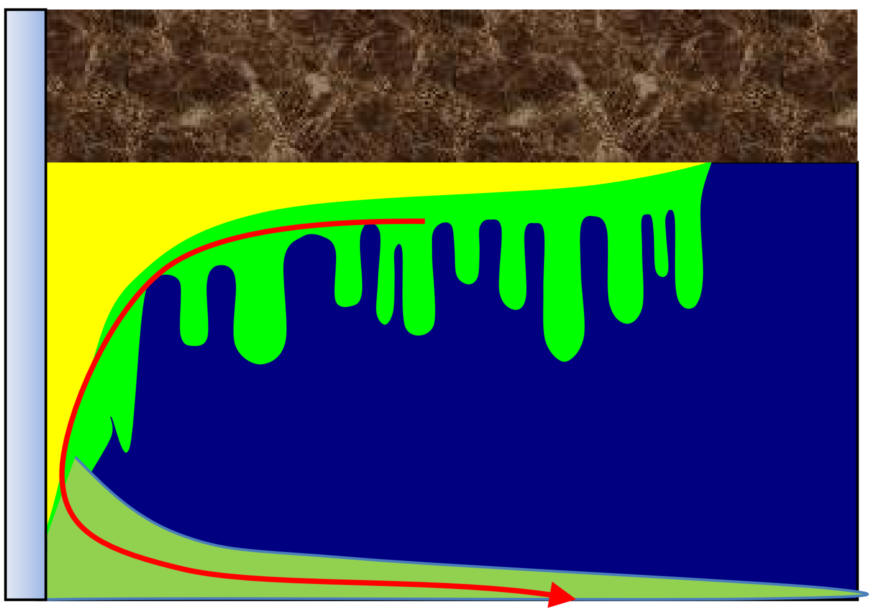
Key issues

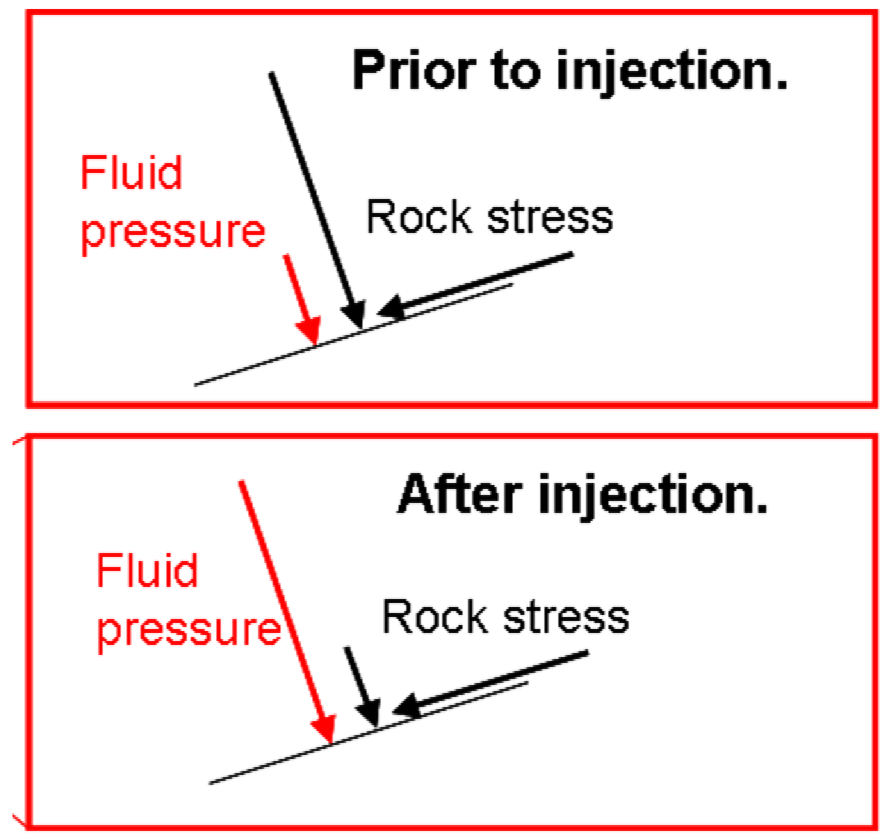
Mechanical properties: Control

Compressibility: storage capacity

Long term safety

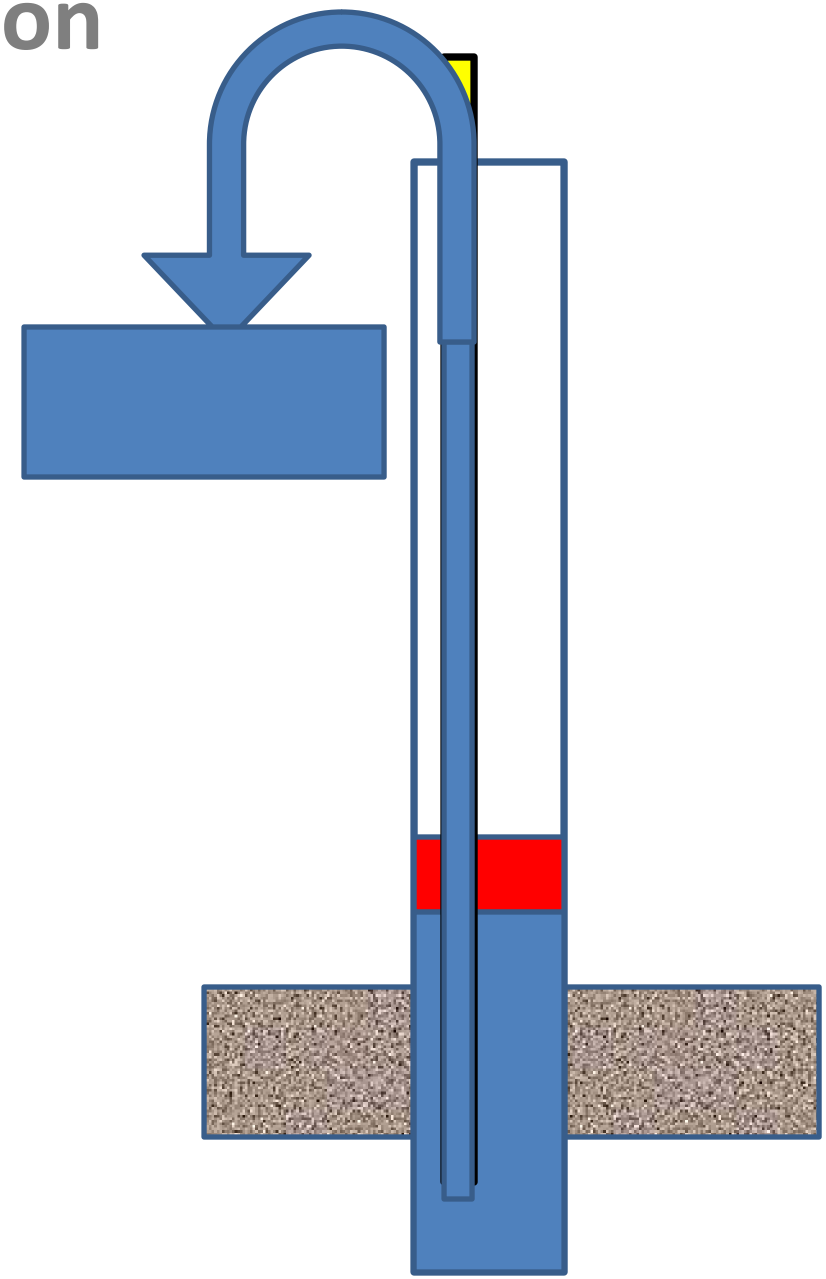
Social perception





Water Injection-extraction
1. Pumping (Quita)

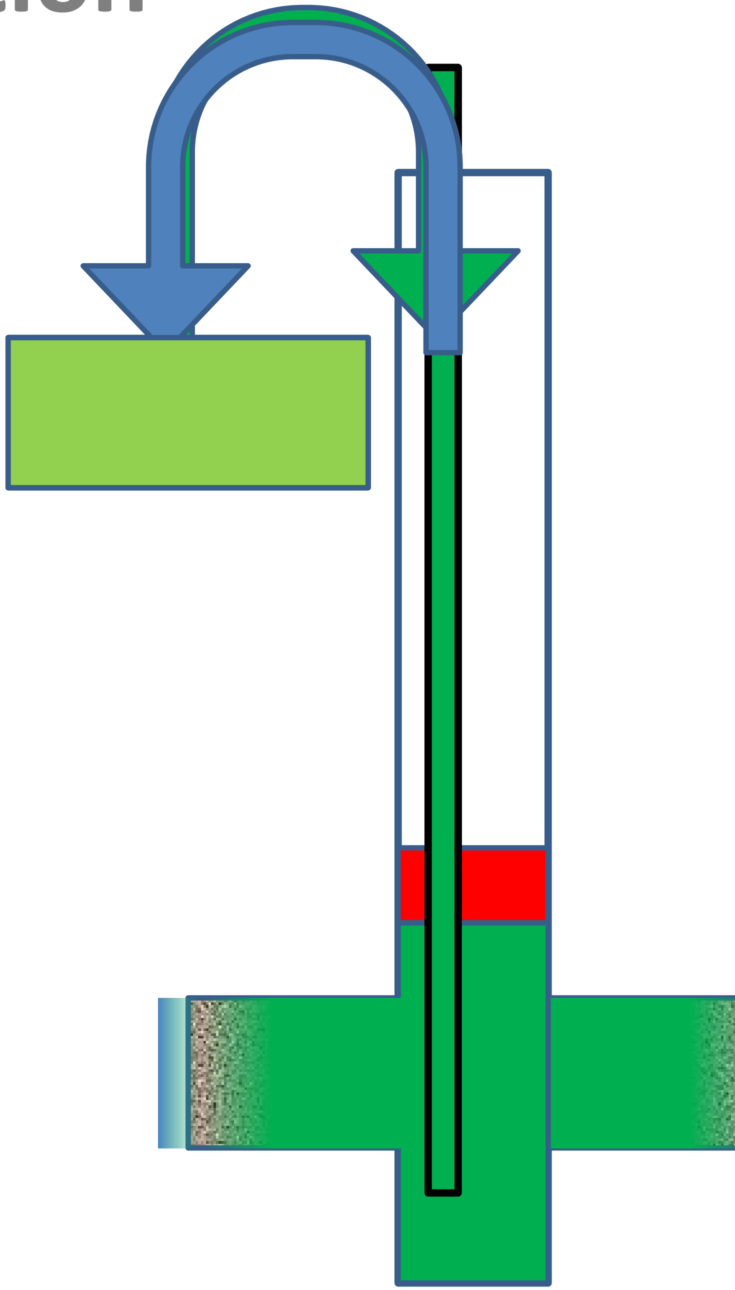
1. Pumping tests = 0.1-10L/s
2. Pumped water needs to be stored (conditioning and storage of up to 10000 m3)
3. Monitor drawdowns at all intervals to obtain Klocal, Keff, Kvert, and S. Also monitor deformation (but expect little).



Water Injection-extraction

2. Injection ("y pon")

1. Add tracer (and biocide)
2. Inject traced water
3. Rest
4. Extract water and monitor tracer(s) breakthrough. To obtain porosity structure, reactivity.
5. Repeat varying nature of tracers (conservative and reactive) and T
6. Repeat varying injection volume and rest time.



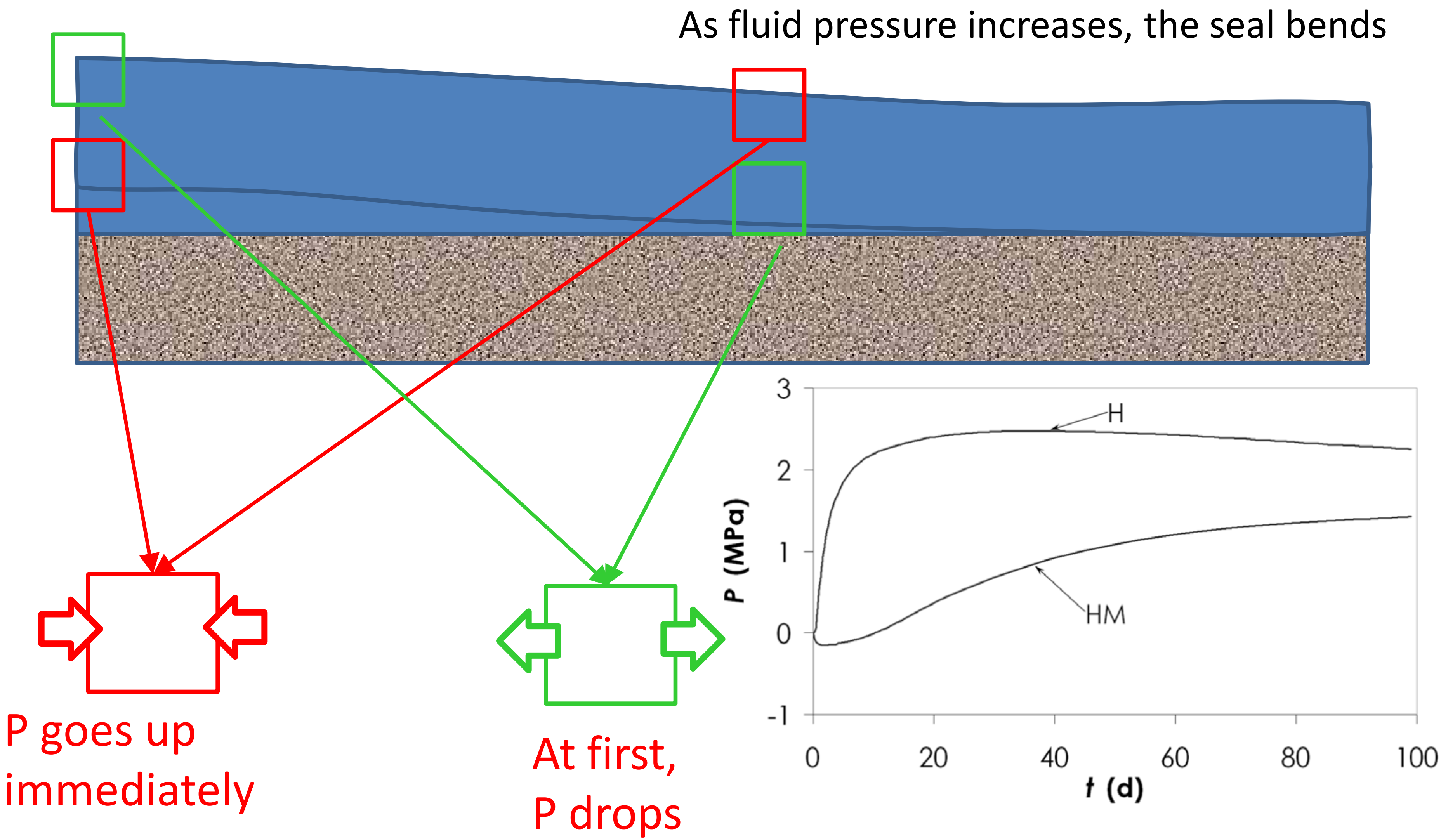
CO_2 push-pull (Mete-saca) test

1. Inject CO_2 (and gaseous tracers). Some 100 t de CO_2
2. Electrical and thermal (heating) tests
3. Extract gas and evaluate mass of CO_2 y concentration of gaseous tracers
4. Electrical and thermal tests
5. Informs about trapping mechanisms (specifically contact area and capillary trapped CO_2)

High pressure (and flow rate) injection test ("apretón")

- Inject a high flow rate at a very high pressure (some 100 bar at surface)
- Observe pore fluid pressure, rock deformation and possible microseisms

Hydro-mechanical coupling during "apretón"



Heating test (“calentón”)

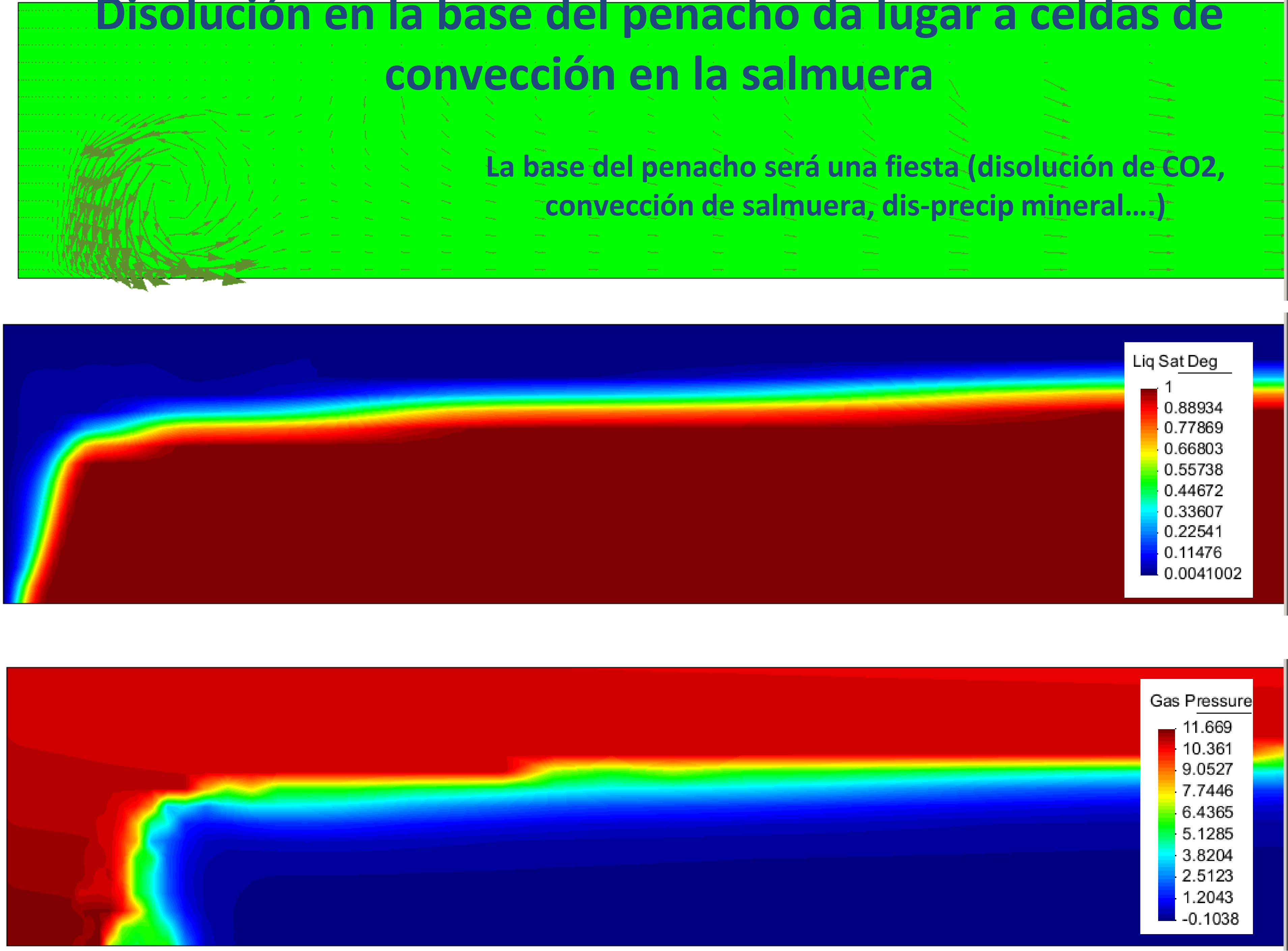
- Heat up the heater along the whole borehole
- Observe temperature buildup
- Deduce termal capacity and conductivity
- Deduce presence of CO_2 (either continuous phase durind injection tests, or capillary trapped during CO_2 “mete-saca”)

CO_2 injection tests

- Conventional
- Fluctuating flow rate
- Liquid CO_2 injection
- Others

Disolución en la base del penacho da lugar a celdas de convección en la salmuera

La base del penacho será una fiesta (disolución de CO2, convección de salmuera, dis-precip mineral….)



Thanks for your attention